QUANTUM COMMUNICATION

TOWARDS

REAL-WORLD APPLICATION

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Jeroen Anton Willem van Houwelingen

de

Leiden / Pays-Bas

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“Light thinks it travels faster than anything but it is wrong. No matter how fast light travels, it finds the darkness has always got there first, and is waiting for it.”

Terry Pratchett, Reaper Man
Abstract

This thesis is devoted to the development and study of quantum optical techniques that allow the use of quantum communication protocols such as a quantum repeater in out-of-the-lab conditions. Up until now almost all experiments in this research field were inside the laboratory. The experiments performed in this thesis aimed to overcome the particular problems that can arise from non-laboratory environments and investigate if there are unexpected complications involved in this.

The first experiment we performed was an entanglement swapping experiment inside the laboratory, but using systems that we believe are suitable for out-of-the-lab use. In order to provide a proof of principle of the employed techniques we used standard single mode optical fibers to simulate a ‘real world’ telecommunication environment. The results of this experiment showed that indeed the chosen systems work in such situations.

In our second experiment we investigated a new technique of performing Bell state measurements. The technique was found to work but the usefulness for real world experiments is hindered by the added losses with regards to more basic Bell state measurements. The technique might have applications in quantum information protocols that require more than one Bell state to be measured.

Next we performed the first teleportation experiment that was performed out of the lab that uses prior entanglement distribution. A qubit was teleported from the laboratory to a Swisscom switching station located 500m away from the lab. For this experiment the qubit was created by a different laser pulse than the entangled pair. This experiment again showed the robustness of our systems in real world environments and effectively dealt with some of the problems that arise from using multiple sites. The only remaining non real-world part of this experiment is that all photons were created in the same lab.

The final part of this work shows the progress made in developing photon-pair sources that can be separated by significant distances. This is required to make a true quantum relay or repeater in which every link is located at a different location.

Some other contributions made during this thesis are tests of a new type of semiconductor photon-pair sources. Also some fundamental Bell test were performed that test some alternative theories to explain correlations found in experiments.

The overall conclusion of this thesis is that the techniques developed are useful for long distance quantum communication in general and specifically for out-of-the-lab application.
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Chapter 1

Introduction

“In the beginning...there was light”[1], or at least that is what a lot of people around the world believe. This phrase applies itself very well to quantum physics. The beginning of quantum physics was when Max Planck discovered, in 1900AC, that he could explain the optical emission spectrum of a thermal source by postulating quantized energy[2]. Five years later Einstein published an important paper[3] on the photoelectric effect in which he introduced “light quanta” which we now call photons[4]. This was the birth of quantum physics. Therefore, indeed, the beginning...was light.

In recent times the interest of physicists has grown beyond that of a fundamental interest and curiosity in quantum physics. A new idea was introduced in 1983 by S. Wiesner[5] in which the quintessential quantum properties were used as resources to perform a certain task that cannot be performed using only ‘classical thinking’. In his specific case the use of the no-cloning theorem[6] in order to create unforgeable “quantum money”. It took a long time for this general idea to catch on but it got a kick-start when P. Shor[7] discovered an algorithm by which a quantum computer could factorize primes rapidly. Since this result a broad interest has grown into a new field of research, quantum communication and information.

1.1 Quantum Communication and Information

Quantum information(QI) is the research field which uses quantum properties to perform computations or simulations that would take a classical computer much longer to solve. For example on a quantum computer Shors algorithm allows the factoring of a large integer number \(N\) in short times (polynomial), but in classical computing such calculations can only be done by brute force and take exponentially long calculation times. Since this long calculation time is the basis for most current cryptography schemes a quantum computer would seriously affect all encrypted communication and storage of data in the world. A second aspect of QI is that a quantum computer is capable of simulating complex quantum systems that cannot be simulated with a classical computer, such as many-body systems with local interactions[8].

Quantum communication(QC) is the research field that tries to distribute quan-
The principle problem in the field of quantum communication is that it is not possible to increase the signal strength during transmission. This is caused by the no cloning theorem.

Figure 1.1: The principle problem in the field of quantum communication is that it is not possible to increase the signal strength during transmission. This is caused by the no cloning theorem.

Figure 1.2: Graphic representation of a quantum repeater. The squares represent quantum memories and the stars photon-pair sources. At the position where the arrows meet a Bell-state analyzer (BSA) is used which ‘swaps’ the entanglement.

tum states between two or more locations. Such a distribution is required for a quantum world-wide-web once quantum computers are developed, but in a shorter term quantum states can be distributed in order to perform quantum key distribution (QKD)[9]. QKD is currently the only system in the world that makes it possible to secretly share two random series of bits at two distant locations. Combined with one-time-pad encoding[10] this means that QKD is the only way in which provably secure cryptography can be performed.

At first glance it might seem simple to distribute a quantum state. You take a photon, encode the desired quantum state, send it through a fiber and wait until it arrives at the other end, voila! Unfortunately such simple methods only work well for short distances since fibers and any other means of transmission have losses. In classical communication such losses can be dealt with by adding ‘signal boosters’ (Fig. 1.1). In quantum physics, however, the no cloning theorem shows that an amplifier is not possible therefore another form of long distance transmission must be found (Fig. 1.1). The answers to this problem can be found in the quantum relay and quantum repeater based on quantum teleportation[11, 12, 13], entanglement swapping[14] and quantum memories[15]. A quantum repeater is a cascade of entanglement swapping protocols and quantum memories which allow the distribution of an entangled state in multiple independent steps. A quantum relay is very similar but doesn’t use quantum memories (Fig. 1.2).
1.2 This thesis

This thesis contains the work performed at the university of Geneva in the group of applied physics under guidance of prof. N. Gisin and dr. H. Zbinden since October 2003. The goal of this thesis is to experiment with the possibility to take quantum teleportation out of the lab and into a so-called ‘real world’ environment. Several experiments have been done in order to test the viability and difficulties which can arise for a long distance quantum link. The contents of this thesis is arranged as follows:

In the first chapter a short introduction will be given as well as the layout of the thesis. The next four chapters will explain some of the basic knowledge used throughout the rest of the thesis. The second chapter will describe in general what a qubit is and more specifically which type of qubit will be used during the rest of the thesis. In the third chapter we will discuss photon-pair sources and single photon sources. Chapter four introduces single photon detectors. The fifth chapter discusses the use of entanglement in quantum communication.

The chapters after this each concern one of the main experiments performed during this thesis. Chapter six discusses long distance entanglement swapping. Chapter seven will discuss the importance of the Bell-state measurements and a new method for this is introduced. The eighth chapter discusses the first out-of-the-lab demonstration of quantum teleportation and chapter nine discusses the progress towards creating synchronized photon sources.

Some other contributions made during this thesis will be described in chapter ten. The last chapter will give some overall conclusions and a short outlook for the continuation of this work.
Chapter 2

Qubits and time-bins

2.1 Qubits

In information science the elemental building block is the bit, a number being either 0 or 1. In the field of quantum information there is a similar concept: the quantum bit, commonly called a qubit. A qubit is a quantum-state in a coherent superposition of being $|\psi_0\rangle$ and $|\psi_1\rangle$, where $|\psi_0\rangle$ and $|\psi_1\rangle$ are two orthonormal quantum-states. In order to simplify the notation we define $|0\rangle \equiv |\psi_0\rangle$ and $|1\rangle \equiv |\psi_1\rangle$. A general qubit state $|\Psi\rangle$ can be written as:

$$|\Psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$$  (2.1)

where $\alpha^2 + \beta^2 = 1$ and $\phi$ is the phase difference between $|0\rangle$ and $|1\rangle$. It is possible to represent a qubit on a Poincaré-sphere (Fig. 2.1).

There are some important differences between a qubit and a bit. The first difference can be clearly seen on the Poincaré-sphere. A classical bit is represented by either of the two poles, whereas a qubit is represented by any point on the shell of the sphere. This is because the qubit can be in a superposition state of $|0\rangle$ and $|1\rangle$ and a classical bit cannot.

Another difference between a bit and a qubit is caused by the no-cloning theorem which states that it is not possible to create a perfect copy of an arbitrary and unknown quantum-state. Therefore it is not possible to create a perfect copy of a qubit. Obviously copying classical bits is possible. This difference has direct applications in the field of quantum cryptography.

Finally it is possible for several qubits to be in an entangled state. This be will extensively used and explained later in this thesis.

So far bits and qubits were discussed as concepts, obviously their physical implementation is also important. It is possible to create many different types of (qu)bit-systems but they can be broadly separated into two different groups: stationary-(qu)bits and flying-(qu)bits. As the names indicate, the flying (qu)bits are (qu)bits

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1The Poincaré-sphere is generally used in optics to describe the polarization state. Since polarization is the most used form of qubit encoding the Poincaré-sphere is also often used to represent qubits. For spin qubits the Bloch-sphere is used. Sometimes the more general term qubit-sphere can also be found.
Figure 2.1: A representation of a qubit on a Poincaré-sphere. Any point on the shell of the sphere corresponds to a state $|\Psi\rangle = \cos \frac{\theta}{2}|0\rangle + \sin \frac{\theta}{2}e^{i\phi}|1\rangle$ with $0 \leq \theta \leq \pi$ and $0 \leq \phi < 2\pi$. A classical bit corresponds to either of the two poles ($\theta = 0$ or $\pi$).

which can be transmitted over significant distances without a change in their (qu)bit-state and are used for (quantum) communication. Stationary (qu)bits are typically motionless and interesting for (quantum) information storage and computing.

2.1.1 Stationary-(qu)bit implementations

Stationary classical bits are usually encoded in ensemble properties such as the magnetic dipole-moment. In such systems there is a very small chance of measuring a ‘0’(‘1’) when the encoding is a ‘1’(‘0’) and furthermore there is a very small chance of a physical change between values (a bitflip). For qubits there is a large zoology of possible two-level quantum mechanical systems that have been investigated. One of the added problems with qubits compared to bits is the sensitivity to decoherence. Once a quantum state is encoded many effects can force a change in the qubit, most often a phase-decoherence. Decoherence means that the state no longer corresponds to a point on the qubit sphere but the vector has a length $<< 1$. The most important reason to choose a particular quantum system is its experimental feasibility and ease of manipulation. The most common stationary-qubits are spins[17] or different energy levels[18] but many others exist[19]. Stationary qubits won’t be discussed further in this thesis. Several flying qubit implementations are discussed below.

2.1.2 Flying-(qu)bit implementations

Flying classical bits are often different voltages in cables or light intensities in optical fibers. Flying qubits are usually encoded onto photons. The reason for this is obvious: a photon can travel long distances quickly and with small losses in optical fibers. Furthermore the telecommunication industry is nowadays extremely active and still growing, therefore potential applications of photonic qubits can count on a large and well developed industry if the proper wavelengths are used. In this thesis time-bin qubits are used but it is instructive to first consider some other types of flying qubits.
Figure 2.2: Schematic representation of how to generate and then measure a spatial mode qubit. A photon passes through variable coupler VC. Both outputs are then sent to an analyzer where one path gets a phase delay $\gamma$ with regards to the other path. The paths are combined on another variable coupler and detected by detector $D_0$ or $D_1$.

**Polarization mode**

A common form of qubit encoding is in the polarization mode[20, 21] of a photon. A single polarized photon is in a state $|\Psi\rangle = \alpha|H\rangle + \beta e^{i\phi}|V\rangle$. Here the notation $|H\rangle$ ($|V\rangle$) is used for a single photon Fock-state in which the photon is polarized along the H (V)-axis. It is easy to recognize this as a qubit state (eq. 2.1) with $|H\rangle \equiv |0\rangle$ and $|V\rangle \equiv |1\rangle$.

Polarization qubits can be generated by passing a photon through a polarizer followed by a birefringent medium. The angle of the polarization determines $\alpha$ and $\beta$ and the birefringence determines $\phi$.

Analysis of a polarization encoded qubit can be done by passing the photon through a polarizing beamsplitter. This projects the state on either $|0\rangle$ or $|1\rangle$. For other projections it is possible to use a half-wave plate to turn the polarization just before the beamsplitter and birefringent materials to adjust the phase relation.

Although polarization qubits are easy to create and manipulate, they are subject to polarization mode dispersion (PMD)[22] in optical fibers. For this reason other types of encoding are of interest when one is interested in using fiber links.

**Spatial mode**

Another possibility for encoding flying qubits is the spatial mode of a photon, this type of qubit encoding is also known under the name ‘dual-rail’ encoding[23]. Lets consider what happens with a photon that passes a fiber-optics coupler. After the coupler the photon is in one of the two exit ports and can be defined by the states $|T\rangle$ and $|R\rangle$, where $|T\rangle$ ($|R\rangle$) is the one photon Fock-state in the transmission (reflection) mode of the coupler. The quantum state after the coupler is $|\Psi\rangle = t|T\rangle + re^{i\phi}|R\rangle$ with $r^2 + t^2 = 1$. Again we readily identify the qubit-state with $|T\rangle \equiv |0\rangle$ and $|R\rangle \equiv |1\rangle$ (Fig. 2.2). For a 50/50-coupler $r = t = 1/\sqrt{2}$ but arbitrary $r$ and $t$ can be created by using a variable coupler. The phase $\phi$ depends on the difference of path lengths travelled. In fiber optics experiments this parameter can be highly unstable due to fluctuations in fiber length caused mainly by temperature drifts and
vibrations making this scheme impractical for many applications.

Analysis of a spatial-mode encoded qubits can be done by directly measuring each mode. This projects the state on either $|0\rangle$ or $|1\rangle$. Alternatively recombining the modes on a variable beamsplitter with a certain phase difference $\gamma$ allows projection onto two points opposite each other on the Poincaré-sphere (Fig. 2.2).

Here it should be noted that both polarization and spatial mode can also be considered as the same type of encoding, namely propagational-mode encoding. The big difference for experiments is that two different polarization modes can pass through the same spatial mode which is experimentally more useful than two spatial modes having the same polarization mode.

Time-bin

As noted above, it is very challenging to maintain a fixed phase $\phi$ when using spatial mode encoding. A modified version of this scheme is better suited for quantum communication in optical fibers. First the ideal situation will be explained followed by a small adaptation caused by technical limitations.

Consider the following situation (Fig. 2.3): a photon from a pulsed source passes through a variable coupler and is separated into two different spatial modes, at this point the state is a spatial mode qubit. Both modes are allowed to propagate a short distance but one of the two modes propagates a distance significantly longer than the other mode (the difference has to be larger than the coherence length). Both modes are then recombined using an ultra-fast optical switch. This is possible since the time of arrival of the photon on the switch is different for both modes. After the switch the photon will be in one spatial mode (the guided-mode of the switch) but at two different times. The state created in this manner is of the form:

$$|\Psi(t)\rangle = \alpha|\psi(t)\rangle + \beta e^{i2\pi \frac{\tau}{\lambda}}|\psi(t-\tau)\rangle$$

(2.2)

where $\tau$ is the difference in time of arrival on the switch, $c$ the speed of light and $\lambda$ the wavelength. For the qubit state define $|\psi(t)\rangle \equiv |0\rangle$, $|\psi(t-\tau)\rangle \equiv |1\rangle$ and $\phi \equiv 2\pi \frac{\tau c}{\lambda}$. 

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**Figure 2.3:** Schematic setup for creating and analyzing a time-bin qubit. First a photon is send through a variable coupler (VC), after travelling different distances the two path are recombined using a switch (SW). For analysis of the state this process is reversed.
As indicated in the beginning of this section, this encoding scheme is much easier to stabilize, there are two experimental constraints. First of all a stabilization of the path length difference $\tau c$. This is required in order to have a well defined qubit. Secondly a stability of the transmission fiber on timescales of the order of $\tau$ is required in order not to alter the qubit during transmission. The last requirement is automatically satisfied for ns-scale delays whereas the first requirement is experimentally feasible. This encoding scheme is called time-bin encoding[24]. For simplicity we will often use “a time-bin qubit” or simply “qubit” when we mean “a photon encoded with a time-bin qubit”.

Analysis of time-bin qubits can be done as follows. If it is desired to project the state on $|0\rangle$ or $|1\rangle$ it is sufficient to determine the time of arrival relative to the time of emission of the photon. For a more general projection it is possible to do the inverse of the time-bin creation. First the qubit will pass through a switch followed by path length difference identical to the one used in the creation of the qubit. At this point the photon arrives at a coupler in a superposition of being in one input port or the other. The output port of the photon will then be determined by the phase difference of the encoding and decoding paths. This method determines the phase of the qubit.

Unfortunately the time-bin scheme is not technologically feasible when $\tau$ is small (order of a ns). The above mentioned low-loss fast optical switches required in order to create and analyze the qubits don’t exist yet. An alternative is to use a 50/50 coupler. This means that half of the time the photon will exit through the wrong port and will be lost. When this technique is used the encoding device corresponds to an unbalanced interferometer. All experiments in this thesis use this technique.

At this point it is interesting to note another difference between polarization encoding and both time-bin encoding and dual-rail encoding. It is possible to extend the time-bin or dual-rail scheme to multiple dimensions ie. create $d$-dimensional qudits[25, 26] This can be done by using multi channel couplers and switches and having $d$ different possible time delays (Fig. 2.4) for the time-bin scheme or $d$ different paths for the dual-rail system. Polarization encoding is limited to the two polarization modes, and can therefore only be used for 2-dimensional qubits.

For the experiments done in this thesis all qubit encoding was done using time-bins created with the described interferometer techniques. Technical details will be
Figure 2.5: It is possible to create time-bin qubits based on spatial mode dispersion or polarization mode dispersion. The two resulting qubits are completely equivalent. PM is a polarization modulator.

discussed later in this thesis.

2.1.3 Alternative time-bin creation

The relation between time-bin encoding and spatial mode encoding is very clear. Time-bin encoding is a truncated version of spatial mode encoding. Since there is also a large similarity between polarization encoding and spatial mode encoding it is interesting to consider if it is possible to also make a truncated version of polarization-encoding?

It is possible to transform a polarization qubit into a spatial mode qubit by separating the polarizations on a polarizing beamsplitter. It is then possible to proceed as above to construct a time-bin qubit. This method has no experimental advantages over directly creating spatial mode qubits since the requirements are basically the same. Another alternative would be to directly go from polarization to time-bin (Fig. 2.5). This can be achieved with a large delay which is generated between both polarization modes while they are in the same spatial mode. This can, for example, be done with high-birefringence (hibi) materials. After a certain length of such hibi-material the two polarization modes are well separated in time/space. The final step is to put both polarization modes into the same mode. This can either be done by a fast polarization modulator in analogy with a fast switch, or by having a PBS at 45 degrees with respect to the qubit encoding axes. In this last case the two exit ports are equivalent to the two exit ports of the time-bin generating unbalanced interferometer. This method for generating time-bin qubits hasn’t been experimentally investigated to our knowledge because it requires large amounts of expensive hibi-materials, but if higher birefringence materials can be found it will be interesting to see if it is not experimentally more convenient.
Chapter 3

Photon-pair sources and single photons

3.1 Introduction

In the previous chapters it was assumed that it is possible to create and to manipulate single photons and photon pairs. Since such sources will be extensively used later in this thesis an explanation of their functioning will be given in this chapter.

Naively one would think that it is easy to create a photon. Just think of a humble light-bulb, it easily generates $10^{18}$ photons per s (assuming 50W with 1% efficiency and only 400nm photons), so how hard can it be to create one photon? It turns out that, although it is easy to create a photon, it is a lot more difficult to create a single specific photon at a specific time.

The important parameters for both single photon sources and photon-pair sources are:

1. Output rate
2. Collection efficiency and internal losses
3. Wavelength and tunability
4. Bandwidth of created photons
5. Statistics

The importance of the first parameter is obvious. Since high transfer rates are commonplace in modern telecommunication, QC applications also require reasonably high rates in order to be useful. Transfer rates are in practice often limited by transmission and detection losses. However, it is not the case that the output rate should be as high as possible in order to compensate. Currently sources are mainly probabilistic sources, and for protocols such as quantum teleportation to function the probability of emitting more than one photon(-pair) needs to be kept small.

The second parameter is of importance mainly in photon-pair sources, in single-photon sources a low collection efficiency can, in principle, be compensated by higher
output rates. In photon-pair sources, however, it is important that whenever one photon is collected that there is a large probability of collecting the second photon of the same pair, and that this probability is higher than the possibility of collecting a photon from another pair.

The wavelength (point three) is obviously of importance because all manipulations depend on the wavelength and tunability is important because in many QC protocols it is important to create photons with the same wavelength in different sources. For experiments that use standard fiber optics the wavelengths with lowest losses are around 1.5µm. Also wavelengths around 1.3µm have low losses and furthermore have zero dispersion.

The bandwidth and coherence length are important mainly in experiments that aim to use indistinguishable photons. For the case of gaussian pulseshapes the coherence length $l_c$ is linked to the bandwidth as follows:

$$l_c = \frac{2\ln2}{\pi} \frac{\lambda^2}{\Delta\lambda}$$

(3.1)

In the QC protocols used for this thesis it is important that photons arrive ‘at the same time’. This means that the photons should arrive within their coherence lengths. In order to make this experimentally feasible large coherence lengths are useful, and thus smaller bandwidths are desirable.

Finally the statistics of the source are important. In other words the $g^{(2)}(0) = 2p_i^2$ parameter should be as low as possible. $p_i$ is the probability to create $i$ pairs or single photons at the same time. An ideal source has $g^{(2)}(0) = 0$.

### 3.2 Single photon sources

The techniques used for single-photon sources have seen a lot of development recently. Some of the designs involve quantum dots[27], vacancy centers in diamond[28] and heralding from frequency conversion photon-pair sources. In this thesis the last technique will be used. It consists of using a photon-pair source (see section 3.3) and a single photon detector. Assuming that both photons from the pair are not identical, in our case because of different wavelengths, it is possible to deterministically separate them. After this separation one of the two photons is sent to a detector. If the detector finds a photon it is known the other photon was created as well and the detector sends out a heralding signal (Fig. 3.1). Note that although it is certain that both photons are always created as a pair, it is not guaranteed that both photons will be collected.

Another type of single photon source used in this thesis is a photon-pair source from which a single photon is discarded without detection. Such a source has a higher output rate than a heralded source but it has more noise. However the $g^{(2)}(0)$ parameter of such a source ($g^{(2)}(0) = 2$) is worse than that of a attenuated laser ($g^{(2)}(0) = 1$), it should therefore be considered as a pseudo-single photon source.
3.3 Photon-pair sources

The most commonly used technique for photon-pair creation is spontaneous parametric downconversion (SPDC)[29]. Other, less used, techniques will be briefly reviewed at the end of this chapter.

3.3.1 Spontaneous parametric downconversion

Non-linear effects can happen in media with a strong non-linear coefficient $\chi^{(n)}$, $n > 1$. Non-linear in this case relates to the non-linear response of the polarization $P$ of a media to the electric field $E$ of light. The dielectric polarization can be written as follows:

$$P(t) \propto \chi^{(1)}E(t) + \chi^{(2)}E^2(t) + \chi^{(3)}E^3(t) + \text{etc.} \quad (3.2)$$

Effects caused by higher order terms are normally not visible because they occur with extremely low probability. $\chi^{(2)}$ is zero in centro-symmetrical systems such as a standard optical fiber but in certain materials they can be large enough to see effects, such as in Lithium Borate (LBO) crystals. A large $\chi^{(2)}$ results in three-wave mixing effects, such as spontaneous parametric downconversion (SPDC) or second harmonic generation (SHG).

In SPDC a single photon is transformed into a pair of photons (Fig. 3.2) through a non-linear interaction with the medium. Energy and momentum conservation lead to the following constraints on this process:

$$\omega_p = \omega_s + \omega_i \quad (3.3)$$

$$\vec{k}_p = \vec{k}_i + \vec{k}_s \quad (3.4)$$

here $\omega_j$ is the frequency and $\vec{k}_j$ the wavevector. The subscripts p, s and i stand for pump, signal and idler respectively.

In order to adhere to the first constraint the created photons must have frequencies symmetrically located around half the pump frequency.
The second constraint is more demanding, since the medium in which the SPDC occurs has chromatic dispersion the velocities of all components of the SPDC are not equal. This leads to a dephasing of pump-photons and signal/idler-photons which in turn leads to destructive interference. There are two practical solutions to this problem.

The first solution is so-called phasematching by birefringence. By using a material which has a large difference in refractive index as a function of the polarization it is possible to achieve a situation in which the pump-photons and the created photons travel at the same speed (ie. their phase will remain matched). This type of phase matching is limited to certain wavelengths depending on the refractive index $n$. A method to tune which wavelengths can be generated is changing the temperature and thus the phase-matching conditions. Materials which are suited for such techniques are for example LBO, beta-Barium Borate (BBO) and Potassium Titanium Phosphate (KTP).

The second solution is quasi phase-matching. This solution requires a material in which $\chi^{(2)}$ changes its sign periodically. In such a material the phase-matching is such that the photons are never interfering destructively but there is always (non-optimal) constructive interference. In this case the requirement 3.4 is changed to:

$$\vec{k}_p = \vec{k}_i + \vec{k}_s + \vec{K}$$

$$|\vec{K}| = \frac{2\pi}{\Lambda}$$

here $\Lambda$ is the poling period. Materials using this type of phase matching are referred to as periodically poled (PP), for example PP Lithium Niobate(PPLN) or PPKTP. Quasi phasematching has the advantage over birefringence phasematching that it is possible to create a very large range of wavelengths since there is a different parameter that can be changed. Futhermore it allows the use of higher non-linear coefficients.

The overall efficiency of the SPDC process is determined by the $\chi^{(2)}$ parameter of the non-linear medium and the interaction length. The efficiency is thus limited by the choice of material and in that respect it cannot be easily increased. One method that can be used to increase overall conversion is to use a longer non-linear medium. An increase of the power density can be accomplished by using waveguide structures to confine the light. The use of waveguides with birefringent phasematching is complicated by the polarization requirements of the guide. However it is possible to create waveguides in PP-materials, for example by using soft-proton exchange techniques in order not to affect to the periodical poling.

### 3.3.2 Alternative sources

Besides SPDC several other types of photon-pair sources exist. Not all of them will be discussed here but some of the better known sources will be briefly explained.

One promising type of source of telecommunication wavelength photon-pairs uses 4-wave mixing. The process used is similar to SPDC but it uses two pump-photons to generate a pair.

$$\omega_{p1} + \omega_{p2} = \omega_s + \omega_i$$

14
The use of waveguides allows for a better collection of the generated photon-pairs. Because of the waveguide the length doesn’t influence the collection efficiency.

The efficiency of this process is determined by $\chi^{(3)}$. The main advantage of such a source is that it is possible to use optical fibers as non-linear medium, therefore coupling to the fiber should be near perfect. Phasematching is possible for frequencies near the pump frequencies when using the fiber around its zero-dispersion frequency leading to the disadvantage that a very efficient filtering system is required to filter the large amount of pump photons from the generated photon-pairs. At the moment such sources don’t reach their full potential since the filtering system is not fibered and therefore the main advantage is negated.

Another type of source are quantum dot (QD)[27]. A QD is a nanostructure in a semi-conductor which restricts the free electron-holes. This can create a situation in which an excited electron-hole pair releases its energy in the form of a pair of photons. This technique works but it is difficult to get a good collection efficiency from a QD, progress in this field is made by trying to create micro cavities around a QD.

As part of this thesis a collaboration with the group of G. Leo in Paris for a photon-pair source based on SPDC in semiconductor waveguides was performed. A short description of this experiment will be given in section 10.1

### 3.3.3 Frequency upconversion

SPDC is closely related to another frequency conversion technique: frequency upconversion. In this case the process is exactly the opposite of the process described above. Two photons with frequency $\omega_1$ and $\omega_2$ are transformed into one photon with frequency $\omega_3 = \omega_1 + \omega_2$. Phasematching is created by using the same techniques as before. This process can for example be used for information transfer from one
wavelength to another[32]. Later in this thesis it will be used to create a bright source of pulsed light that cannot be easily made without such a technique.
Chapter 4

Single Photon Detection

4.1 Introduction

So far we have discussed the creation of single photons or pairs of photons that can be used in a multitude of QI and QC protocols. All such protocols require detection of the photons either to obtain the result or as a part of the protocol. Unfortunately this is not a trivial task, especially for low energy photons such as photons at telecom wavelengths.

For our purposes there are several important parameters for photon detectors:

1. Detection efficiency
2. Dark count probability
3. Duty cycle
4. Maximum countrate
5. Temporal resolution

The detection efficiency $\eta$ is defined as the probability for the detector to click when a single photon arrives. Most detector research focusses on this crucial parameter. For avalanche photodetectors (see the next section) efficiency can be changed by varying the bias voltage of the device. However an increase in $\eta$ generally also means an increase in the dark count probability $P_{\text{DC}}$ which is defined as the probability per ns of having a click when there is no photon present. In such detectors a compromise between $\eta$ and $P_{\text{DC}}$ must be reached. In general it is important to find an optimal signal to noise ratio (SNR).

The duty cycle of a detector is important in order to make optimal use of the detector. Not all situations are limited by a duty cycle as will be shown later. The maximum countrate is important as well for high bit rate experiments. In most protocols using the detector too close to the maximum countrate (saturation) results in a large reduction of the output rate. This is caused by the deadtime (explained later) which reduces the duty cycle.
In some experiments the temporal resolution is very important, for the experiments in this thesis a resolution high enough to distinguish a photon at time \( t_0 \) from a photon at time \( t_0 + \tau \) is sufficient. In our experiments the timebin separation \( \tau \) equals 1.2ns.

## 4.2 Avalanche photodetectors

All the single photon detectors used for this thesis were avalanche photodetectors (APDs). A short explanation of their functioning will be given here. Some alternative detection devices will be discussed in section 4.3.

An APD is a reverse biased diode sensitive to absorption of a single photon. Three types of diode are used in this thesis. Indium gallium arsenide (InGaAs), germanium (Ge) and silicon (Si). Each type of diode is sensitive to different wavelengths.

Before detection the diode is prepared in a stable state with a voltage below the breakdown voltage \( V_{\text{breakdown}} \). This corresponds to point \( A \) in figure 4.1. The bias voltage is then increased to above \( V_{\text{breakdown}} \) (point \( B \)). This creates an unstable situation and a small fluctuation can start an electron avalanche which changes the situation to point \( C \). One of the possible causes of such an avalanche is the absorption of a photon. Detection of the sudden increase in current (the avalanche) signals a possible photon detection, also called a ‘click’. After the avalanche the current is reduced and the diode returns to its original state (point \( A \)).

### 4.2.1 Modes of operation

There are several different techniques that can be used with APDs. Which technique is used depends on the particular characteristics of the diode and the experimental
Figure 4.2: Different methods can be used to stop the current flowing through an APD after it has passed its breakdown voltage. On the left the scheme for short pulse gated mode operation is shown, in the middle passive quenching and on the right active quenching.

requirements. The techniques can be roughly separated in the following two groups.

The first group we will call ‘gated mode operation’ (GMO) also known as ‘triggered detectors’. It is possible to ready the detector (point B) for detection during a time $T_{gate}$ after which the bias voltage is reduced to below $V_{breakdown}$ (point A) regardless of photon detection. An important consequence of this form of biasing is that it is required to tell the detector when to expect a photon. In experiments where this is approximately known this technique can be very useful since it permits a reduction of the number of darkcounts.

The second group of techniques is ‘freerunning operation’ (FO) also called ‘passive detectors’. In this case the bias voltage is almost always kept high (position B), and is only reduced after detection. This technique doesn’t require any knowledge about the approximate arrival time of the photons. If the arrival time of the photons is not known but FO is not possible GMO detectors can be used with random triggers. This technique simulates a FO detector with a GMO detector. The disadvantage is that often the detector will not be ready for a photon and the resulting duty cycle effectively reduces the efficiency. When using a large amount of short gates this technique is also known as rapid gating.

For both groups it is important to stop the current through the diode as soon as possible after a detection. This is known as ‘quenching’. If GMO is used with short gates (typically of the order of a few ns) quenching is not required since the current is stopped at the end of the gate. In all other cases quenching is required mainly in order to protect the diodes but also to reduce noise. There are two different possibilities for quenching, active or passive quenching (Fig. 4.2).

For passive quenching it is sufficient to add a resistance to the circuit. As soon as a current starts to flow the increased voltage loss over the resistance will result in an effective reduction of the bias voltage. Once the diode is sufficiently back below breakdown the current stops and the original situation (point A) is restored. This method of quenching has the advantage that it is very easy to implement and
therefore it can be used in some situations were more complicated circuits would be problematic. The disadvantage is that the time it takes to quench an avalanche is relatively long. This type of quenching is in general used in combination with FO detectors, but can also be used in GMO with long gates (> 20ns).

Active quenching works by adding a circuit that reduces the bias voltage to below the breakdown level as soon as it detects a current. The advantage of this method is an increase in the performance of the detector since the time above the breakdown level is very short. The disadvantage is that the detector electronics become a lot more complex. For InGaAs detectors this type of quenching is usually used in combination with long duration (> 5ns) gates in GMO but recently an actively quenched FO detector was developed[33]. An overview of the different modes of operation discussed above is given in table 4.1.

Three types of APDs are used in this thesis. The principle ones are commercial InGaAs APDs. They function in GMO and actively quench avalanches during the gates[34, 35]. Typical measured characteristics for one of our InGaAs detectors is shown in figure 4.3. InGaAs diodes have a high darkcount probability but are required for certain wavelengths. Secondly a FO passively quenched GE-diode cooled with liquid nitrogen was used and finally an actively quenched FO Si-diode. The efficiency of these devices can be tuned by changing the bias voltage and for the first two is around 10% ($\lambda \approx 1550$nm) and for the Si-diode around 35% ($\lambda \approx 775$nm). The temporal resolution of these detectors is a few hundred ps which is sufficient since we use $\tau = 1.2$ns. The choice of detectors is largely based on the wavelength(Fig. 4.4).

The duty cycle and maximum countrate are mainly determined by the deadtime of the system. The deadtime is an artificially created period during which the bias voltage across the detector is kept low after a click. This is required because if one were to try and detect a photon rapidly after a detection there is a large increase in $P_{DC}$ caused by remaining trapped charges (Fig. 4.5).

### 4.3 Alternative detectors

In recent years several other types of detectors have been developed, each with their own strengths and weaknesses. Two of such detectors are explained below.

<table>
<thead>
<tr>
<th>Biasing</th>
<th>Quenching</th>
<th>Notes</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMO</td>
<td>none</td>
<td>only for short gates</td>
<td>InGaAs</td>
</tr>
<tr>
<td>GMO</td>
<td>active</td>
<td>only with long gates</td>
<td>Si</td>
</tr>
<tr>
<td>FO</td>
<td>active</td>
<td>simplest electronics</td>
<td>Ge</td>
</tr>
<tr>
<td>FO</td>
<td>passive</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Different possibilities for biasing and quenching APDs. The “Type” column indicates which type of diodes were used in this thesis for the particular techniques.
Figure 4.3: A typical relation between the efficiency of a APD and the dark count rate. Note the logarithmic scale which means that a small increase in efficiency is accompanied by a large increase in noise.

Figure 4.4: Illustration of the working range of different types of APD. The working range highly depends on the fabrication process and requirements of the diodes.

Figure 4.5: Probability of detection a dark count shortly after a detection.
Detection after upconversion

One alternative detection technique for measuring single photons at telecommunication wavelengths is to convert the photon to be detected to another wavelength in which good APDs exist. For telecommunication wavelengths such a detector consists of an upconversion of the photon at $\omega_1$ combined with a photon from an auxiliary source $\omega_2$ to a photon with $\omega_3 = \omega_1 + \omega_2$, followed by the detection of this photon with an Si-APD[36]. Efficiencies up to 5% have been reached but the dark count probability is relatively high with $10^{-4}$ dark counts per ns. This detector technique has the advantage that it has low jitter (50 ps) if a low jitter Si APD is used.

Superconduction meanders

Another technique for single photon detection involves specially structured superconductors [37]. Typically a thin film of superconducting material is deposited on a substrate. A meandering structure is created using etching techniques. A current slightly below the critical current $I_c$ is passed through this structure. If a photon hits the meander this will heat up a small region, which causes a reduction of $I_c$. If this drop is large enough the current in the meander will be larger then the critical current and therefore a small non-superconducting region will be created. The current will avoid this area and therefore the surrounding areas will have a current increase. Since the current was close to $I_c$ such an increase will in turn cause those areas to stop being superconductive. This process creates a “band” of non-superconductive material which means that the device now has a detectable resistance.

A measured change of the resistance of such a detector equals a ‘click’ of an APD. After a detection it suffices to reduce the current in order to make the whole system superconducting again and the whole cycle can start over. A disadvantage is that the detectors require a cryostat in order to reach superconductivity (typically with temperatures of a few Kelvin) but it has advantage that it has a low dark count rate. Furthermore it has been suggested that such detectors might be able to distinguish between a single or multiple photons[38, 39]. Finally the detectors can be used as passive detectors which is very useful for many protocols.
Figure 4.7: Schematic of the functioning of a superconductive photon detector. A photon hits the meander and gets absorbed. The resulting increase in temperature will decrease $I_c$ sufficiently to make the region resistive. The current now passes around this region which makes increase the local currents there to above $I_c$. This process creates a band of non-superconducting material.
Chapter 5

Entanglement

If the differences between a quantum world and a classical world had to be defined by a single property it would probably be entanglement. Entanglement describes properties of multiple distinct systems which cannot be properly described for each system individually. The results of entanglement can be completely counterintuitive and very different from what can be predicted with classical theories. In order to explain entanglement it is useful to directly consider one particular type of entanglement, in our case time-bin entanglement[24].

5.1 Time-bin entanglement

Consider the following situation (Fig. 5.1). A bright laser pulse is send through an unbalanced interferometer. After the interferometer there are two pulses with a fixed phase relation between the two:

\[ |\alpha\rangle_p \rightarrow |\frac{\alpha}{2}\rangle_0 |e^{i\phi}\frac{\alpha}{2}\rangle_1 \] (5.1)

where we assumed 50/50 couplers and we ignored the second output port. The subscript \( p \) stands for pump and ‘0’, ‘1’ indicate the temporal mode \( t_0(t_1) \). The

![Figure 5.1: Experimental setup to create time-bin entangled qubits. An intense laser pulse is send through an unbalanced interferometer. One of the outputs is send through a NLC in which a SPDC process can occur. The pump-photons are then filtered out and the remaining photons are entangled photon-pairs.](image-url)
pulses after the interferometer are sent through a non-linear medium. At this point there is a certain probability that a SPDC process occurs: i.e. a single photon is transformed into a pair of photons as discussed in section 3.2.

\[
\left( \hat{b}_0^\dagger \hat{c}_0^\dagger + \hat{b}_1^\dagger \hat{c}_1^\dagger \right) |\alpha \sqrt{2}\rangle_0 |\text{vac}\rangle_1 \rightarrow c(\alpha) \left( \hat{b}_0^\dagger \hat{c}_0^\dagger + e^{i\phi} \hat{b}_1^\dagger \hat{c}_1^\dagger \right) |\alpha \sqrt{2}\rangle_0 |\text{vac}\rangle_1
\]

The operators \( \hat{a}_j, \hat{b}_j^\dagger, \hat{c}_j^\dagger \) stand for the creation operators of the pump, signal and idler photons respectively. The subscript \( j = 0, 1 \) again indicate temporal mode and \( c(\alpha) \) is the amplitude with which the process occurs.

The pump photons are at more or less half the wavelength of the generated photons making it easy to remove the pump-photons with either a filter or a wavelength division multiplexer(WDM). The remaining photons are in an entangled state:

\[
(\hat{b}_0^\dagger \hat{c}_0^\dagger + e^{i\phi} \hat{b}_1^\dagger \hat{c}_1^\dagger) |\text{vac}\rangle_{si} = |0, 0\rangle_{si} + e^{i\phi} |1, 1\rangle_{si}
\]

Let’s look at some of the properties of such a state. If one of the two photons is measured at time \( t_0(t_1) \), this collapses the overall state onto a state where both photons exist at time \( t_0(t_1) \) albeit that one of them was destroyed during measurement. For example measuring photon A at time \( t_0 \) makes a projection of the state \( \Psi \) onto this result, the state \( |1, 1\rangle_{si} \) is therefore eliminated the state of the second photon is also completely determined. In other words, if both photons are measured there will always be a perfect correlation between the measurement times. Looking at each photon individually however the results cannot be predicted and are probabilistically determined.

### 5.1.1 Bell-states

For two qubits it is possible to construct a complete orthonormal basis using four maximally entangled states. These states are called the ‘Bell-states’:

\[
|\phi^\pm\rangle = \frac{1}{\sqrt{2}} (|0, 0\rangle_{ab} \pm |1, 1\rangle_{ab}) \quad (5.3)
\]

\[
|\psi^\pm\rangle = \frac{1}{\sqrt{2}} (|1, 0\rangle_{ab} \pm |0, 1\rangle_{ab}) \quad (5.4)
\]

Since these states are a complete basis for two-qubit states it is also possible to describe non-entangled or partially entangled states using the Bell-states. For the states \( |\psi^\pm\rangle \) there is complete anti-correlation when detecting the photons instead of the correlation as was shown in the last paragraph.

### 5.2 Other types of entanglement

As seen above the defining property of entanglement is inseparability. This can be achieved with time-bins but many other forms of entanglement exist. Probably the most commonly investigated type of entanglement is polarization entanglement,
where through a type II SPDC event two photons are created with orthogonal polarization, $|\Psi\rangle = |HV\rangle + |VH\rangle$. Another type is energy-time entanglement, which can be viewed as a ‘continuous-wave version’ of time-bin entanglement. In this thesis only time-bin entanglement is used.

### 5.3 Tests of entanglement

As mentioned above, entangled states have very counterintuitive properties. The correlation of seemingly random measurement results was something that met with a lot of scepticism in the physics community. Notably A. Einstein is famously quoted calling it “spooky action at a distance” and saw entanglement as a sign that quantum physics was not complete\[40\]. The alternative theories required to complete quantum mechanics are called local hidden variable theories (LHVT). The debate on whether or not these are true got a new turn when Bell discovered an inequality\[41\] that made it possible to test whether there really was “spooky action”.

Consider the following experiment (Fig. 5.2). Time-bin entangled photon-pairs are split up and send to distinct locations. On each of these locations an analysis of the incoming qubit is performed using an interferometer and detectors as explained in chapter 2. The coincidence countrate between detector $A_i$ and $B_j$ is given by:

$$R_{A_iB_j}(\alpha, \beta, \gamma) = R_0 (1 + ijV \cos(\alpha + \beta - \gamma))$$

(5.5)

where $R_0$ is the average rate, both $i, j$ equal ±1, the phases of the interferometers are $\alpha, \beta$ and $V$ is the visibility (value between 0 and 1). The phase $\gamma$ of the entangled qubits can be taken by definition to be zero. The correlation coefficient is defined as follows:

$$E(\alpha, \beta) = \frac{\sum_{i,j} ij R_{A_iB_j}(\alpha, \beta)}{\sum_{i,j} R_{A_iB_j}(\alpha, \beta)}$$

(5.6)

Combining the last two equations gives:

$$E(\alpha, \beta) = V \cos(\alpha + \beta).$$

(5.7)

In the experience described above this result can be easily tested. By varying the phase of one of the analyzing interferometers the correlation coefficient should show
a sinusoidal behavior. However, this is not sufficient as a test for entanglement, since LHVT can also show this behavior. The difference is in the maximum visibility that can be achieved. This is where Bells work was important, as can be shown as follows.

One of the most frequently used forms of the Bell inequality is the CHSH-inequality[42] and it goes as follows:

$$S = |E(\alpha, \beta) + E(\alpha, \beta') + E(\alpha', \beta) - E(\alpha', \beta')| \leq 2$$ \hspace{1cm} (5.8)

The maximum limit for quantum mechanics is reached when \( \alpha = 0^\circ, \alpha' = 90^\circ, \beta = -45^\circ \) and \( \beta' = 45^\circ \). When filling in these phases in eq. 9.5 one finds:

$$S = 2\sqrt{2}V \leq 2$$ \hspace{1cm} (5.9)

A value of \( V > \frac{1}{\sqrt{2}} \) implies violation of CHSH bell inequality and therefore the correlations cannot be explained by LHVT. As illustration one of the many Bell-tests performed during this thesis is shown (Fig. 5.3). Note that the maximum value allowed by quantum physics is smaller than the maximum value allowed mathematically (Fig. 5.2), thus a large S could even disprove quantum mechanics, but such a value has to our knowledge never been found.
Chapter 6

Long distance entanglement swapping [A]

6.1 Introduction

In the previous chapters a lot of the basic tools for QI and QC have been discussed. In the following chapters some experiments will be described that use these techniques.

Entanglement swapping, also known as teleportation of entanglement, is a protocol in which two entangled pairs “swap” the entanglement between their constituent parts. This creates the counterintuitive situation in which qubits can be entangled without having had a common past. The general scheme (Fig. 6.1) shows how this is done: first two entangled photon-pairs are created, one part of each pair is sent to a Bell-state analyzer (BSA) where a Bell-state measurement (BSM) is performed on these photons. After a successful BSM the remaining photons are entangled, even though they have no common history.

This protocol is not just interesting because of its fundamental implications, but it also plays an essential role in applications such as a quantum repeater and quantum relays, which are meant to increase the maximum distance at which QC works. The first experiments with entanglement swapping were performed in 1998 and used pairs of polarization entangled photons with $\lambda = 800\text{nm}$ created with SPDC in a single NLC[14]. The quality of this experiment was not sufficient to prove nonlocal correlation (ie. no violation of Bell-inequality). Later a similar experiment was performed which confirmed the non-locality of this protocol[43]. Experiments have also been done using entanglement between a single photon Fock-state and the vacuum[44] and with continuous variable encoding[45, 46]. All of the experiments done before have been experiments over short distances. We interest ourselves in experiments that can be used to cover large distances.

We performed an entanglement swapping experiment optimized for long distance use in standard telecommunication networks. For this reason time-bin quantum entanglement was used with photons at 1310 and 1550nm. Furthermore the photon-pairs were created in two separate crystals which were pumped by the same laser. As a proof of principle the capabilities of the long-distance compatibility of this
scheme were tested by adding additional fiber lengths to the experiment.

### 6.2 Entanglement swapping

Let's take a closer look at the entanglement swapping protocol. After the creation of two entangled pairs the overall quantum-state of the system is for example: $|\Psi\rangle_{abcd} = |\phi^+_\delta\rangle_{ab} \otimes |\phi^-_\delta\rangle_{cd}$ where $|\phi^\pm_\delta\rangle_{ab} = \frac{1}{\sqrt{2}} (|0, 0\rangle_{ab} \pm e^{i\delta}|1, 1\rangle_{ab})$. The state $|\Psi\rangle_{abcd}$ can be rewritten as follows:

\[
|\Psi\rangle_{abcd} = |\phi^+_\delta\rangle_{ab} \otimes |\phi^-_\delta\rangle_{cd} = \frac{1}{2}(|\phi^+\rangle_{bc} \otimes |\phi^-_\delta\rangle_{ad} + |\phi^-\rangle_{bc} \otimes |\phi^+_\delta\rangle_{ad} + |\psi^+\rangle_{bc} \otimes e^{i\delta} |\psi^-\rangle_{ad} + |\psi^-\rangle_{bc} \otimes e^{i\delta} |\psi^+\rangle_{ad})
\]

where $|\psi^\pm\rangle_{bc} = \frac{1}{\sqrt{2}} (|0, 1\rangle_{bc} \pm e^{i\delta}|1, 0\rangle_{bc})$. When a BSM is performed on photons $b$ and $c$ the rest of the system is projected onto the result of this measurement and thus photons $a$ and $d$ end up in one of the Bell-states as well. If the BSM finds $|\psi^\pm\rangle_{bc}$ the remaining photons will be in the state $|\psi^\mp\rangle_{ad}$ with a global phase factor $\delta$ hence this phase is not important for $|\psi^\pm\rangle_{bc}$. For the other cases the state will be dependent on $2\delta$. This can be corrected with a unitary transformation for protocols in which the same output state is required.

#### 6.2.1 Experimental setup

The following experimental scheme was used (Fig. 6.2) to perform an entanglement swapping experiment. A mode-locked femto-second laser with $\lambda = 710\text{nm}$ creates pulses with a length of about $200\text{fs}$. These pulses are sent into an unbalanced bulk Michelson-interferometer. The path length difference in this interferometer has been
Figure 6.2: A scheme of the experimental setup used to perform the entanglement swapping protocol.
tuned to $\tau = 1.2\text{ns}$ which corresponds to a path length difference of 18cm back and forth in air, or 12cm of standard optical fibers.

In our pump interferometer retro-reflectors are used which facilitate the use of the input port as an output port without requiring a circulator. Each of the outputs is sent to a separate Lithium-Triborate (LBO) non-linear crystal. SPDC creates collinear non-degenerate photon-pairs at telecommunication wavelengths (1310 and 1550nm). At this point the overall state equals eq. 6.1:

$$|\Psi\rangle_{abcd} = |\phi^+\rangle_{ab} \otimes |\phi^-\rangle_{cd}.$$  

The difference between $|\phi^+\rangle_{ab}$ and $|\phi^-\rangle_{cd}$ is a result of the different amount of reflections in the interferometer. Note that the phase $\delta$ is automatically the same for both pairs because of the use of a single pump interferometer.

The generated pairs are coupled into a single-mode fiber (SMF) where they are separated using a wavelength division multiplexer (WDM). The photons at 1310nm are both sent to the BSA, which in this case is just a simple 50/50-coupler. More on the workings of this BSA in chapter 7.1. For the BSA to function it is required that both incoming photons are completely indistinguishable in temporal, polarization and spectral modes. This is verified by first performing a Hong-Ou-Mandel dip[47](HOM-dip) before the swapping experiment. This means scanning a variable optical delay in order to minimize the amount of coincidences.

The photons at 1310nm are filtered with 5nm bandwidth interference filters in order to increase their coherence time to 500fs and to assure that both have the same spectrum. It is required to have coherence lengths longer than the pulse length in order to assure temporal indistinguishability (Fig. 6.3).

The remaining photons each travel through 1.1km of dispersion shifted fiber and are filtered with a 18nm bandwidth filter. This filtering is required in order not to saturate the detectors with uncorrelated photons belonging to photon-pairs that do not pass the wavelength requirements of the 1310nm filter. The entanglement of the two remaining photons is analyzed by performing a Bell-test as explained in chapter 5.3. For this purpose two fibred Michelson-interferometers with Faraday-mirrors are used. These mirrors have the advantage of automatically aligning the polarization of the interferometers.

Since the experiment requires four-fold coincidences it takes a long time to finish a measurement. It is required that the phases of the analyzing interferometers remain constant during this time. This is guaranteed by having an active feedback system that probes the phase of the interferometers from time to time using a stabilized
diode-laser at a different wavelength. Adjustments of the phase are possible since one of the arms in the interferometer is partially wrapped around a cylindrical piezo-actuator. When changing the voltage over this piezo the optical length of the fiber changes and thus the phase of the interferometer (Fig. 6.4). The phase of the pump-interferometer is not stabilized in this experiment. This is not required since only the phase difference between the pairs plays a role. Since both pairs pass trough the same interferometer this difference is stable (see eq. 6.2).

In this experiment there are three different interferometers, one pump interferometer and two analyzing interferometers. It is important to align the lengths of the different interferometers with each other. In order to do this two preliminary experiments are performed. The first is a straightforward single photon interference experiment. When putting both fiber interferometers in series and passing a photon through them it is possible to find an interference fringe. By changing the lengths of the fibers it is possible to optimize the visibility of this fringe and thereby aligning both of the interferometers to within the coherence length of the photons. As a second step these interferometers need to be aligned with the bulk interferometer. This is done by performing and optimizing Bell-tests with an additional interferometer for the 1310nm photons.

The photons are detected using APDs. One of the outputs of the 50/50-coupler is sent to a Ge-diode cooled with liquid nitrogen and operated using passive quenching. It has an efficiency of around 10% for 40kHz of dark counts. The three other photons are detected using commercial id-200[34] detectors which are triggered InGaAs APDs with an efficiency of around 30% and $10^{-4}$ darkcounts per ns of gate. The trigger signal of these detectors is given by an electronic coincidence between a detection of the Ge-APD and a reference signal from the mode-locked laser. This step eliminates a large part of the noise of the passive detector. It is possible to do this since a pulsed setup is used and therefore photons can only arrive at fixed times. The signals from the InGaAs detectors are sent to a multichannel time-to-digital converter (TDC)
6.2.2 Results and conclusions

In order to prove that conditionally on a successful BSA the photons $a$ and $d$ are entangled we scan the phase of one of the interferometers and record the coincidence counts. In theory this should show a sinusoidal dependance on the phase

$$R_c = R_0 (1 + V \cos(\alpha + \beta))$$

with a visibility $V$. As shown in section 5.3 a visibility $V > \frac{1}{\sqrt{2}}$ is sufficient to violate the Bell- inequality. The result obtained in this experiment was $V = 0.80 \pm 0.04$ (Fig. 6.5) which is sufficient to prove entanglement between the photons $a$ and $d$.

The Bell-test done so far was only a test of entanglement swapping of states that are on the equator of the Poincaré-sphere. In principle it should also be possible to perform a swapping with the poles of the sphere. This can be analyzed by removing the analysis interferometers from the setup. The result (Fig. 6.6) of this experiment has a fidelity $F$ of $0.90 \pm 0.03 (F = \frac{1+V}{2})$ which proves that the poles can also be swapped.

From these results it is possible to conclude that indeed we are capable of entanglement swapping in a quantum relay configuration over large distances. The approach taken for this experiment is very promising for new ”out-of-the-lab” experiments and will be built upon later in this thesis.
Figure 6.6: Result of an entanglement swapping experiment in which the qubits were located on the poles of the Poincaré-sphere. The fidelity $F$ equals $0.90 \pm 0.03$. 
Chapter 7

Three Bell-state analyzer [B, C]

Up till now we have not discussed the functioning of one of the vital parts of an entanglement swapping or teleportation experiment: the Bell-state analyzer (BSA). In this chapter we will show how the BSA that was used in the previous chapter functions and also a new type of BSA is discussed: the three Bell-state analyzer. A quantum teleportation experiment is performed in order to demonstrate the functioning of this new BSA.

7.1 Bell-state analyzers

As mentioned in the last chapter a BSA is a device that measures the quantum state of two distinct input states in the Bell-basis $|\phi^\pm\rangle, |\psi^\pm\rangle$. In general a BSA is useful in many experiments, not only teleportation or entanglement swapping but also for example quantum dense coding [48, 49]. There are different variations of the BSA possible for different types of qubits, but in all quantum teleportation or entanglement swapping experiments done to date using only linear optics and no auxiliary resources a partial BSA was used[50, 12, 13, 14]. This is an analyzer not capable of distinguishing all four Bell-states. For the protocols that interest us this leads to a reduced success rate but is of no further consequence. Using linear optics it is impossible to create a BSA that works more than 50 percent of the time without the use of auxiliary modes[51, 52]. In principle it is possible to have a complete BSA using non-linear optics[53] but since this is highly inefficient this is not a viable option for most purposes. Here we will first show the most basic BSA followed by a more complicated and capable analyzer.

7.1.1 Beamsplitter Bell-state analyzer

A BSA is a device in which different Bell-states at the input give a distinguishable result, in other words it allows the detection of a Bell-state.

Let’s consider the simplest manipulation that can be performed on two qubits, simply detection of the inputs. The measurement will project the state one of four possible states: $|0, 0\rangle, |0, 1\rangle, |1, 0\rangle$ or $|1, 1\rangle$. Since these four states form the
Figure 7.1: A scheme of the beamsplitter-BSA.

Table 7.1: The table shows the probability to find specific coincidences as a function of the input Bell-state in the case of a single beamsplitter as a BSA. A ‘0’(‘1’) in row D1 means that a photon was found at detector ‘D1’ at time $t_0$($t_1$) etc. Note that only half of the combinations of detection are possible for only one Bell-state (the bold entries), therefore when such a combination is found a projection onto this Bell-state was performed. The theoretical success-probability is 50%.

For Bell-states as input the result of this simple calculation is shown in table 7.1. By convention, a detection click at time ‘0’(‘1’) means that the photon was detected in time-bin $t_0$($t_1$).

The output possibilities show that it is possible to detect the Bell-state $|\psi^+\rangle$ by detecting two photons in the same detector with a time-bin difference, since this result could not have been caused by any other Bell-state. For example detection of both a ‘0’ and a ‘1’ in detector $D1$ equals the detection of the input as $|\psi^+\rangle$.

When the photons arrive at different detectors with a time-bin difference, such as $D1$ detects a ‘0’ and $D2$ a ‘1’, the input-state is projected onto the state $|\psi^-\rangle$. However, when one measures two photons in the same time-bin in the same detector the state could either be $|\phi^+\rangle$ or $|\phi^-\rangle$ and therefore the state has not been projected onto a single Bell-state but onto a superposition of two Bell-states. In this case the
BSM was unsuccessful. Note that due to photon bunching the situation where both photons exit a different path at the same time does not occur.

This BSA has a success rate of 50% which corresponds to the maximal possible success rate that can be obtained while using only linear optics and no auxiliary photons as mentioned above. When using realistic detectors the success rate of this BSA is 25%. This reduced efficiency is caused by the deadtime of the detectors which makes it impossible to detect one photon after another in a single detector (see also Fig. 4.5). This means the BSA is only capable of detecting $|\psi^\pm\rangle$. It is possible to measure $|\psi^+\rangle$ adding a switch and additional detectors in order to simulate a rapid detector. From now on this BSA is referred to as a BS-BSA. Note that the equivalent BSA for polarization encoded qubits is capable of a 50% success rate since there are never two detections required by the same detector.

7.1.2 The three Bell-State analyzer

The 50% limit of success for a BSA doesn’t mean it is impossible to detect more than two Bell-states. Here we introduce a new type of BSA. It is capable of distinguishing more than two Bell-states while still having the maximum success rate of 50%. This is possible by replacing the beamsplitter with a time-bin interferometer equivalent to the ones used to encode and decode time-bin qubits (Fig. 7.2). We will call this BSA a 3-BSA. This BSA is capable of distinguishing three out of four Bell-states, but $|\phi^+\rangle$ and $|\psi^-\rangle$ will only be discriminated 50% of the time as will be explained shortly.

Two qubits enter in port $a$ and $b$, respectively. The first beamsplitter acts like the BS-BSA, allowing the distinction of two Bell-states ($|\psi^\pm\rangle$ and $|\psi^-\rangle$) if the photons were detected. A second possibility for interference is added by another BS for which the inputs are the outputs of the first BS, with one path having a delay corresponding to the time-bin separation $\tau$. The two-photon effects on this beamsplitter lead to fully distinguishable photon combinations of one of the two remaining Bell-states ($|\phi^\pm\rangle$) while still allowing a partial distinction of the first two.

One might expect that when it is possible to measure three out of four states that the fourth, non-measured, state can simply be inferred from a negative measurement result of the three measurable states. This is, however, not the case. The above described measurement is a positive operator valued measure (POVM) with 21 possible outcomes, some of these outcomes are only possible for one of the four
Bell-states. Therefore when such an outcome is detected it unambiguously discriminates the corresponding input Bell-state. The rest of the 21 outcomes can result from more than one input Bell-state. In other words, their results are ambiguous and the input state is not projected onto a single Bell-state but onto a superposition of Bell-states.

The state after the interferometer can be calculated for any input-state using:

\[
\hat{a}^\dagger(t) \rightarrow \frac{1}{\sqrt{4}} [-\hat{e}^\dagger(t) + e^{i\theta}\hat{e}^\dagger(t + \tau) + i\hat{f}^\dagger(t) + ie^{i\theta}\hat{f}^\dagger(t + \tau)] \\
\hat{b}^\dagger(t) \rightarrow \frac{1}{\sqrt{4}} [i\hat{e}^\dagger(t) + ie^{i\theta}\hat{e}^\dagger(t + \tau) + \hat{f}^\dagger(t) - e^{i\theta}\hat{f}^\dagger(t + \tau)]
\]

where \(\hat{a}^\dagger(j)\) is the creation operator of a photon at time \(j\) in mode \(i\). When the input-states are qubits and the photons are detected after the interferometers the detection-patterns are readily calculated and are shown in Table 7.2. The output coincidences on detectors \(D_1\) (port \(e\)) and \(D_2\) (port \(f\)) are shown as a function of a Bell-state as input. By convention, a detection at time ‘0’ means that the photon was in time \(t_0\) after the BSA-interferometer. This is only possible if it took the short path in the BSA and it was originally a photon in time-bin \(t_0\) (Fig. 7.2). Similarly a detection at time ‘1’ means that either the photon was originally in \(t_1\) and took the short path of the BSA interferometer or it was in \(t_0\) and took the long path. A detection at time ‘2’ means the photon was in \(t_1\) and took the long path. In Table 7.2 we see that some of the detection combinations corresponds to a single Bell-state and therefore the measurement is unambiguous. For the other cases the result could have been caused by two Bell-states, i.e. the result is ambiguous and hence inconclusive. More specifically, the Bell-state \(|\psi^+\rangle\) is detected with probability 1, \(|\phi^-\rangle\) is never detected and both \(|\psi^-\rangle\) and \(|\phi^+\rangle\) are detected with probability 1/2.

The above described approach is correct in the case were the separation \(\tau\) of the incoming qubits is equal to the time-bin separation caused by the interferometer. If this in not exactly the case and the interferometer creates a time-bin separation of \(\tau + \frac{n\lambda\theta}{2\pi c}\), where \(\theta\) is a phase, the situation is slightly more complicated. In such a case, our BSA still distinguishes 3 Bell-states, but these are no longer the standard Bell-states but are:

\[
|\phi^\pm\rangle = |0, 0\rangle \pm e^{2i\theta}|1, 1\rangle = (\sigma_\theta \otimes \sigma_\theta)|\phi^\pm\rangle \\
|\psi^\pm\rangle = e^{i\theta}(|0, 1\rangle \pm |1, 0\rangle) = e^{i\theta}|\psi^\pm\rangle
\]

Here \(\sigma_\theta = |0\rangle\langle 0| + e^{i\theta}|1\rangle\langle 1|\) is a phase shift of \(\theta\) to be applied to the time bin \(|1\rangle\). These new Bell-states are equivalent to the standard states except that the \(|1\rangle\) is replaced by \(e^{i\theta}|1\rangle\) for each of the input modes.

In a realistic experimental environment the success probabilities of the BSA are affected by detector limitations. Again this is because existing photon-detectors are not fast enough to distinguish photons which follow each other closely in a single measurement cycle. When including this limitation we find that the maximal probabilities of success in our experimental setup are reduced to 1/2, 1/4 and 1/2 for \(|\psi'^+\rangle, |\psi'^-\rangle\) and \(|\phi'^+\rangle\), respectively. This leads to an overall probability of success
Table 7.2: The table shows the probability to find any of the 21 possible coincidences as a function of the input Bell-state. A ‘0’ in row D1 means that a photon was found at detector ‘D1’ and at a time corresponding to the photon having taken the short path in the interferometer and it was originally a photon in time-bin $t_0$, a ‘1’ corresponds to $t_0 + 1 \times \tau$ with $\tau$ corresponding to the difference between the time-bins and ‘2’ refers to $t_0 + 2 \times \tau$. Note that several combinations of detection are possible for only one Bell-state (the bold entries), therefore when such a combination is found a Bell-state Measurement was performed. The theoretical probability of a successful measurement is 0.5 which is the optimal value using only linear optics[51].
7.1 Detector Limitation

The detector-limitation could be partially eliminated by using a beamsplitter and two detectors in order to simulate a rapid multi-photon detector half of the time, or it could be completely eliminated by using an ultra-fast optical switch (sending each time-bin to a different detector). Both of these methods are associated with a decrease in signal-to-noise ratio. This is caused by additional noise from the added detector and by additional losses from the optical switch, respectively. Note that as was the case for the BS-BSA the polarization equivalent of the 3-BSA does not encounter this problem.

7.2 Quantum Teleportation

In order to show the functioning of the 3-BSA we performed a teleportation-experiment. The protocol is very similar to the entanglement swapping shown in the last chapter. An entangled photon-pair is created and distributed, the qubit to be teleported is sent to the BSA along with half of the entangled pair and a BSM is performed on them. As a function of the result of this BSM a unitary transformation is performed on the remaining photon which is then equal to the original qubit (Fig. 7.3). In the case of the 3-BSA a small adaptation of the Bell-states and unitary transformations is required to take account of the phase of the interferometer:

\[
|\zeta_{abc}\rangle = |\zeta\rangle_a \otimes |\phi^+\rangle \quad (7.7)
\]

\[
= \frac{1}{\sqrt{4}}(|\psi'_+\rangle_{ab} \otimes e^{-i\theta}\sigma_x|\zeta\rangle_c + |\psi'_-\rangle_{ab} \otimes e^{-i\theta}\sigma_x\sigma_z|\zeta\rangle_c + |\phi'^+\rangle_{ab} \otimes \sigma_x|\zeta\rangle_c + |\phi'^-\rangle_{ab} \otimes \sigma_x\sigma_z|\zeta\rangle_c + |\phi''^+\rangle_{ab} \otimes \sigma_z\sigma_x|\zeta\rangle_c + |\phi''^-\rangle_{ab} \otimes \sigma_z\sigma_x\sigma_z|\zeta\rangle_c \quad (7.8)
\]

where \(|\zeta\rangle\) is the qubit to be teleported, \(\sigma_x\) is a bitflip and \(\sigma_z\) a phaseflip.
The experimental setup (Fig. 7.4) used to perform the teleportation shows similarities with the setup used for the entanglement swapping experiment in chapter 6. There are however a few important differences.

As a source for the entangled photons a similar setup is used as in the last chapter. A mode-locked femtosecond laser sends bright laser pulses through an unbalanced interferometer followed by SPDC in a NLC. In contrast to the entanglement swapping experiment it is required that the interferometer is stabilized. For this purpose we use a high-stability HeNe-laser in a path slightly different from that of the pulses. The path length is changed by a piezo connected to one of the retro reflectors. This setup allows permanent feedback to stabilize the interferometer during measurements in contrast with the fiber interferometers which cannot function while the stabilization is done. Long term drifts are avoided by having the whole interferometer in a temperature controlled box.

The source of the qubit is an adapted version of the entangled photon-pair source. A part of the light from the mode-locked laser is diverted into a LBO crystal. This creates a pair of photons through SPDC. The pair is coupled into a SMF and split-up using a WDM. The photon created at 1550nm is discarded and the photon at 1310nm is send through a fiber interferometer. After the interferometer the photon is in a qubit state. This interferometer is also stabilized in phase as in the last chapter.

The BSA is either a BS-BSA, or a stabilized 3-BSA. The photons after the BSA are detected using a liquid-nitrogen cooled GE-diode for one path and a triggered ID-200 for the other path. The trigger of this last detector is again a coincidence between a detection of the Ge and the laser. After a successful BSA the teleported state is analyzed using a stabilized interferometer. By scanning the phase of this interferometer it is possible to see an interference fringe in the coincidence countrate as before. For each different result of the BSA (|ψ-⟩, |φ±⟩) a different fringe can be seen.

As with the last experiment it is important for the BSA that all arriving photons are identical. The filters used to assure wavelength indistinguishability had a spec-
A second alignment procedure that is required is the alignment of the interferometers, this is done much the same as in the last chapter. The interferometers are mutually aligned by performing several Bell-tests and single photon interference experiments.

7.3 Results and conclusion

Two different types of teleportation experiments were performed. A BS-BSA teleportation in order to benchmark our equipment followed by an 3-BSA experiment. The BS-BSA teleportation consisted of Bob making a scan of his interferometer phase while the other interferometers were kept constant, we therefore expect to find a single interference curve of the form \( 1 + V \sin(\beta + \beta_0) \) where \( \beta_0 = -\gamma + \alpha \) is a constant, \( \gamma \) is the phase of the bulk interferometer and \( \alpha \) the phase of the qubit interferometer. The results of the experiment (Fig. 7.6) shows the expected behavior. The visibility measured was \( V = 57\% \pm 3\% \). After conservative noise substraction we find \( V = 83\% \pm 4\% \). This is clearly higher than the strictest limit that has been associated with quantum teleportation of \( V=2/3 \)[54, 55] and shows that the...
quantum state has been teleported. The limiting factors of this experiment are the
detectors and the coupling after the crystals.

After this experiment the BS-BSA was changed to the 3-BSA. For each of the
different possible results of the 3-BSA we analyzed the results separately (Fig. 7.7).
It is expected that each of the BSA outcomes has its own fringe of the form $1 + V \sin(\alpha + \alpha_0)$ where $\alpha_0$ is a function of $\beta, \theta$ and $\gamma$ which are kept constant during the experiment. The fringes for outcomes that belong to the same Bell-state should be in phase, whereas between states there is a phase difference depending on phaseshifts, phaseflips or bitflips. The results show the expected behavior, although the matches are not perfect. The curves ‘20’, ‘02’ are in phase as are the curves ‘01’, ‘10’ and ‘12’, ‘21’. The last four curves are expected to be in phase but there is a phase difference caused by noise (an extensive noise analysis is given in article [C]). The visibilities in the curves are shown in Table 7.3. The difference in visibilities are in part due to noise. Note the average relative phases of all curves corresponds within its error to the expected phase differences.

If we add all the before mentioned outcomes of the BSA in order to look at the complete teleportation we expect interference fringes after Bob’s interferometer of the form $1 \pm \cos(\alpha + \beta - \gamma)$ for a projection on $|\psi^+\rangle$, $1 \pm \cos(\alpha + \beta - \gamma + \pi)$ for $|\psi^-\rangle$ and $1 + \cos(\alpha - \beta + \gamma - 2*\theta)$ for $|\phi^{+}\rangle$. Hence one would expect to find three distinct curves, two with a phase difference of $\pi$, and the third dephased by $-2*(\beta - \gamma + \theta)$. Where $\alpha, \beta, \gamma$ and $\theta$ are the phases of Alice, Bob, the entangled pair preparation interferometer and the BSA measurement interferometer respectively.

Note that one can set the phase $\gamma$ to 0 as reference phase and that Bob is able to derive the phase value $\theta$ of the BSA interferometer just by looking at the phase differences between the fringes made by $|\psi^{+}\rangle$ and $|\phi^{+}\rangle$ and his knowledge about $\beta$. 

Figure 7.6: The result of the teleportation experiment using a BS-BSA. $V_{raw} = 57\% \pm 3\%$ and $V_{net} = 83\% \pm 4\%$. 

![Graph showing interference fringes with minimum noise level at 0 and 180 degrees phase shift]
Figure 7.7: Measured coincidence counts as a function of phase. Left: BSA-results ‘01’, ‘10’, ‘12’ and ‘21’. Right: BSA-results ‘02’ and ‘20’. The fringe for BSA-results ‘11’ is shown in Fig. 7.8 as $|\psi_+\rangle$.

Table 7.3: For each of the different detection possibilities the fitted result are shown before and after noise correction. ‘$V$’ refers to the Visibility (%), ‘$\rho$’ to a phase-shift (degrees) and ‘$P$’ to the normalized probabilities of a coincidence detection (%) . The results for the Bell-states are fitted after adding the corresponding coincidences.

<table>
<thead>
<tr>
<th>Result 3BSA</th>
<th>$V_{\text{raw}}$</th>
<th>$V_{\text{net}}$</th>
<th>$\rho_{\text{raw}}$</th>
<th>$\rho_{\text{net}}$</th>
<th>$P_{\text{raw}}$</th>
<th>$P_{\text{net}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[01]</td>
<td>35±3</td>
<td>61±6</td>
<td>98±4</td>
<td>-81±5</td>
<td>13±1</td>
<td>14±1</td>
</tr>
<tr>
<td>$</td>
<td>\psi_+\rangle$</td>
<td>43±3</td>
<td>83±13</td>
<td>159±4</td>
<td>126±8</td>
<td>11±1</td>
</tr>
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<td>[12]</td>
<td>18±3</td>
<td>72±7</td>
<td>160±7</td>
<td>-22±4</td>
<td>14±1</td>
<td>7±1</td>
</tr>
<tr>
<td>[21]</td>
<td>13±2</td>
<td>55±2</td>
<td>97±9</td>
<td>136±1</td>
<td>17±1</td>
<td>10±1</td>
</tr>
<tr>
<td>[11]</td>
<td>43±3</td>
<td>64±13</td>
<td>-44±3</td>
<td>-18±10</td>
<td>29±1</td>
<td>41±1</td>
</tr>
<tr>
<td>[02]</td>
<td>39±5</td>
<td>62±10</td>
<td>-49±4</td>
<td>153±8</td>
<td>8±1</td>
<td>6±1</td>
</tr>
<tr>
<td>[20]</td>
<td>38±4</td>
<td>36±8</td>
<td>-32±4</td>
<td>-80±12</td>
<td>9±1</td>
<td>9±1</td>
</tr>
<tr>
<td>$</td>
<td>\psi_-\rangle$</td>
<td>22±1</td>
<td>51±3</td>
<td>-49±3</td>
<td>-49±3</td>
<td>54±1</td>
</tr>
<tr>
<td>[11]</td>
<td>43±3</td>
<td>69±10</td>
<td>136±3</td>
<td>139±7</td>
<td>29±1</td>
<td>41±1</td>
</tr>
<tr>
<td>[02]</td>
<td>38±5</td>
<td>55±3</td>
<td>140±6</td>
<td>136±3</td>
<td>17±1</td>
<td>15±1</td>
</tr>
</tbody>
</table>
Figure 7.8: Uncorrected teleportation fringes found when scanning the interferometer at Bob. The fitted curves have visibilities of 0.22, 0.43 and 0.38 for $|\psi'^+\rangle$, $|\phi'^+\rangle$ and $|\psi'^-\rangle$. The average visibility of the BSA is $V_{avg} = 0.34$ ($F=0.67$).

In Fig. 7.8 we show the raw coincidence interference fringes between Bob and a successful BSA. As expected fringes for $|\psi'^-\rangle$ and $|\psi'^+\rangle$ have a $\pi$ phase difference due to the phase flip caused by the teleportation. On the other hand fringes for $|\psi'^+\rangle$ and $|\phi'^+\rangle$ are dephased by $-2(\beta + \theta)$ which in this case we had arranged to be approximately 0. The raw visibilities obtained for the projection on each Bell-state are $V_{\psi_-} = 0.38 \pm 0.05$, $V_{\phi_+} = 0.22 \pm 0.01$, $V_{\phi_-} = 0.43 \pm 0.03$ which leads to an overall value of $V = 0.34 \pm 6$ ($F = 0.67 \pm 3$). In order to check the dependence of $|\phi'^+\rangle$ on $\theta$ we also performed a teleportation with a different value and we clearly observe the expected shift in the fringe (Fig. 7.9) while measuring similar visibilities.

After noise correction the results correspond well with theoretical predictions. The visibilities of the different curves are similar within their errors (see table 7.3). The difference in phase between $|\psi'^+\rangle$ and $|\psi'^-\rangle$ ($189^\circ \pm 9^\circ$) corresponds with theory ($180^\circ$). Also, since the phases were arranged so that $\theta + \beta = 0$, the fringe of $|\phi'^+\rangle$ is in phase with $|\psi'^-\rangle$ (phase difference of $4^\circ \pm 9^\circ$). The normalized probabilities of a measurement show that $|\psi'^+\rangle$ and $|\phi'^+\rangle$ have the same probability (43% resp. 41%) and these values correspond with the theoretical value of 40%. The probability of $|\psi'^-\rangle$ is 15% with a theoretical value of 20%. These agreements with theory suggest that the discrepancies as seen for the individual results are caused by differences in noise that cancel out when they are added to each other.

From the results shown above we can conclude that indeed the 3-BSA functions as expected. It is therefore possible to detect more than two Bell-states using only linear optics without auxiliary photons. The 3-BSA is in principle more efficient than a BS-BSA but because of the added losses caused by the interferometer the BS-BSA has a higher rate. If for the protocol it is not required to have more than two Bell-states a BS-BSA should be used. Otherwise the 3-BSA can be used. It is still unknown whether all four Bell-states can be probabilistically discriminated using only linear optics and no auxiliary modes.
Figure 7.9: Teleportation fringes measured in two distinct measurement with a $\theta$ which had changed by $70 \pm 10^\circ$. In the measurement a clear shift is visible of the fringe $|\phi'\rangle$ by $74^\circ$ with regards to the other fringes.

Figure 7.10: Results of the 3-BSA experiment corrected for noise.
Chapter 8

Out-of-the-lab Teleportation [D] [P1-P3]

8.1 Introduction

The goal of QC is the distribution of quantum states between different locations. So far the experiments discussed have all been experiments that were done in the same lab, albeit in a configuration ready for work outside the lab. To prove that these techniques work as well outside of a controlled laboratory environment we performed a teleportation experiment between our lab and a Swisscom (Swiss national telecom provider) switching station.

8.2 Experimental improvements

Quantum teleportation experiments have been performed that use optical fiber to simulate a distance[13] or that are ‘out-of-the-lab’ but without prior entanglement distribution and creation [58, 56]. No experiment has been performed which uses prior entanglement distribution outside of the laboratory. This means the Bell-state measurement always took place before the remaining photon was distributed. In all experiments a single laser pulse was used to create all photons. We performed the following experiment in which all these points were addressed.

The setup (Fig. 8.1) consists of a femtosecond laser at 711nm. The pulses coming from this laser are split in two using a variable coupler. One part is sent through an unbalanced bulk interferometer (stabilized as before using a stable HeNe) followed by SPDC in a LBO NLC. The other part of the laser is send through another LBO NLC again to create photon-pairs using SPDC. The created photons are separated from the pump photons using Si-filters and coupled into SMFs. A WDM is used to split the pairs.

The pair of photons created after the interferometer is time-bin entangled. The photon at 1310nm is sent to a rudimentary quantum memory, namely a fiber with a length of 179.7m on a spool. The photon at 1555nm is sent out of the lab to a Swisscom switching station. For this purpose a dedicated fiber is used. The fiber is
Figure 8.1: Scheme of the experimental setup. The Swisscom location was a switching station located 550m from the laboratory. QM stands for quantum memory, in this case a long fiber on a spool. PBS stands for polarizing beamsplitter.
a standard single-mode telecommunications fiber as used throughout the Swisscom network. The length of the fiber is 800m while the physical distance between the lab and the switching station is 550m (Fig. 8.2).

From the other source of photons the 1310nm photon is sent into an optical delay, in this case a fiber with a length of 177m. The difference in length between the two fiber spools is adjusted so that it corresponds to a single cycle of the mode-locked laser. In other words, the photons pairs that will be used for the BSA are not created by the same pulse but by two subsequent pulses. This is a step towards independent photon-pair sources\[^{57, 59}\]. The photon at 1555nm of this pair is detected by an id200 single photon detector. This detector serves as a heralding detector and is of no influence on the teleportation protocol other than allowing an improvement of the SNR at the cost of a reduced coincidence rate.

After the 177m fiber QM the photon passes through a stabilized unbalanced fiber interferometer such as those described earlier in this thesis (Fig. 6.4). Only at this point is the qubit encoded onto the photon. Since this only takes place after the delay the 1555nm photon that has been send to the Swisscom station has already
Figure 8.3: Result of the Hong-Ou-Mandel experiment used to align the fiber lengths in the setup. The two different dips are for coincidences at two different time, namely ‘00’ and ‘11’. The raw visibilities are $V_{00} = 0.25 \pm 0.02$ and $V_{11} = 0.26 \pm 0.02$.

left the lab at this point.

The 1310nm photons are sent to a BS-BSA. The detectors in this BSA are again a Ge-diode and an id200 InGaAs-diode. The trigger for the InGaAs is given by coincidences between the laser and a click on the Ge-diode. If the BSA is successful a signal is sent to the Swisscom station though an optical fiber different from the quantum channel. This signal will trigger the detector used at the switching station.

The 1555nm photon that was sent to the switching station is first sent into another quantum memory (fiber on spool). After this the photon is sent through a stabilized interferometer which is used to analyze the result of the teleportation. The photon is detected using an id200 InGaAs detector which was triggered by the result of the BSA. The countrate is registered by computer.

All the stabilization of the interferometers is done locally. Since the fiber interferometers cannot be used during stabilization a TCP/IP link was used to perform the stabilization of all the interferometers at the same time. This technique optimizes the duty cycle of the experiment.

In order for the BSA to function the incoming photons are filtered to an identical 5nm spectrum. Furthermore alignment of the fiber lengths is tested by performing HOM-dip experiments as explained in the previous chapters. Its result (Fig. 8.3) show clear indistinguishability of the photons with corrected visibilities near the maximum of $\frac{1}{3}$. Note that the photons used for this HOM-dip are not created by the same pulse because of the difference in the fiber delays.

This experiment requires one additional stabilization. Since the photons need to arrive on the BSA at the same time the length of the delay fibers they travel through should remain stable. However fluctuations in temperature mean that the length and refractive index of the fibers are not constant. In order to minimize the effects of these fluctuation both fibers were placed in a common isolation box so that fluctuations were equal for both spools. Two effects remain that influence the time of arrival. First of all the repetition frequency of the mode-locked laser has a small dependance on temperature. Second, the fluctuation of the 2.7m difference in
length of the fiber spools isn’t automatically compensated. In order to compensate for both effects it is possible to adjust the bulk optical delay line used in the path which creates the qubit to be teleported. It was empirically determined that by measuring the repetition frequency of the mode-locked laser and moving the delay 0.07µm /Hz the setup was sufficiently stable to perform a teleportation (Fig. 8.4).

8.3 Results and Conclusions

A first experiment was performed that didn’t use the heralding detector in order to have larger countrates. The phases of all interferometers were locked except for the analyzing interferometer which was deterministically scanned using the piezo in one of its paths. In order to reduce statistical errors each measurement point took 53 minutes of acquisition. The result (Fig. 8.5) shows a raw visibility $V_{\text{raw}} = 0.46\pm0.06$. It is possible to measure various detector noises that influence the measurement. When correcting for these problems a net visibility $V_{\text{net}} = 0.92\pm0.13$ is found. This value is higher than the strictest limit that has been associated with teleportation of $V = 2/3$ (cloning limit)[54, 55].

A second experiment was performed with the heralding detector as an additional constraint. The result (Fig. 8.6) also clearly shows the expected sinusoidal behavior with raw visibility $V_{\text{raw}} = 0.87\pm0.07$ which also is higher than $V = 2/3$. Since the noise-rate in this experiment was very low it wasn’t possible to measure the net visibility.

From these results it is possible to conclude that we performed a quantum teleportation protocol outside the lab. This experiment is very close to being a quantum relay which is usable in a ‘real world’ setting. The only point that is missing is that it is not yet possible to separate the qubit source and the entanglement source since they rely on the same laser. The next chapter will show a method which might one
Figure 8.5: Result of the teleportation experiment. The fit shows a net visibility of $V_{\text{net}} = 0.92 \pm 0.13$.

Figure 8.6: Result of the teleportation experiment when using a heralded qubit-source. The raw visibility is $V_{\text{raw}} = 0.87 \pm 0.07$. 
day allow a teleportation with multiple lasers.
Chapter 9

Synchronized photon sources [E]

9.1 Introduction

Consider the following situation: two independent photon-pair sources are used to perform an entanglement swapping experiment. For the BSM it is required that photons coming from the two sources are completely indistinguishable. This means that the time of arrival at the BSM has to be identical for both photons. In other words the coherence length must be longer than the temporal uncertainty. In order to achieve this most experiments use pulsed synchronized sources as shown in previous chapters. The synchronization is achieved by using a single laser pulse which generates two photon-pairs in one crystal in a back-and-forth configuration[12] or in two separate crystals each of which creates one pair[58]. In the previous chapter we also showed the use of two crystals and different laser pulses. Although such systems are practical they are not sufficient when trying to do long range experiments. If it is desired to have photon-pair sources at different locations, the use of only one laser would mean sending high-power pulses through optical fibers. The pulses will be distorted in the fibers by different effects and also compensation for path length fluctuations is required.

One logical alternative would be to use two different pulsed lasers which are synchronized. Innovative experiments on this subject have been done[57, 59] that have shown that in principle it is possible to create indistinguishable photons with independent lasers. However, neither of the techniques developed in these experiments can be easily used to truly make a quantum repeater. In the first case[57] the two independent sources had a common optical element, making it impossible to physically separate both sources. And in both experiments the photons have short coherence lengths, making the system very sensitive to path length fluctuations and drifts of repetition frequency and adding difficulty to synchronization at distance. When using optical fibers at telecommunication wavelengths these path lengths can fluctuate up to the order of several millimeters per day[60]. In terms of jitter this corresponds to several picoseconds. Therefore an active control of path length is required. As an alternative the next sections show our efforts in making separable sources that are useful for quantum repeaters and have a high tolerance against these path length fluctuations. Another interesting approach is using continuous
wave sources[61], this has its own particularities and won’t be discussed here.

9.2 Narrow-band photons

An important parameter for the quality of synchronization is jitter. One can easily imagine that the quality of a BSA is greatly reduced if one or both sources have a large jitter because this introduces temporal distinguishability between the created photons. If we assume the use of pulsed lasers and parametric-downconversion to create photon-pairs several different sources of jitter can be identified. First of all there is the intrinsic jitter, every laser has a certain uncertainty in the time of emission of a pulse. This jitter is minimal in a free-running modelocked-laser but can be important in pulsed diode-lasers. Second, there is a timing jitter which is created by the synchronization system itself. Finally there is the path-length jitter as mentioned before. Obviously an effort has to be made to limit all of these quantities, but one method to overcome them all is to increase the coherence length of the photon-pairs(Fig. 9.1) since this will effectively reduce the jitter per pulsewidth. The result of such a change is best illustrated by calculating the visibility of a HOM-dip.

Consider the probability $P$ of photon bunching when two identical photons arrive at a different time on a beamsplitter.

$$P_{\text{bunch}} = \frac{1}{2} \left( \left( \int f^*(t)f(t+\tau)dt \right)^2 + 1 \right)$$  \hspace{1cm} (9.1)

where $f(t)$ is the amplitude of the temporal distribution function of the photon and $\tau$ is the difference of arrival time. When assuming a gaussian distribution for the photons we find:

$$f(t) = \sqrt{N}e^{-8\ln 2 \frac{\tau^2}{w^2}}$$  \hspace{1cm} (9.2)

$$P_{\text{bunch}} = \frac{1}{2} \left( \left( N \int e^{-\frac{8\ln 2}{w^2}(t^2+(t+\tau)^2)}dt \right)^2 + 1 \right)$$  \hspace{1cm} (9.3)

$$= \frac{1}{2} \left( e^{-\frac{4\ln 2 \tau^2}{w^2}} + 1 \right)$$  \hspace{1cm} (9.4)
here $N$ is a normalization factor and $w$ is the FWHM of $P_{\text{bunch}}$. It is convenient to rewrite this last formula in dimensionless units:

$$\Delta \equiv \frac{\tau}{w}$$  \hspace{1cm} \text{(9.5)}

$$P_{\text{bunch}} = \frac{1}{2} \left( e^{-4\ln2\Delta^2} + 1 \right)$$  \hspace{1cm} \text{(9.6)}

where $\Delta$ is the amount of FWHMs the photons arrive apart.

When considering jitter the time-of-arrival difference will fluctuate. There is a probability $P_j$ to find the photon at a delay $\Delta$ of:

$$P_j(\Delta, w_j) = \frac{2}{w_j} \sqrt{\frac{\ln2}{\pi}} e^{-4\ln2\frac{\Delta^2}{w_j^2}}$$  \hspace{1cm} \text{(9.7)}

where we assumed a gaussian distribution with FWHM $w_j$. When performing a standard HOM-dip experiment with these parameters the average visibility of the system equals

$$\bar{V} = \int P_j(\Delta, w_j) V(\Delta) d\Delta$$  \hspace{1cm} \text{(9.8)}

$$= \int P_j(\Delta, w_j) (2P_{\text{bunch}}(\Delta) - 1) d\Delta$$  \hspace{1cm} \text{(9.9)}

$$= \frac{2}{w_j} \sqrt{\frac{\ln2}{\pi}} \int e^{-4\ln2\Delta^2 \left( \frac{1}{1+w_j^2} \right)} d\Delta$$  \hspace{1cm} \text{(9.10)}

$$= \frac{1}{\sqrt{1 + w_j^2}}$$  \hspace{1cm} \text{(9.11)}

This result shows (Fig. 9.2) a clear decrease of the visibility as a result of time-of-arrival jitter. It also shows that some jitter can be tolerated without a dramatic loss in visibility as long as $w_j$ remains small. The limit on the overall jitter at which it is still possible to see a visibility high enough to violate Bell’s inequality when performing Bell-tests ($\sqrt{0.5}$) is a jitter equal to the FWHM of the displacement per pulse length.

If we consider Fourier limited gaussian pulses the pulse width is given by the coherence length $l_c$.

$$l_c = \frac{2\ln2 \lambda_0^2}{\pi \Delta\lambda}$$  \hspace{1cm} \text{(9.12)}

where $\lambda_0$ the central wavelength and $\Delta\lambda$ the spectral FWHM. In order to increase the coherence length and thus effectively reducing $w_j$ the only viable option is to have a very small $\Delta\lambda$. The generation of photon-pairs with SPDC usually creates a large spectrum which can easily exceed several dozens of nm. At telecommunication wavelengths ($\lambda_0 = 1550\text{nm}$) such a spectrum corresponds to coherence lengths of the order of $10^{-5}\text{m}$ which is not enough since in previous experiments path length
fluctuations of up the several mm were found. One obvious approach is to use only a small part of the spectrum generated by the source (spectral filtering).

If coherence lengths of the order of a cm are desired extremely narrow filters are required. The filters used for our experiment are a combination of a fiber-bragg-grating(FBG) and a phase-shifted FBG. The phase-shifted FBG has an Airy-function shaped transmission spectrum with a width of about 40pm ($\omega_i$). The rejection of other wavelengths only works for a couple of nm so in order to filter them a standard FBG is used (Fig. 9.3). This combination is cascaded so it is possible to select pairs of photons, the second filter combination has a transmission width of 120pm ($\omega_s$). The two transmission wavelengths are symmetrically located around the pump wavelength ($\omega_p$).

In order to have a well defined correlation between the wavelengths of the photon-pairs it is required to filter the pump-photons. Since we use large coherence lengths the relatively large pulse length of the pump pulses is not a problem[62].

The visibility of a HOM-dip directly shows the maximum visibility that can be achieved in other QC experiments such as entanglement swapping. This makes it a very useful test, however other methods can also be used to show that two sources are synchronized. One alternative is to perform a cross-correlation measurement. This has the advantage that it is a lot simpler but the disadvantage that it only test the synchronization and not the other important parameters such as indistinguishability. It can be done by passing light form two sources through a non-linear crystal(NLC) cut for type II phasematching. When both pulses arrive at the same time in the NLC there will be frequency-doubling with an intensity dependent on their overlap. Assuming gaussian functions this means that the FWHM of the detectable frequency-doubled light is equal to $w_{fd} = \sqrt{w_{s1}^2 + w_{s2}^2 + w_j^2}$ where $w_{fd}, w_{s1}, w_{s2}$ and $w_j$ are the FWHM for the frequency-doubled light, first source, second source and the synchronization jitter respectively. In order to find the value of $w_j$ it is required to first measure the pulse lengths $w_{s1}$ and $w_{s2}$ using an auto-correlation measurement. This is similar to the cross-correlation but both sources

Figure 9.2: Visibility as a function of $w_j$. A visibility of $\sqrt{0.5}$ corresponds to $w_j = 1$ (dashed lines).
Figure 9.3: Narrow band filters. ps-FBG is a phase-shifted FBG. Cascaded filters are required because the rejection of the ps-FBGs is only a few nm wide. The combination between a FBG and a ps-FBG results in a very narrow transmission spectrum. The transmission wavelengths $\omega_s$ and $\omega_i$ are symmetrically located around $\omega_p$. The illustration on the right is exaggerated to better show the principle, in reality the two transmission spectra are very close to the center of the input spectrum.

are one half of a single pulse.

9.3 Pulsed sources

It is important for quantum communication to have ‘simple’ entanglement sources. With this in mind we developed a photon-pair source based on a pulsed laser diode, instead of the more common bulky mode-locked lasers (Fig. 11.1). The diode produces pulses with a FWHM of about 25ps at a wavelength of 1550nm. The power of the diode is 20 $\mu$W. This power is not enough for the type of photon sources we would like to build. In order to increase the pump power the light is send through two Er-doped fiber pre-amplifiers. After this the noise is filtered by a variable FBG. The resulting pulses are then send into the main Erbium amplifier. The pulses are send trough a PPLN crystal which trough upconversion generates 2mW of the desired light at 775nm with a spectral width of 0.4nm.

The other source used for the experiments is a more conventional modelocked-laser (MIRA) generating picosecond pulses with a wavelength of 775nm, bandwidth of 1nm and a pulse length of about 5ps. The synchronization of these two sources was performed using a Master-Slave configuration. For this purpose a small part of the output of the mode-locked master laser was sent to a fast diode. The signal from this diode is used to trigger the slave diode-laser.

9.4 Tests of synchronization

In order to test the synchronization jitter of our sources a cross-correlation measurement (Fig. 9.5) was performed. It consists of combining the output of the diode-based laser with the mode-locked laser on a polarizing beamsplitter (PBS).
Figure 9.4: Representation of the diode-laser source. A pulsed laser diode with a wavelength $\lambda_p = 1550\text{nm}$ and a power of $20\mu\text{W}$ is used. The pulses are sent into two Erbium pre-amplifiers in series. The resulting pulses are filtered by a FBG in order to remove the undesired amplified spontaneous emission (ASE). This light is then sent through the main Erbium amplifier. The resulting pulses are strong enough ($\approx 350\text{mW}$) for frequency doubling in a PPLN crystal. The resulting wavelengths are spatially separated using a prism.

Figure 9.5: Experimental setup used to measure correlations. Two pulses of light are combined on a BBO NLC. If both pulses arrive at the same time there is up-conversion creating light which can then be measure with a Si-APD. It is possible to combine light from a single source (auto-correlation) or two different sources (cross-correlation).
Figure 9.6: Results of the cross- and auto-correlation measurements. top: Cross-correlation with a gaussian fit FWHM=8.27mm. bottom-left: Autocorrelation of the diode-based source, fitted pulselength FWHM=6.2mm. bottom-right: Autocorrelation of the mode-locked source, fitted pulselength FWHM=1.5mm. Note that the fitted width is equal to the convolution of the involved pulses.

The mode-locked laser had a large variable optical delay-line which was scanned in order to change the difference of time of arrival of the two sources on the PBS. Behind the PBS there was an BBO-crystal cut for type-II parametric downconversion. Such a crystal is also efficient for upconversion of two 775 photons to a single 387.5nm photon. These blue photons were separated from the other wavelengths with a prism and measured using a Si-APD. The delay was scanned while recording the countrate. The result of this measurement (Fig. 9.6) shows a FWHM of 8.3mm (28ps). This length corresponds to a combination of jitter and pulse widths so in order to know the jitter it is also required to measure the pulse lengths. This was done with a setup similar to the cross-correlation but the two inputs of the PBS now came from the same source. The measured pulse widths were 1.5mm (5.0ps) and 6.2mm (20.7ps) (Fig. 9.6). Using these measurements it is possible to calculate the jitter, $\omega_j = 18$ps (5.9mm).

The jitter found in the cross-correlation experiment puts a minimal limit on the pulse width required to find a high visibility in a HOM-dip. From its value it is possible to conclude that if a visibility greater then 95% is desired pulse lengths of about 20mm (67ps) are required. The filters described in section 9.2 are used to achieve a coherence length of $l_c = 2.6$cm.

Other than measuring jitter through cross-correlation we also performed a HOM-dip. The setup(Fig. 9.7) consisted of the same two sources as used for the cross-correlation measurement. The light from these sources was send into PPLN-waveguides in order to produce pairs of photons through SPDC. These pairs were send into opti-
Figure 9.7: Experimental setup used to measure a HOM-dip with independent sources. The photons combine at the 50/50 beamsplitter and will bunch depending on the delay-line.

Figure 9.8: The resulting coincidence countrates show a visibility $V = 0.26 \pm 0.5$, and a spectral width corresponding to $w = 38.0 \pm 0.9 \text{pm}$. Note that the maximum visibility that can be found is again $\frac{1}{3}$ because the sources are probabilistic\cite{63}. Unfortunately it is difficult to make a conclusion about the distinguishability caused by jitter from this value of $V$. Either the visibility is reduced by jitter or by other factors. The FWHM of the dip corresponds to the expected value, if jitter would have caused a loss in visibility the width would also have increased so the value found for the width suggests that the loss of visibility is caused by something else than the jitter.

In order to test whether the cause of the low visibility was jitter we also performed a HOM-dip using only the MIRA as pump. In this setup there is minimal jitter from the pump photons. The result (Fig. 9.9) of this experiment shows a visibility $V = 0.22 \pm 1.5$, and $w = 38.9 \pm 3.8 \text{pm}$. These two results combined lead to the conclusion that the loss of visibility is not caused by jitter and therefore the sources presented in this chapter can be useful for future experiments with separated sources if the limiting factor of the visibility is eliminated. Furthermore it suggests that the loss of visibility is caused by the mode-locked laser.

In order to test whether we could distribute the signal between the master and slave laser an optical transmission line was build. We used a small laser-diode with a wavelength of 1550nm to generate an optical pulse from the electrical trigger signal. This pulse is send through one km of fiber before being detected by a PIN-diode. This signal is amplified and used as the trigger. The results above include this trigger distribution showing that it is possible to distribute the trigger signal between two
Figure 9.8: Measured HOM-dip using two independent and separable sources.

Figure 9.9: Measured HOM-dip using the MIRA as pump for both waveguides.
locations. For experiments with more than 2 sources it would be very interesting to use a distributed clock. This experiment doesn’t investigate this option but it would be a possibility for the near future.
Chapter 10

Other contributions

In this chapter some of the other contributions made for this thesis are briefly discussed, more details can be found in the corresponding articles[F-G]. The first section concerns a alternative type of photon-pair source and the second section is about some fundamental tests of physics involving Bell-tests in particular configurations.

10.1 Semiconductor waveguide source [F]

As has been shown in the last chapter it is possible to synchronize photon-pair sources pairs for QC protocols by creating narrow-band sources. Ideally such sources are small and easily integrated into existing systems. In this section we will briefly look at the results of a collaboration of our group with the group of G.Leo et al. in Paris. The subject of this collaboration was the construction of a source of twin photons in semiconductors.

10.1.1 Introduction

Parametric generation of photon pairs using semiconducting waveguides has a couple of potential advantages over the other techniques used in this thesis.

1. Room-temperate operation
2. Waveguide structure enhances collection efficiency (similar to PP waveguides)
3. Counter-propagating photons eliminate need for WDMs
4. Smaller optical spectra
5. Pump-photons are not in guided mode (vertical pumping)
6. Possible integration with other semiconductor techniques on same chip

This last advantage is especially interesting if one imagines such a source combined with a vertical cavity surface emitting laser (VCSEL). The ultimate goal would thus indeed be a small completely integrated source which only needs to be plugged into a power supply.
Figure 10.1: Left: Schematic representation of the experimental setup. Right: The result of the TAC measurement shows a clear peak with a FWHM of 750ps. The flat background is caused by detector noise counts and luminescence photons.

10.1.2 Experiment

The semiconductor waveguide is a multilayered AlGaAs-waveguide of 4µm width and 2mm length on top of a GaAs substrate. The setup (Fig. 10.1) uses vertical pumping. This means that contrary to PP waveguide sources, as discussed in previous chapters, the pump light is not coupled into the waveguide but impinges on it from the top. In order to illuminate almost the entire sample a cylindrical lens is used to create a cigar-shaped mode-profile. The pump is a Ti:sapphire pulsed laser which provides 100W peak power at 768.2nm with a 3kHz repetition rate and 100ns pulses. Note that the use of vertical pumping minimizes the probability of detecting a pump photon at the end of the experience.

The conversion of the pump photon into the signal and idler is done by type-II SPDC (Fig. 10.2) using counterpropagating phasematching[64, 65, 66]. The conservation of momentum is maintained since the difference between the two generated photons corresponds to the lateral component of the pump photons. Two different type-II processes can happen. One in which the TM component goes in the z-direction and one in which it goes in the opposite direction. These two processes have different output spectra caused by the birefringence of the multilayered geometry.

In order to show the twin character of the generated photon pairs a time to amplitude converter (TAC) was used. Both photons were detected using InGaAs detectors in GMO. The trigger for the detectors was synchronized with the laser emission. By using one detector as start for the TAC and the other as stop one would expect to find a single peak with a width corresponding to a combination of pulse width and detector jitter. This behavior was verified and the width of the peak (750ps) was found to be essentially due to the detection jitter. The flat background
Figure 10.2: Generation of counterpropagating photon-pairs in a waveguide. (a) A photon at frequency $\omega_p$ impinges on the waveguide with angle $\theta$ and is converted into two photons with frequency $\omega_s$ and $\omega_i$. (b) The conversion is type-II and momentum is conserved in longitudinal direction ($z$) for appropriate values of $\vec{k}_s$ and $\vec{k}_i$. (c) Tuning curves show a change of wavelength is possible by changing the angle $\theta$.

is caused by dark counts of the detector and photons emitted by the substrate of the waveguide structure. This last contribution can be eliminated by removing the substrate. This source currently generates about one pair per pulse, which is more than required for current QC experiments. Unfortunately the low repetition rate is a significant drawback which

The next step in this research could be the inclusion of other semi-conductor techniques in order to reduce the required pump power and to integrate a VCSEL. If this succeeds this could be an important step towards truly portable sources for QC.

### 10.2 Entanglement and waveform collapse [G]

When is a quantum measurement finished? This little question has no clear answer in quantum theory and many different interpretations exits, such as the “many-worlds” interpretation[67]. Unfortunately it is not yet possible to test the different theories although progress is being made in this field[68, 69]. One particular possibility assumes that a quantum measurement is made before space-time gets into a superposition of different geometries[70, 71]. If we follow this theory the time of
collapse of the wavefunction is given by:

$$t_D = \frac{3\hbar V}{2\pi Gm^2d^2}$$  \hspace{1cm} (10.1)

where \(G\) is the gravitational constant and \(m\) is the mass of an object with volume \(V\) that moved a distance \(d\). According to this theory the measurement of a photon doesn’t provide a rapid collapse of the wavefunction since it only involves movement of tiny masses (electrons). This leads to the conclusion that none of the Bell-test done to date involved space-like separated events[72].

An experiment can be done to close this loophole. By moving a significant mass every time a detector finds a click the wavefunction can be forced to collapse rapidly. If the two collapses happen space-like separated there can be no communication slower or at light speed between both parties. We performed such an experiment were the mass was a small mirror \((m = 2mg, \ V = 0.9mm^3)\) moved by a piezo actuator \((d = 15nm)\). The scheme of the experiment (Fig. 10.3) shows a continuous wave single mode diode laser, with a power of 2.7mW and a wavelength of 785.2nm, used to pump a PPLN-waveguide. The photon-pairs created here are coupled into a SMF and the pump is removed using a Si-filter. The photon pairs are separated using two FBGs with a width of 1nm and two circulators. One photon is sent approximately east towards a town called Jussy \((17.5km\ of\ fiber,\ 10.7km\ distance)\) and the other towards Satigny \((13.4km\ fiber\ plus\ 4.1km\ of\ fiber\ on\ a\ spool,\ 8.2km\ distance)\). At each of these locations there is an unbalanced interferometer with a path length difference of 1.3ns. After the interferometers the photons are detected using InGaAs APDs triggered by a synchronization signal coming from the lab in Geneva. Wherever there is a click in an APD a signal is sent to the local piezo which moves the mass. The phase of one of the interferometers was scanned by scanning its temperature. The resulting interference fringes(Fig. 10.4) shows a raw visibility \(V = 0.905 \pm 0.015\) which clearly violates the Bell-inequality \((V \leq \frac{1}{\sqrt{2}})\). This experiment therefore closes the locality loophole even if we assume a quantum
Figure 10.4: Result of a scan of one of the interferometers. The fitted curve has a raw visibility \( V_{\text{raw}} = 0.905 \pm 0.15 \).

measurement isn’t finished until there is movement of a significant mass.
Chapter 11

Conclusions

In conclusion we presented several experiments aiming towards the realization of quantum communication protocols such as a quantum relay in a real world situation outside the lab. In order to allow this timebin encoding was used for our qubits because of its robustness and photons at telecommunications wavelengths as a medium due to their capability to travel large distances in optical fibers.

In this thesis we first described an entanglement swapping experiment performed inside the laboratory. Its success ($V = 0.80 \pm 0.04$) showed that the techniques developed might also work for out of the lab experiments. In order to demonstrate the long distance capability of this experiment $2 \times 1.1$km of standard single mode optical fiber were used.

After this experiment we tested a new type of Bell-tate analyzer. Instead of measuring only one Bell-state the new method is capable of measuring three Bell-states, albeit probabilistically. The results of this teleportation experiment prove the functioning of the analyzer. For out-of-the-lab experiments the system doesn’t have enough benefits to outweigh the additional losses which are unavoidable in its use. Fundamentally this experiment is interesting since it tested timebin teleportation with different Bell states. Furthermore there might be protocols for which it is interesting to measure multiple Bell states.

Following this experiment we performed the first teleportation experiment outside the laboratory in which there was distribution of the entangled pair prior to the creation of the qubit. This is more proof showing that our techniques are robust enough to work independently outside the lab. The only factor of this experiment which makes it unscalable to a multi-location quantum relay is the fact that a single laser source was used.

As a next step we investigated the possibilities of using multiple laser sources. In order to create sufficient tolerance against jitter and path length fluctuations we created pulsed sources of photon-pairs with narrow bandwidths. The coherence length of these photons is of the order of several cm which makes these sources interesting for future experiments.

Some other contributions made during this thesis involved the testing of new sources of photon-pairs in semiconductor waveguides. These sources might one day be used as small integrated sources for many entanglement experiments. Further-
more work was done on fundamental test of physics by performing Bell-tests with moving masses and by setting a high lower bound on the hypothetical speed of quantum information in all possible reference frames.

11.1 Outlook

The work done for this thesis is a step towards the realization of a true quantum repeater with multiple locations capable of creating entangled states separated by very large distances. Once such an experiment is done that would be an important milestone for the field of quantum communication. It would mean that the realization of a global quantum web would merely be a question of economic forces and political will. Also it will allow truly private communications around the world that are provably secure.
Le début de la physique quantique se trouve dans les premières années du vingtième siècle. Max Planck avait découvert qu'on pouvait expliquer le spectre émis par une source thermique en postulant des quanta d’énergie. Albert Einstein a ensuite aussi utilisé cette idée pour expliquer l’effet photo-électrique avec des quanta de lumière, aujourd’hui connus sous le nom de photons.

Dans les dernières décennies l’intérêt des physiciens pour la physique quantique a grandi au-delà d’un intérêt purement fondamental. Une nouvelle idée, introduite par S. Wiesner, était d’utiliser les propriétés typiquement quantiques comme ressource. Cette idée a pris des ailes quand P. Shor à découvert un algorithme quantique pour factoriser des nombres premiers. Depuis cette idée s’est développée dans une nouvelle avenue de recherche: la communication et l’informatique quantique.

L’informatique quantique est le terrain de recherche qui utilise les propriétés quantique pour faire des ordinateurs quantiques ou encore des simulations quantiques. L’algorithme de Shor mentionné ci-dessus est l’algorithme qui explique le mieux l’intérêt de ces ordinateurs. En effet, par ce nouvel algorithme il est possible de factoriser une grand chiffre \( N \) en ses facteurs premiers. Sur un ordinateur classique cette opération est très difficile et prends un temps exponentiel par rapport à la largeur du chiffre. Avec l’algorithme de Shor il est possible de faire la même tâche sur un ordinateur quantique dans un temps polynomial. Cette possibilité aura des conséquences énormes sur les méthodes de cryptographie actuelle.

La communication quantique sert à distribuer des états quantiques entre plusieurs endroits. Ceci sera requis pour un réseau quantique le jour où les ordinateurs quantiques seront communs. Dans une période moins lointaine, il est possible de faire de la distribution quantique de clefs. Ceci permet a deux lieux de partager une série des bits aléatoires en secret. Combiné avec l’encodage à masque jetable (aussi appelé chiffre de Vernam ou, plus communément en anglais, “one-time pad”) ceci donne une forme de cryptographie absolument sûre et inviolable.

À première vue on pourrait s’imaginer qu’il est simple de distribuer un état quantique. On prend un photon, on le mets dans l’état désiré et on l’envoie par une fibre optique. On attends que le photon arrive de l’autre coté et voilà, l’état a été distribué. Malheureusement des méthodes aussi simples ne fonctionnent pas pour des distance qui nous intéresse à cause des pertes dans les fibres optiques. Pour la communication classique ceci n’est pas un problème car il suffit de mettre des amplificateurs de signaux dans le chemin. Pour les états quantiques par contre une telle amplification est malheureusement impossible. Ceci peut être démontré par le théorème de non-clonage.
Il y a une solution à ce problème. Il est possible d’utiliser un répétiteur quantique. Dans un répétiteur les états quantiques ne sont pas amplifiés mais téléportés vers leur destination finale. Utiliser plusieurs répéteurs en série permet de franchir de grandes distances. Pendant cette thèse plusieurs expériences ont été faites pour tester les possibilités de fabriquer un répétiteur quantique.

Premièrement, nous avons fait une expérience de téléportation d’intrication. L’intrication est la propriété qu’ont deux états quantique de ne pas pouvoir être décrits séparément. Nous avons réussi à téléporter cette propriété d’un photon à un autre. Ce faisant, nous avons créé la situation très contre-intuitive où deux photons sans aucune histoire commune ne peuvent être décrits qu’ensemble.

Notre expérience a utilisé des photons aux longueurs d’onde utilisées par les compagnies de télécommunications et en codage temporel. Cette combinaison en fait un système idéal pour atteindre des longues distances. Notre expérience a montré une téléportation d’intrication sur une distance de 2.2 km de fibre optique en laboratoire.

Ensuite, nous avons étudié et développé une nouvelle méthode pour faire des mesures des Bell, la partie le plus importante d’un protocole de téléportation. Jusqu’ici, tous les systèmes pour faire ces mesures ont été partiels. En général il n’est possible de détecter que 2 des 4 états de Bell. Nous avons développé un système qui permet de mesurer 3 des 4 états de Bell. Pour montrer le fonctionnement de ce système nous l’avons utilisé dans une expérience de téléportation.

Après avoir compris et maitrisé toutes ces techniques, nous avons fait la première expérience de téléportation hors du laboratoire qui distribue les états intriquée avant de créer le qubit à téléporter. Nous avons fait ceci sur une distance de 800m, entre notre laboratoire et une station de relais de Swisscom. Cette expérience a finalement prouvé que les techniques que nous avons développées sont suffisamment robustes pour fonctionner hors du labo. Le seul défaut de cette expérience est que les deux sources de photons étaient encore pompées par le même laser.

La dernière expérience de cette thèse essaie d’adresser le problème des paires de photon toujours crées au même endroit. Nous utilisons un système de deux lasers indépendants dans une configuration Maître-Esclave. Le signal d’horloge du maître est envoyé avec une fibre optique et il est donc possible de vraiment séparer les deux sources. Pour avoir une bonne tolérance contre la gigue des signaux optiques et les changements de longueur de chemin nous utilisons des filtres très fin pour avoir des photons à large bande. Pour montrer le fonctionnement de nos sources nous avons fait une expérience d’agglomération de photons.

Des résultats de toutes les expériences faites pendant cette thèse nous pouvons conclure que nos techniques sont très utiles pour des expériences de téléportation hors des laboratoires. Nous avons commencé le chemin pour faire un véritable relais quantique dans le futur.
Appendix

This appendix takes a closer look at the amplification of the diode-based source used in chapter 9. The general scheme of the source is shown again in figure 11.1.

![Figure 11.1: Representation of the diode-laser source. A pulsed laser diode with a wavelength $\lambda_p = 1550\,\text{nm}$ and a power of $20\,\mu\text{W}$ is used. The pulses are sent into two Erbium pre-amplifiers in series. The resulting pulses are filtered by a FBG in order to remove the undesired amplified spontaneous emission (ASE). This light is then sent through the main Erbium amplifier. The resulting pulses are strong enough ($\approx 350\,\text{mW}$) for frequency doubling in a PPLN crystal. The resulting wavelengths are spatially separated using a prism.](image)

In the next series of images the spectra after each step of the amplification process shown. The system was empirically optimized to get high power short pulses.
Figure 11.2: Spectrum of the diode-laser

Figure 11.3: Spectrum after the first Erbium pre-amplifier. The small peak is the amplification of the signal coming from the diode laser. The background is caused by amplified spontaneous emission (ASE). There is a lot more power in the ASE then in the main peak.
Figure 11.4: Spectrum after the second Erbium pre-amplifier. The amplified pulses are well above the level of ASE.

Figure 11.5: Spectrum after the FBG. The level of ASE is reduced and a small part of the amplified emission is selected.
Figure 11.6: Final spectrum after the main Erbium amplifier. One powerful peak with some fine structure.

Figure 11.7: Example of the spectrum after the conversion in the PPLN. The structure of this final spectrum depends heavily on the setting of the FBG.
Bibliography


Publication list


Newspaper articles

In the next few pages some newspaper clippings about the teleportation experiment between our lab and the Swisscom station at Plainpalais are shown. These were added here as an illustration that it is possible to interest a general public for the kind of research done in this thesis. Despite our efforts the articles contain a few errors but that seems unavoidable when popularizing this subject.

La téléportation fait un pas vers le monde réel

Des chercheurs de l’Université de Genève ont téléporté une particule en utilisant le réseau Swisscom.


La méthode consiste à créer deux photons ‘intriqués’. ‘Ce sont des particules que l’on a créées ensemble, de façon bien prête, pour qu’ils réagissent comme un seul tout’, explique Nicolas Gisin. Comme des jumeaux qui ressembleraient la même chose, même à distance si l’on blesse l’un d’entre eux, l’autre souffre aussi. Le premier photon reste à l’université tandis que l’autre est acheminé via les câbles optiques du réseau Swisscom jusqu’au central de Plainpalais. Par la suite, on pourra retirer le câble, mais en l’occurrence, on ne va pas prêter les Genevois de téléphone.


En 2003, l’équipe genevoise avait déjà réalisé cette expérience sur une distance de 2km. ‘Le fait qu’aujourd’hui nous ayons pu la rendre compatible avec le réseau d’un opérateur commercial est un pas vers le monde réel’, souffle le professeur. L’avenir avancé est d’avoir fait les choses dans l’ordre, les uns après les autres.

‘Ca n’en a peut-être pas l’air, poursuit le scientifique, mais du point de vue technique, c’est un gros progrès si on veut un jour utiliser la téléportation quantique.’

Le physicien rappelle que les principes théoriques qui régissent l’expérience datent de 1993. ‘La mise en pratique a été rapide, sourit Nicolas Gisin. Beaucoup de physiciens s’y sont attelés, parce que ça fait rêver!’ Quand on lui demande quelles sont les applications possibles, il répond d’ailleurs en premier: ‘faciner les scientifiques. Il y a aussi la communication cryptée. ‘Mais on en est encore aux balbutiements, et on ne se rend sûrement pas compte de toutes les applications qu’il pourra y avoir dans le futur’, conclut le physicien.

Lucia Seelig
Les physiciens font entrer dans le ‘monde réel’ la téléportation quantique, Le Temps, (16 juin 2006)
Publications
Long-distance entanglement swapping with photons from separated sources

H. de Riedmatten, I. Marcikic, J. A. W. van Houwelingen, W. Tittel, H. Zbinden, and N. Gisin

Group of Applied Physics, University of Geneva, Geneva, Switzerland

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We report the experimental realization of entanglement swapping over long distances in optical fibers. Two photons separated by more than 2 km of optical fibers are entangled, although they never directly interacted. We use two pairs of time-bin entangled qubits created in spatially separated sources and carried by photons at telecommunication wavelengths. A partial Bell-state measurement is performed with one photon from each pair, which projects the two remaining photons, formerly independent onto an entangled state. A visibility high enough to infer a violation of a Bell inequality is reported, after both photons have each traveled through 1.1 km of optical fiber.

Quantum theory is nonlocal in the sense that it predicts correlations between measurement outcomes that cannot be described by theories based solely on local variables. Many experiments confirmed that prediction using pairs of entangled particles produced by a common source. It is only in 1993 that Zukowski and colleagues noticed that this “common source” is not necessary: nonlocality can manifest itself also when the measurements are carried out on particles that have no common past, but have been entangled via the process of entanglement swapping. It consists of preparing two independent pairs of entangled particles (see Fig. 1), and to subject one particle from each pair (B and C) to a joint measurement called Bell-state measurement (BSM). This BSM projects the two other particles (A and D), formerly independent, onto an entangled state that may exhibit nonlocal correlations. Let us emphasize that this kind of quantum nonlocality cannot be used to signal faster than light. There is thus no direct conflict with relativity. In the entanglement swapping process this aspect goes as follows. Initially, particles A and D have independent pasts, hence share no correlation (except possibly for some classical correlation). They share quantum nonlocal correlations only after their twins B and C have been jointly measured and only conditioned on the outcome of this measurement: without the conditioning they appear as independent. Hence, as long as the classical information about the joint measurement outcome is not available, no nonlocal correlation can be observed.

Besides its fascinating conceptual aspect, entanglement swapping also plays an essential role in the context of quantum information science. It is for instance the building block of protocols such as quantum repeaters [2,3] or quantum relays [4–6] proposed to increase the maximal distance of quantum key distribution and quantum communication. It also allows the implementation of a heralded source of entangled photon pairs [1]. Finally, it is a key element for the implementation of quantum networks [7] and of linear optics quantum computing [8]. More generally, coherent manipulations of several quantum systems, as in a BSM, are essential for all quantum computing and simulation processes.

Experimental demonstration of entanglement swapping has been reported in 1998, using two pairs of polarization entangled qubits encoded in photons around 800 nm created by two different parametric down conversion (PDC) events in the same nonlinear crystal [9]. The fidelity of this experiment was, however, insufficient to demonstrate nonlocal correlations. In 2002, an improved version allowed a violation of a Bell inequality [10], thus confirming the nonlocal character of this protocol. More recently, an experiment with qubits entangled in the Fock basis (one photon with the vacuum) has been reported [11]. However, it involves only two photons instead of four. All the experiments realized so far have demonstrated the principle of entanglement swapping over short distances (of the order of a meter). However, most applications in quantum communication require this process to happen over large distances. A promising approach for this purpose is to use the existing network of optical fibers. However, none of the previously demonstrated schemes was well adapted for this task.

In this paper, we present the experimental demonstration of entanglement swapping with a quantum architecture optimized for long-distance transmission in optical fibers. We use two pairs of time-bin entangled qubits encoded in photons at telecommunication wavelengths created by PDC. This type of encoding has been proven to be robust against decoherence in optical fibers [12] and has been used to achieve long-distance quantum teleportation in optical fibers [6,13]. Contrary to the previous swapping experiments involving four photons [9,10], the two pairs are created in spatially separated sources although pumped by the same laser. As a proof of principle of the robustness of this scheme, we demonstrate entanglement swapping over more than 2 km of...
of the four Bell states, photons \( A \) and \( B \) create the corresponding entangled state. Note that when photons are projected onto the state \( |1,1\rangle \) in the early time bin and \( |0,0\rangle \) in the delayed time bin, with \( c_0^2 + c_1^2 = 1 \). In our experiment, we employ two spatially separated sources of entangled photons. In one of these sources, we create a state \( |\phi^+(\delta)\rangle_{AB} \), while in the other one we create a state \( |\phi^+(\delta + \pi)\rangle_{CD} \). Initially, the two photon pairs are independent and the total state can be written as the tensor product: \( |\Psi_{ABCD}\rangle = |\phi^+(\delta)\rangle_{AB} \otimes |\phi^+(\delta)\rangle_{CD} \). This state can be rewritten in the form:

\[
|\Psi_{ABCD}\rangle = \frac{1}{2} \left[ |\phi^+\rangle_{BC} \otimes |\phi^-(2\delta)\rangle_{AD} + |\phi^+\rangle_{BC} \otimes |\phi^+(2\delta)\rangle_{AD} + |\phi^-\rangle_{BC} \otimes e^{i\delta} |\phi^-\rangle_{AD} + |\phi^-\rangle_{BC} \otimes e^{i\delta} |\phi^-\rangle_{AD} \right],
\]

where the four Bell states are \( |\phi^+\rangle = 1/\sqrt{2} (|0,0\rangle \pm e^{i\delta} |1,1\rangle) \) and \( |\phi^-\rangle = 1/\sqrt{2} (|1,0\rangle \pm e^{i\delta} |0,1\rangle) \). When photons \( B \) and \( C \) are measured in the Bell basis, i.e., projected onto one of the four Bell states, photons \( A \) and \( D \) are projected onto the corresponding entangled state. Note that when photons \( B \) and \( C \) are projected onto the state \( |\phi^+\rangle \) or \( |\phi^-\rangle \), the state of photons \( A \) and \( D \) is independent of the phase \( \delta \), which appears only as a global factor. This means that in this case, the creation process is robust against phase fluctuations in the pump interferometer and pump-laser wavelength drifts [15]. Hence, this experiment can also be considered as a postselected heralded source of entangled photon pairs robust against phase fluctuation in the preparation stage [16]. If, however, photons \( B \) and \( C \) are projected onto the state \( |\phi^+\rangle \) or \( |\phi^-\rangle \) the state of photons \( A \) and \( D \) depends on twice the phase \( \delta \). In our experiment, we make a partial BSM, looking only at projections of photons \( B \) and \( C \) onto the \( |\phi^+\rangle \) Bell state. Another interesting feature to note is that all the four Bell states are involved in the experiment, since we start from \( |\phi^+\rangle \) and \( |\phi^-\rangle \) states, and make a projection onto the \( |\phi^+\rangle \) state, which projects the two remaining photons onto the \( |\phi^+\rangle \) state.

A scheme of our experiment is presented in Fig. 2. Femtosecond pump pulses are sent to an unbalanced bulk Michelson interferometer with a travel time difference of \( \tau = 1.2 \) ns. Thanks to the use of retroreflectors, we can utilize both outputs of the interferometer, which are directed to spatially separated lithium triborate (LBO) nonlinear crystals. Collinear nondegenerate time-bin entangled photons at telecommunications wavelengths (1310 and 1550 nm) are eventually created by PDC in each crystal. Because of the phase acquired at the beam splitter in the pump interferometer there is an additional relative phase of \( \pi \) between the terms \( |0,0\rangle \) and \( |1,1\rangle \) in the second output of the interferometer. This explains why a state \( |\phi^+(\delta)\rangle \) is created in one crystal while a state \( |\phi^-(\delta)\rangle \) is created in the other one.

The created photons are coupled into single-mode optical fibers and deterministically separated with a wavelength-division multiplexer (WDM). The two photons at 1310 nm (\( B \) and \( C \)) are subject to a partial BSM using a standard 50-50 fiber beam splitter [17]. It can be shown that whenever photons \( B \) and \( C \) are detected in different output modes and different time bins, the desired projection onto \( |\phi^+(\delta)\rangle_{BC} \) is achieved [18]. For this kind of measurement, the two incoming photons must be completely indistinguishable in their spatial, temporal, spectral, and polarization mode. The indistinguishability is verified by a Hong-Ou-Mandel experiment [19,20]. The two photons at 1310 nm are filtered with 5 nm bandwidth interference filters (IF) in order to increase their coherence time to 500 fs, larger than the pump pulse’s duration (200 fs), which is necessary in order to make the photons temporally indistinguishable [21].

The two photons at 1550 nm, filtered to 18 nm bandwidth (\( A \) and \( D \)), each travel over 1.1 km of dispersion shifted fiber (DSF). Their entanglement is then analyzed with two fiber Michelson interferometers with the same travel time difference as the pump one. The phase of each interferometer can be varied with a piezoactuator (PZA). Since the demonstration of entanglement swapping necessitates the detection of four photons, the coincidence count rate is very low. This requires the ability to perform interferometric measurements over an extended period of time and thus asks for a drastic

**FIG. 2.** Experimental setup. The pump laser is a mode-locked femtosecond Ti-sapphire laser producing 200 fs pulses at a wavelength of 710 nm with a repetition rate of 75 MHz. After the crystals, the pump beams are blocked with silicon filters (SF). The Faraday mirrors (FM) are used to compensate polarization fluctuations in the fiber interferometers.
improvement in the setup stability, compared to our previous experiments [6,13]. In order to control the phase, and to obtain a sufficient long-term stability, the fiber interferometers are actively controlled using a frequency stabilized laser (Di-cos) and a feedback loop on the PZA. The phase of each fiber interferometer is probed periodically and is locked to a user-defined value [12]. This technique allows us to obtain excellent stability tested over up to 96 h. Note that the pump interferometer requires no active phase stabilization.

The photons are detected with avalanche photodiode (APD) single-photon detectors. One of the 1310 nm photons (detector \(C_1\)) is detected with a liquid-nitrogen-cooled Ge APD (NEC), with an efficiency of around 10% for 40 kHz of dark counts. The three other photons are detected with In_{GaAs}APDs (id-Quantique) with an efficiency of 30% for a dark probability of around \(10^{-4}\) per ns. The trigger signal for those detectors is given by a coincidence between the Ge APD and the emission of the pump pulses. The coincidence events between different detectors are recorded with a multistop time-to-digital converter (TDC). The coincidence between the Ge APD and the emission time of the laser is used as “Start” while the other APDs are used as “Stops.” Note that the classical information about the BSM is delayed electronically by roughly 5 \(\mu s\), corresponding to the travel time of the 1550-nm photons inside optical fibers. Hence, the swapping process is completed only when the photons are already 2 km apart. A homemade program allows us to register any combination of coincidence count rate between the four detectors, which is useful to characterize the stability of the whole setup during the measurement process. In our experiment, the average pump power for each source was about 80 mW, leading to a probability of creating an entangled pair per laser pulse of around 6%.

If entanglement swapping is successful, the two photons \(A\) and \(D\) at 1550 nm should be in the entangled state \(|\psi^{+}\rangle\), conditioned on a projection on the \(|\psi^{+}\rangle\) Bell state. However, as real measurements are imperfect, there will be some noise that we suppose will be equally distributed between all possible outcomes. Hence, the created state can be written as

\[
|\psi\rangle = F_2 |\psi^{+}\rangle|\psi^{-}\rangle + \frac{1 - F_2}{3} (|\psi^{+}\rangle|\psi^{-}\rangle + |\psi^{-}\rangle|\psi^{+}\rangle + |\psi^{+}\rangle|\psi^{-}\rangle)
\]

where \(V\) is the visibility and \(F_2\) the two-qubit fidelity defined as \(F_2 = \langle |\psi^{+}\rangle |\langle \psi^{+}\rangle \rangle\). \(V\) is related to \(F_2\) as

\[
V = \frac{4F_2 - 1}{3}.
\]

The Peres criteria [22] shows that the two photons are entangled (i.e., in a nonseparable state) if \(V > 1/3\), and consequently if \(F_2 > 1/2\). It can also be shown that in the Clauser-Horne-Shimony-Holt Bell inequality can be in principle violated if \(V > 1/2\) [23] (see also [12] for an experimental demonstration with time-bin entangled qubits).

To verify the entanglement swapping process we perform a two-photon interference experiment with the two photons at 1550 nm, conditioned on a successful BSM. This is done by sending photons \(A\) and \(D\) to two interferometers. The evolution of \(|\psi^{+}\rangle\) in the interferometers is

\[
|\psi^{+}\rangle \rightarrow |0_A,1_D\rangle + e^{i\alpha}|1_A,0_D\rangle + e^{i\beta}|0_A,2_D\rangle + e^{i(\alpha+\beta)}|1_A,2_D\rangle
+ |1_A,0_D\rangle + e^{i\alpha}|2_A,0_D\rangle + e^{i\beta}|1_A,1_D\rangle + e^{i(\alpha+\beta)}|2_A,1_D\rangle,
\]

where \(|i_A,j_D\rangle\) corresponds to an event where the photon \(A\) is in time bin \(i\) and the photon \(D\) is in time bin \(j\). A photon traveling through the long arm of an interferometer passes from time bin \(i\) to time bin \(i+1\). If the arrival time difference between photons \(A\) and \(D\) are recorded, Eq. (4) shows that there are five different time windows, with \(\Delta t = t_A - t_D = \{0, \pm \tau, \pm 2\tau\}\). This is in contrast with previous experiments using time-bin entangled qubits in the state \(|\psi^{(a)}\rangle\), where only three time windows were present (see, e.g., [12]). If only the event with \(\Delta t = 0\) is selected, there are two indistinguishable events leading to a coincident count rate,

\[
R_c \sim 1 + V \cos(\alpha - \beta),
\]

where \(V\) is the visibility of the interference which can in principle attain the value of 1, but is in practice lower than 1 due to various experimental imperfections. Figure 3 shows a measurement of two-photon interference. The plain squares represent coincidences between photons \(A\) and \(D\), without conditioning on a BSM. The errors bars are too small to be represented. The open circles represent four-photon coincidences, i.e., two-photon interference conditioned on a BSM.
significantly higher than the one obtained in previous demonstrations of long-distance quantum teleportation [6,13]. Hence, in this case the teleported entanglement can be used directly for quantum communication purposes, without further purifying. The whole measurement lasted 78 h, which demonstrates the robust character of our scheme. The non-perfect visibility of the interference fringe is attributed mainly to the limited fidelity of the BSM. The main limiting factor is the nonvanishing probability of creating multiple photon pairs in one laser pulse, due to the probabilistic nature of PDC [20,24]. The visibility could be improved by reducing the pump power but this would reduce the four-photon coincidence count rate. Note that the key parameters in order to increase the four-photon coincidence count rate without degrading the correlations are the quantum efficiencies of detectors and the coupling efficiencies into the single-mode fibers.

In summary, we have reported the demonstration of entanglement swapping over long distance in optical fibers. We used two pairs of time-bin entangled qubits encoded into photons at telecommunications wavelengths and created in spatially separated sources. The visibility obtained after the swapping process was high enough to demonstrate a teleportation of entanglement and to infer a violation of Bell inequalities with photons separated by more than 2 km of optical fibers that have never directly interacted. This constitutes a promising approach to push quantum teleportation and entanglement swapping experiments out of the laboratory, using the existing optical-fiber network.

The authors would like to thank Claudio Barreiro and Jean-Daniel Gautier for technical support. Financial support by the Swiss NCCR Quantum Photonics, and by the European project RamboQ, is acknowledged.

[15] Note that this is valid only if the laser used is the same for both sources. In case of distant sources pumped by independent lasers, the pump interferometer phases should be stabilized.
[16] Because of the probabilistic nature of PDC, the probability to create two photon pairs in one source is the same as the probability of creating one pair in each source. Hence, the four photons need to be detected in order to postselect the cases where (at least) one pair is created in each source, which are the events we are interested in.
Quantum Teleportation with a Three-Bell-State Analyzer

J. A. W. van Houwelingen, N. Brunner, A. Beveratos, H. Zbinden, and N. Gisin
Group of Applied Physics, University of Geneva, Rue de l’École-de-Médecine 20 CH-1211 Genève 4, Switzerland
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We present a novel Bell-state analyzer (BSA) for time-bin qubits allowing the detection of three out of four Bell states with linear optics, two detectors, and no auxiliary photons. The theoretical success rate of this scheme is 50%. Our new BSA demonstrates the power of generalized quantum measurements, known as positive operator valued measurements. A teleportation experiment was performed to demonstrate its functionality. We also present a teleportation experiment with a fidelity larger than the cloning limit.

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A Bell-state analyzer (BSA) is an essential part of quantum communications protocols such as a quantum relay based on quantum teleportation [1–7], entanglement swapping [8,9], or quantum dense coding [10,11]. It has been shown that, using only linear optics, a BSA for qubits has a maximal success rate of 50% when no auxiliary photons are used [12,13]. This, however, does not limit the number of Bell states one can measure, but only the overall success rate. A complete BSA could be achieved using either nonlinear optics [14] or using continuous variable encoding [15,16]. However, each of these two alternatives carry some significant drawback. The nonlinear optics approach has exceedingly low efficiency; while continuous variable encoding has the disadvantage that postselection is not possible. Note that postselection is a very useful technique that allows one to use only “good” measurement results and straightforwardly eliminate all others without the need for a lot of computing power [17].

Today’s optimal BSA schemes based on linear optics for qubits are only able to detect two out of four Bell states [2,6,8,9], or are able to detect more than two states but not optimally [18]. Here we present a novel scheme for a BSA which achieves the 50% upper bound of success rate, but can distinguish three out of the four Bell states. We demonstrate this scheme in a quantum teleportation experiment at telecom wavelengths. The new BSA is inspired by, although not limited to, the time-bin implementation of qubits, and is thus fully compatible with the field of quantum communications [19].

At first, one may think that detecting 3 out of 4 Bell states provides a full BSA. Indeed, if the BSA would consist of a standard von Neumann projective measurement, then the fourth Bell state would merely correspond to the nondetection of the 3 others. But our BSA is a new example of the power of generalized quantum measurements, it uses a positive operator valued measurement (POVM) with 21 possible outcomes. Some outcomes of this POVM (see Fig. 1) correspond to one of the 3 Bell states that can be distinguished unambiguously and thus detect this state. The others correspond to inconclusive results. More specifically, the Bell state $|\psi_\pm\rangle$ is always detected, $|\phi_\pm\rangle$ is never detected, while $|\psi_-\rangle$ and $|\phi_+\rangle$ are detected with a 50% success rate.

In previous BSAs, the main method was to use a beam splitter followed by detectors to determine the input Bell state. We replace this standard approach by a time-bin interferometer equivalent to the ones used to encode and decode time-bin qubits (Fig. 1) [19]. The two photons of the Bell state enter in port $a$ and $b$, respectively. In a BSA using only a beam splitter, one is able to distinguish between $|\psi_\pm\rangle$ but not $|\phi_-\rangle$, since in the later case the two photons will experience photon bunching but this interference does not contain the phase information that distinguishes $|\phi_-\rangle$ from $|\phi_+\rangle$. In our case, the first beam splitter acts like above, but we introduce a second interference possibility between the two photons on the second beam splitter. This second interference allows one to distinguish more than just two Bell states. The input modes $a$ and $b$ evolve in the interferometer as follows (see Fig. 1):

$$\hat{a}_i^\dagger = \frac{1}{\sqrt{4}}(\hat{e}_i^\dagger + \hat{f}_i^\dagger) = \frac{1}{\sqrt{4}}(\hat{e}_i^\dagger + \hat{f}_i^\dagger + \hat{f}_i^\dagger + \hat{e}_i^\dagger(\hat{e}_i^\dagger \hat{e}_i^\dagger + \hat{f}_i^\dagger \hat{f}_i^\dagger)),$$

$$\hat{b}_i^\dagger = \frac{1}{\sqrt{4}}(\hat{f}_i^\dagger - \hat{e}_i^\dagger) = \frac{1}{\sqrt{4}}(\hat{f}_i^\dagger - \hat{e}_i^\dagger + \hat{e}_i^\dagger + \hat{f}_i^\dagger(\hat{e}_i^\dagger \hat{e}_i^\dagger + \hat{f}_i^\dagger \hat{f}_i^\dagger)),$$

where $\hat{e}_j$ is a photon at time $j$ in mode $i$. Using these equations, one can show that the four Bell states are distinguished as follows: $|\psi_-\rangle$, $|\psi_+\rangle$, $|\phi_-\rangle$, and $|\phi_+\rangle$ are detected with success rates $1/4$, $1/2$, $0$, and $1/2$, respectively. This corresponds to a successful teleportation of the quantum state $\hat{\rho}$ in mode $a$ with fidelity $F = 1 - 1/4 = 1/2$.

FIG. 1. A schematic representation of the new type of Bell-state measurement. When two qubit states are sent into a time-bin interferometer the output state is a mixture of photons in two directional modes and three temporal modes. By looking at certain combinations of these photons a Bell-state measurement can be performed for three different Bell states.
TABLE I. The table shows the probability to find any of the 21 possible coincidences as a function of the input Bell-State. A 0 in row D1 means that a photon was found at detector “D1” and at a time corresponding to the photon having taken the short path in the interferometer and it was originally a photon in time-bin $t_0$, a 1 corresponds to $t_0 \pm 1 \times \tau$ with $\tau$ corresponding to a the difference between the time-bins, etc., Note that several combinations of detection are possible for only one Bell-state (the bold entries), therefor when such a combination is found a Bell-state measurement was performed. The theoretical probability of a successful measurement is 0.5 which is the optimal value using only linear optics [12].

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formulas it is possible to calculate all possible outputs of the interferometer as a function of any input state.

These output coincidences in ports $e$ and $f$, i.e., on detectors D1 and D2, are summarized in Table I. By convention, a photon detected at time “0” means that the photon did not accumulate any delay with regards to a fixed reference. This is only possible if the photon took the short path in the BSA and it was originally a photon in time-bin $t_0$ (Fig. 1). A photon detected at time “1” signifies that the photon was originally in $t_1$ and took the short path of the BSA interferometer or it was in $t_0$ and took the long path. A detection at time “2” then means the photon was in $t_1$ and took the long path.

In Table I one can distinguish two cases. Either the result unambiguously distinguishes one Bell state. Or the result could have been caused by two specific Bell states, i.e., the result is ambiguous and hence inconclusive.

The above described approach is correct in the case were the phase $\delta$ of the BSA interferometer is set to 0. Let us thus briefly analyze in this paragraph the situation of an arbitrary phase $\delta$. In such a case, our BSA still distinguishes 3 Bell states, but these are no longer the Bell states of the computational basis. For a teleportation experiment this means the basis for the measured Bell states is not the same as the basis for the entangled states shared between Bob and Charlie. Still, perfect teleportation is possible, but with the difference that the unitary transformations that Bob has to apply after receiving the classical information about the result of the BSA have changed and no longer include the identity: all unitary transformations are non-trivial, but they remain experimentally feasible. More specifically, the analyzed Bell states are:

$$\phi^{'}_+ = |00\rangle \pm e^{2i\delta}|11\rangle,$$  \hspace{1cm} (3)

$$\psi^{'}_\pm = e^{i\delta}(|01\rangle \pm |10\rangle).$$  \hspace{1cm} (4)

These Bell states are equivalent to the standard states except that the $|1\rangle$ is replaced by $e^{i\delta}|1\rangle$ for each of the input modes. Therefore the unitary transformations that have to be applied to retrieve the original state of the teleported photon also have to be modified from $[I, \sigma_z, \sigma_x, \sigma_y] \rightarrow [\sigma_{2\delta}, \sigma_x\sigma_{2\delta}, \sigma_y, \sigma_z\sigma_{2\delta}]$. Here $\sigma_{2\delta} = e^{-2i\delta}P_{1|1} + P_{0|0}$ is a phase shift of $2\delta$ to be applied to the time-bin $|1\rangle$.

In a realistic experimental environment the success probabilities of the BSA will be affected by detector limitations, because existing photon detectors are not fast enough to distinguish photons which follow each other closely (in our case two photons separated by $\tau = 1.2$ ns) in a single measurement cycle. Hence a coincidence, for example, “02” on D2, cannot be detected with our detectors. This limitation rises from the dead time of the photodetectors. When including this limitation we find that the maximal attainable probabilities of success in our experimental setup are reduced to 1/2, 1/4, and 1/2 for $\phi^{'}_+$, $\psi^{'}_-$, and $\phi^{'}_+$, respectively. This leads to an overall probability of success of 5/16, which is greater by 25% than the success rate of 1/4 with a BSA consisting only of one beam splitter and two identical detectors.

In order to demonstrate successful Bell-state analysis we performed a teleportation experiment. A schematic of the experimental setup is shown in Fig. 2. Alice prepares a photon in the state $|\xi_A\rangle = |0\rangle + e^{i\alpha}|1\rangle$. Bob analyzes the teleported photon and measures interference fringes for each successful BSA announced by Charlie. The setup consist of a mode-locked Ti:sapphire laser creating 150 fs pulses with a spectral width of 4 nm, a central wavelength of 710 nm, and a repetition rate of 76 MHz. The fiber interferometers shown here are in reality Michelson interferometers; for the interferometer in the BSA two circulators are used to have two separate inputs and outputs. Not shown in the figure is the method used for stabilizing the interferometers.
wavelength of 711 nm and a mean power of 400 mW. This beam is split in two beams using a variable coupler (λ/2 and a PBS). The reflected light (Alice) is sent to a Lithium tri-Borate crystal (LBO, Crystal Laser) were by parametric down-conversion a pair of photons is created at 1.31 and 1.55 μm. Pump light is suppressed with a Si filter, and the created photons are collected by a single mode optical fiber and separated with a wavelength-division multiplexer (WDM). The 1.55 μm photon is ignored whereas the 1.31 μm is send to a fiber interferometer which encodes the qubit on the equator of the Bloch sphere. In the same way, the transmitted beam (Bob) is send onto another LBO crystal after having passed through an unbalanced Michelson bulk optics interferometer, the phase of this interferometer is considered as the reference phase. The nondegenerate entangled photons produced in this way corresponds to the $\phi_+$ state. The photons at 1.31 μm are send to Charlie in order to perform the Bell-state measurement. In order to assure temporal indistinguishability, Charlie filters the received photons down to a spectral width of 5 nm. In this way the coherence time of the generated photons is greater than that of the photons in the pump beam, and as such we can consider the photons to be emitted at the same time. Bob filters his 1.55 μm photon to 15 nm in order to avoid multiphoton events [20]. A liquid-nitrogen-cooled Ge avalanche photon detector (APD) D1 with passive quenching detects one of the two photons in the BSA and triggers the commercial infrared APDs (id Quantique) D2 and D3. Events are analyzed with a time to digital converter (TDC, Acam) and coincidences are recorded on a computer.

Each interferometer is stabilized in temperature and an active feedback system adjusts the phase every 100 seconds using separate reference lasers. In this way the quantum teleportation scheme works with independent units and is ready for “in the field” experiments. A more detailed description of the active stabilization is given in Ref. [9].

The temporal indistinguishability of the photons arriving at the BSA is usually tested by measuring a Hong-Ou-Mandel dip. In our BSA this is not directly possible. Photons that have bunched on the first interferometer will be split up by the second interferometer in a nondeterministic manner and as such there will be no decrease in the number of coincidences when looking at the same time of arrival. There will actually be an increase for these coincidences because the amount of photons that took a different path in the interferometer will decrease. In our experimental setup this means one has to look at an increase in the rate of detecting a “0” on both D1 and D2 and the same is true for the rate of “2” on D1 and D2. A typical result from this alignment procedure can be found in Fig. 3.

First we performed a quantum teleportation with independent units using a beam splitter for the Bell-state measurement. This enables us to test our setup in terms of fidelity. In order to check the fidelity of the teleported state, Bob sends the teleported photon through an analyzing interferometer and measures the interference fringes conditioned on a successful BSA. When Bob scans the phase of his interferometer we obtained a raw visibility of $V = 57\% (F = 79\%)$ and a net visibility of $V = 83\% \pm 4 (F = 91\% \pm 2)$ clearly higher than the cloning limit of $F = 5/6$ (Fig. 3). We then switched to the new BSA. This new setup introduces about 3 dB of excess loss, due to added optical elements including the interferometer and its stabilization optics. These losses result in a lower count rate. For experimental reasons we now scan the interferometer of Alice instead of Bob. The experiments were performed for approximately 4.4 hours per point in order to accumulate enough data to have low statistical noise. The expected interference fringes after Bob’s interferometer are of the form $1 \pm \cos(\alpha + \beta)$ for a projection on $\psi_\pm$ and $1 + \cos(\alpha - \beta - 2\delta)$ for a projection on $\phi_\pm$. Hence one would

FIG. 3 (color online). Left: The result of the 1-Bell-state teleportation experiment (a beam splitter instead of the interferometer) with $F_{\text{raw}} = 79\%$ and $F_{\text{net}} = 91\%$. Right: A typical result of the scan in delay of the coincidences “00” and “22”. The predicted antidip is clearly visible in both curves with a visibility after noise subtraction of 32% for “0” on D1 and D2 and 26% for “2” on D1 and D2 (theoretical maximum = 1/3 [22]).

FIG. 4 (color online). These graphs show the interference fringes found when scanning the interferometer at Bob. We found visibilities of 0.22, 0.43 and 0.38 for $|\psi_\pm\rangle$, $|\phi_\pm\rangle$ and $|\psi_\mp\rangle$. The average visibility of the BSA is $V_{\text{avg}} = 0.34 (F = 0.67)$. 

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expect to find three distinct curves, two with a phase difference of \( \pi \), and the third dephased by \(-2(\beta + \delta)\), where \( \alpha, \beta, \) and \( \delta \) are the phases of Alice, Bob, and the BSA interferometer, respectively. Note that Bob is able to derive \( \delta \) using the phase difference between the fringes made by \( \psi_+ \) and \( \phi_+ \) since this difference corresponds to \( 2(\delta + \beta) \), where \( \beta \) is Bob’s local phase.

In Fig. 4 we show the coincidence interference fringes between Bob and a successful BSA. As expected fringes for \(|\psi_\alpha\rangle\) and \(|\psi_\alpha\rangle\) have a \( \pi \) phase difference due to the phase flip caused by the teleportation. On the other hand, fringes for \(|\psi_\alpha\rangle\) and \(|\phi_\alpha\rangle\) are dephased by \(-2(\beta + \delta)\), which in this case we had arranged to be approximately 0.

The count rates for the different Bell states differ because they correspond to different numbers of detection combinations. The raw (Fig. 4) visibilities obtained for the projection on each Bell state are \( V_{\phi_+} = 0.38 \), \( V_{\psi_+} = 0.22 \), \( V_{\phi_+} = 0.43 \), which leads to an overall value of \( V = 0.34 \) (\( F = 0.67 \)). If we subtract the noise we find net visibilities of 0.51, 0.69, and 0.55 for \(|\phi_\alpha\rangle\), \(|\phi_\alpha\rangle\) and \(|\psi_\alpha\rangle\) which leads to an average of \( V = 0.58 \) (\( F = 0.79 \)). Note that the maximal value that can be attained without the use of entanglement is \( V_{\max} = 1/3 \) [21]. Two of the raw visibilities and all of the net visibilities break this limit. In order to check the dependence of \(|\phi_\alpha\rangle\) on \( \delta \) we also performed a teleportation with a different value and we clearly observe the expected shift in the fringe (Fig. 5) while measuring similar visibilities.

Finally the authors would like to stress two points about this novel BSA. First it is possible to implement this BSA for polarization encoded photons by creating a second interference possibility for H and V polarization. This would require 4 detectors, but an overall efficiency of 50% can be achieved with current day detectors. The limit of 50% can also be achieved with time-bin encoded qubits but would require the use of ultra fast optical switches and two more detectors. We did not implement this due to the losses associated with introducing current day high speed integrated modulators. Second, even though three out of four Bell states can be distinguished, one cannot use this scheme in order to increase the limit of log23 bits per symbol for quantum dense coding.

In conclusion, we have shown experimentally that it is possible to perform a three-state Bell analysis while using only linear optics and without any actively controlled local operations on a single qubit. In principle this measurement can obtain a success rate of 50%. We have used this BSA to perform a teleportation experiment, and obtained a non-corrected overall fidelity of 67%, after noise subtraction we find \( F = 76\% \). Also, we performed a teleportation experiment with a one state BSA which exceeded the cloning limit.

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*Electronic address: jeroen.vanhouwelingen@physics.unige.ch

[17] For experiments on the nature of physics, such as Bell tests, postselection can be a drawback. For applications in quantum communication, however, it is advantageous since it selects useful measurement results.
Experimental quantum teleportation with a three-Bell-state analyzer

J. A. W. van Houwelingen,* A. Beveratos, N. Brunner, N. Gisin, and H. Zbinden

Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland

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We present a Bell-state analyzer for time-bin qubits allowing the detection of three out of four Bell states with linear optics, two detectors, and no auxiliary photons. The theoretical success rate of this scheme is 50%. A teleportation experiment was performed to demonstrate its functionality. We also present a teleportation experiment with a fidelity larger than the cloning limit of $F=\frac{5}{6}$.

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I. INTRODUCTION

Bell-state analyzers (BSA) form an essential part of quantum communications protocols. Their uses range from quantum relays based on teleportation [1–7] or entanglement swapping [8,9] to quantum dense coding [10,11]. An important restriction for BSAs is that a system based on linear optics, without using auxiliary photons, is limited to a 50% overall success rate [12,13]. This important result does not restrict the number of Bell states that can be measured, but only the overall efficiency of a measurement. Nevertheless, a complete BSA is possible for at least two different cases: the first approach uses nonlinear optics [14] but this has the drawback of an exceedingly low efficiency and is, therefore, not well adapted for quantum communication protocols. Another possibility is the use of continuous variable encoding [15,16], however, this technique has the disadvantage that postselection is not possible. Note that postselection is a very useful technique that allows one to use only “good” measurement results and straightforwardly eliminate all others without the need for great computational analysis.

Many experiments have been done up to date that use BSAs. In this paper a different BSA is introduced [17]. It has the maximum possible efficiency that can be obtained when using only linear optics without ancilla photons. It is different with respect to other BSAs since it can distinguish three out of the four Bell states. All of the used BSAs up to date can reach the maximum efficiency, without the use of ancilla photons, are limited to two (or less) Bell states [2,6,8,9,18]. There have also been experiments of a BSA that detects all four Bell states but its overall efficiency does not reach 50% and it requires the use of an entangled ancilla photon pair [19].

II. THEORY

A. Time-bin encoding

In our experiments a qubit is encoded on photons using time bins [20]. This means that a photon is created that exists in a superposition of two well-defined instants in time (time bins) that have a fixed temporal separation of $\tau$. By convention the Fock state with $N=1$ corresponding to a photon in the early time of existence $t_0$ is written as $|0\rangle$ and for the later time $t_1=t_0+\tau$ as $|1\rangle$. Photons in such a state can be created in several ways. The simplest method is to pass a single photon through an unbalanced interferometer with a path length difference of $n c \tau$, where $n$ is the refractive index. After the interferometer the photon will be in the qubit state $A|0\rangle + e^{i\alpha}B|1\rangle$. Here $A$ and $B$ are amplitudes that depend on the characteristics of the interferometer and $\alpha$ is the phase difference between the interferometer paths which is directly determined by $\alpha=(2\pi n c \tau / \lambda) \mod 2\pi$. For the sake of readability we will use the word qubit when talking about a “photon that is in a qubit state.”

B. Bell-state analyzer

In a large part of all experiments using BSAs that have been performed up to date, the BSA consists essentially of a beamsplitter and single-photon detectors (SPDs). In such a beamsplitter-BSA(BS-BSA) the “clicks” of the SPDs are analyzed and, depending on their results, the input state will be projected onto a particular Bell state. With time-bin qubits as described above a simple BS-BSA works as follows: two qubits arrive at the same time on a beamsplitter but at different entry ports. Since the four standard Bell states

$$|\phi_+\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle),$$

$$|\phi_-\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

form a complete basis we can write our two-qubit input state as a superposition of these four states. One can calculate for each Bell input state the possible output states. These states can then be detected using SPDs. The different detection patterns and their probabilities are shown in Table I. By convention, a detection click at time “0” (“1”) means that the photon was detected in the time bin $t_0$ ($t_1$). The output combinations show that, if one detects two photons in the same path but in a different time bin, the input state could only have been caused by the Bell state $|\phi_\pm\rangle$ and therefore the overall state of the system is projected onto this state. When the photons arrive at different detectors with a time-bin difference the input state is projected onto the state $|\phi_\pm\rangle$. However, when one measures two photons in the same time bin in the same detector the state could either be $|\phi_+\rangle$ or $|\phi_-\rangle$, and therefore the state has not been projected onto a single Bell

*Email address: jeroen.vanhouwelingen@physics.unige.ch
TABLE I. The table shows the probability of finding specific coincidences as a function of the input Bell state in the case of a single beamsplitter as a BSA. A “0” (“1”) in row D1 means that a photon was found at detector “D1” at time $t_0$ ($t_1$), etc. Note that only half of the combinations of detection are possible for only one Bell state (the bold entries), therefore when such a combination is found a projection onto this Bell state was performed. The theoretical success probability is 50%.

<table>
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<tr>
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<td>\phi_+\rangle$</td>
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<td>\psi_+\rangle$</td>
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<td>$</td>
<td>\psi_\downarrow\rangle$</td>
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state but onto a superposition of two Bell states. This method has a success rate of 50% which corresponds to the maximal possible success rate that can be obtained while using only linear optics and no auxiliary photons [12].

Here we propose a BSA which is capable of distinguishing more than two Bell states while still having the maximum success rate of 50%. This is possible by replacing the beamsplitter with a time-bin interferometer equivalent to the ones used to encode and decode time-bin qubits (Fig. 1). This BSA will be capable of distinguishing three out of four Bell states, but $|\phi_\downarrow\rangle$ and $|\psi_\downarrow\rangle$ will only be discriminated 50% of the time as will be explained shortly. Two qubits enter in port a and b, respectively. The first beamsplitter acts like above, allowing the distinction of two Bell states ($|\phi_\downarrow\rangle$ and $|\psi_\downarrow\rangle$). A second possibility for interference is added by another BS for which the inputs are the outputs of the first BS, with one path having a delay corresponding to the time-bin separation $\tau$. The two-photon effects on this beamsplitter lead to fully distinguishable photon combinations of one of the two remaining Bell states ($|\phi_\downarrow\rangle$) while still allowing a partial distinction of the first two.

One might expect that when it is possible to measure three out of four states that the fourth, nonmeasured, state can simply be inferred from a negative measurement result of the three measurable states. This is, however, not the case. The above described measurement is a positive operator valued measure (POVM) with 21 possible outcomes, some of these outcomes are only possible for one of the four input Bell states. Therefore, when such an outcome is detected it unambiguously discriminates the corresponding input Bell state. The rest of the 21 outcomes correspond to outcomes which can result from more than one input Bell state. In other words, their results are ambiguous and the input state is not projected onto a single Bell state but onto a superposition of Bell states.

The state after the interferometer can be calculated for any input state using

$$\hat{a}^\dagger(t) = \frac{1}{\sqrt{4}}[-\hat{e}^\dagger(t) + e^{i\delta}\hat{e}^\dagger(t + \tau) + i\hat{f}^\dagger(t) + ie^{i\delta}\hat{f}^\dagger(t + \tau)],$$

(3)

$$\hat{b}^\dagger(t) = \frac{1}{\sqrt{4}}[\hat{f}^\dagger(t) - e^{i\delta}\hat{f}^\dagger(t + \tau) + i\hat{e}^\dagger(t) + ie^{i\delta}\hat{e}^\dagger(t + \tau)],$$

(4)

where $\hat{a}(j)$ is the creation operator of a photon at time $j$ in mode $i$. When the input states are qubits and the photons are detected after the interferometers the detection patterns are readily calculated and are shown in Table II. The output coincidences on detectors D1 (port e) and D2 (port f) are shown as a function of a Bell state as input. By convention, a detection at time “0” means that the photon was in time $t_0$ after the BSA interferometer. This is only possible if it took the short path in the BSA and it was originally a photon in time bin $t_0$ (Fig. 1). Similarly a detection at time “1” means that either the photon was originally in $t_1$ and took the short path of the BSA interferometer or it was in $t_0$ and took the long path. A detection at time “2” means the photon was in $t_1$ and took the long path. In Table II we see that some of the patterns corresponds to a single Bell state and therefore the measurement is unambiguous. For the other cases the result could have been caused by two Bell states, i.e., the result is ambiguous and hence inconclusive. More specifically, the Bell state $|\psi_\downarrow\rangle$ is detected with probability 1, $|\phi_\downarrow\rangle$ is never detected, and both $|\psi_\downarrow\rangle$ and $|\phi_\downarrow\rangle$ are detected with probability $\frac{1}{2}$.

The above described approach is correct in the case where the separation $\tau$ of the incoming qubits is equal to the time-bin separation caused by the interferometer. If this is not the case and the interferometer creates a time-bin separation of $\tau + n\lambda \delta/(2\pi c)$, where $\delta$ is a phase, the situation is slightly more complicated. In such a case, our BSA still distinguishes three Bell states, but these are no longer the standard Bell states but are the following:

$$|\phi_\downarrow\rangle = |00\rangle \pm e^{i\delta|11\rangle} = (\sigma_\delta \otimes \sigma_\delta)|\phi_\downarrow\rangle,$$

(5)

$$|\psi_\downarrow\rangle = e^{i\delta(|01\rangle \pm |10\rangle)} = e^{i\delta}|\psi_\downarrow\rangle.$$  

(6)

Here $\sigma_\delta = P_{00} + e^{i\delta}P_{11}$ is a phase shift of $\delta$ to be applied to the time bin $|1\rangle$. These new Bell states are equivalent to the standard states except that the $|1\rangle$ is replaced by $e^{i\delta}|1\rangle$ for each of the input modes.

In a realistic experimental environment the success probabilities of the BSA are affected by detector limitations. This
is because existing photon detectors are not fast enough to distinguish photons which follow each other closely (in our case two photons separated by \( \tau = 1.2 \) ns) in a single measurement cycle. This limitation rises from the dead time of the photodetectors. When including this limitation we find that the maximal probabilities of success in our experimental setup are reduced to \( \frac{5}{8} \), \( \frac{1}{2} \), and \( \frac{3}{8} \) for \( \psi_+ \), \( \psi_- \), and \( \phi_+ \), respectively. This leads to an overall probability of success of \( \frac{5}{16} \) which is greater by 25% than the success rate of \( \frac{1}{2} \) for a BSA consisting only of one beamsplitter and two detectors with the same limitation. This limitation could be partially eliminated by using a beamsplitter and two detectors in order to detect the state 50% of the time, or it could be completely eliminated by using an ultrafast optical switch (sending each time bin to a different detector). Both of these methods are associated with a decrease in the signal-to-noise ratio. This is caused by the additional noise from the added detector and by additional losses from the optical switch, respectively.

C. Bell-state analyzer for polarization qubits

So far the discussion about this BSA only considered time-bin qubits. The authors would like to note at this point that it is also possible to implement a similar BSA for polarization encoded photons. This can be done by the equivalent polarization setup as shown in Fig. 2. This setup would require four detectors but there will never be two photons on one detector and therefore dead times do not hinder the measurement of all the detection patterns and the overall efficiency can reach 50% with today’s technology.

D. Four-Bell-state analyzer?

This paper discusses our results testing a three-Bell-state analyzer. It is obviously interesting to also consider the possibility of a linear optics four-Bell-state analyzer with 50% efficiency and no ancilla photons. Such a system was not used for the simple reason that there is no known method to make such a measurement. Is there a fundamental reason to suspect that such a BSA cannot be performed? No such reason is known to the authors, therefore this paper will be limited to the three-Bell-state analyzer.

E. Teleportation

One of the most stunning applications of a BSA is its use in the teleportation protocol. In order to perform a teleportation experiment an entangled qubit photon pair is created (EPR) as well as a qubit to be teleported (Alice). One photon of the entangled pair is made to interact with Alice’s qubit in a BSA (Charlie). This interaction followed by detection projects the overall state onto a Bell state (if the BSA is successful). The remaining photon (Bob) now carries the same information as the photon from Alice up to a unitary transformation. The situation for the new BSA is slightly different since the entangled pair is not a member of the detected Bell basis [Eqs. (5) and (6)]. However this has no major influence on the theory. After a successful measurement of the BSA the remaining photon at Bob is equal to the original qubit up to a unitary transformation. This transformation, however, has to be adapted with regards to the standard case from \([1, \sigma_z, \sigma_x, \sigma_x] \) to \([\sigma_z^{-1}, \sigma_x, \sigma_z, \sigma_x] \), as can be seen from the following calculation:

FIG. 2. A schematic representation of the new type of a Bell-state analyzer for polarization qubits. The gray cubes represent non-polarizing beamsplitters and the white cubes are polarizing beamsplitters.
Recall Fig. 3; the experiment is an adaptation of a setup used previously for long distance teleportation \[1, 6\] and measures interference fringes for each successful BSA. The BSA was tested in a quantum teleportation experiment. Finally, the results of the experiment are given and discussed.

\[|\psi_{abc}\rangle = |\psi_a\rangle \otimes |\phi_c\rangle = \frac{1}{2}(|\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle - |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle - |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle - |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes \sigma^{+}_{\perp,0}|\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle + |\phi_{c}^\perp\rangle \otimes e^{i\phi} \sigma_x |\psi_a\rangle \]

Recall $\sigma^{+}_{\perp,0} = P_{\langle 0 \mid 0 \rangle} + e^{i\phi} P_{\langle 1 \mid 1 \rangle}$ is a phase shift of the bit $|1\rangle$.

III. EXPERIMENTAL TELEPORTATION

The BSA was tested in a quantum teleportation experiment. Presented in this section is the experimental setup that was used as well as some of the required preliminary alignment experiments. Finally, the results of the experiment are given and discussed.

A. Experimental setup

A rough schematic of the experimental setup is shown in Fig. 3; the experiment is an adaptation of a setup used previously for long distance teleportation \[6\] and for entanglement swapping \[9\]. Alice prepares a photon in the state $|\psi_a\rangle = (1/\sqrt{2})(|0\rangle + e^{i\phi}|1\rangle)$. A BSA is used by Charlie on Alice’s qubit combined with a part of an entangled qubit pair. Bob analyzes the other half of the pair (the teleported qubit) and measures interference fringes for each successful BSA announced by Charlie.

The setup consists of a mode-locked Ti-sapphire laser (MIRA with 8W VERDI pump-laser, Coherent) creating 150 fs pulses with a spectral width of 4 nm, a central wavelength of 711 nm, a mean power of 400 mW and a repetition rate of 80 MHz. This beam is split in two beams using a variable coupler ($\lambda/2$ and a PBS). The reflected light (Alice) is sent to a scannable delay and afterwards to a lithium triborate crystal (LBO, crystal laser) where by parametric downconversion a pair of photons is created at 1.31 and 1.55 $\mu$m. Pump light is suppressed with a Si filter, and the created photons are collected by a single mode optical fiber and separated with a wavelength-division multiplexer (WDM). The 1.55 $\mu$m photon is ignored, whereas the photon at 1.31 $\mu$m is send to a fiber interferometer which encodes the qubit state $|\psi_a\rangle$ onto the photon. The transmitted beam (Bob) is passed through an unbalanced Michelson-type bulk interferometer. The separation between the two time bins after this interferometer is considered as the reference for all the other separations. The phase of the interferometer can, therefore, be considered as a reference phase and can be defined as 0. After the interferometer the beam passes a different LBO crystal. The nondegenerate photon pairs created in this crystal are entangled and their state corresponds to $|\phi_c\rangle = (1/\sqrt{2})(|00\rangle + |11\rangle)$. The photons at 1.31 $\mu$m are send to Charlie in order to perform the Bell-state measurement. To assure temporal indistinguishability, Charlie filters the received photons down to a spectral width of 5 nm using a bulk interference filter. Because of this the coherence time of the generated photons is greater than that of the photons in the pump beam, and as such no distinguishability between photons can be caused by jitter in their creation time \[22\]. Bob filters his 1.55 $\mu$m photon to 15 nm in order to avoid multi photon-pair events \[23, 24\], this filtering is done by the WDM that separates the photons at 1.31 and 1.5 $\mu$m. This filter is larger than Charlie’s filter for experimental reasons. A liquid nitrogen cooled Ge avalanche-photon detector (APD) D1 with passive quenching detects one of the two photons in the BSA and triggers the InGaAs APDs (id Quantique) D2 and D3. Events are analyzed with a time to digital converter (TDC, Acam) and coincidences are recorded on a computer.

Each interferometer is stabilized in temperature and for greater stability an active feedback system adjusts the phase every 100 s using reference lasers. The reference for Bob’s interferometer is a laser (Dicos) stabilized on an atomic transition at 1531 nm and for both Alice’s and Charlie’s
interferometer a stabilized distributed-feedback (DFB) laser (Dicos) at 1552 nm is used. It is possible to use different lasers for Alice and Charlie if one wants to create two independent units. By using independent interferometer units using different stabilization lasers it was assured that this experiment is ready for use “in the field.” A more detailed description of the active stabilization of the interferometers is given in Ref. [9]. For sake of clarity the interferometers shown in the setup (Fig. 3) are Mach-Zender-type interferometers but in reality they are Michelson interferometers which use Faraday mirrors in order to avoid distinguishability due to polarization differences [25].

B. Alignment experiments

There are two important, nontrivial alignments that have to be made before one can perform a quantum teleportation experiment with time-bin encoded qubits. First, one would have to assure that all the time-bin interferometers have the same difference in length between the two paths. Second, it is required that there is temporal indistinguishability between qubits coming from Alice and Bob on the BSA. The equalization of the interferometers is needed in order to assure that all the interferometers have a difference in length of \( c \tau / n \) with a precision higher than the coherence length of the photons (\( \approx 150 \mu \text{m} \)). We have two mechanisms to actively change the optical path lengths: the first is changing the temperature of the interferometers and thus allowing the long arm to increase or decrease its length more than the short arm and the second is to directly change the length of only one arm by means of a cylindric piezoelectric element. When changing the voltage over the piezo we change the diameter of the cylinder and thus the length of the fiber changes. This is used for the active feedback stabilization system. In order to align the interferometers with each other we perform two different experiments: First, we optimize the visibility of single-photon interference fringes for photons from Alice detected in D1. This aligns Alice’s interferometer with the BSA interferometer. Next, we optimize a Fransson-type Bell test of the entangled photon pair [26]. While optimizing this experiment we do not change the BSA interferometer. This optimization aligns the bulk interferometer and Bob’s analysis interferometer to the other two. Using this method we found visibilities of 97% ± 1% for the single photon interference and 94% ± 1% for the Bell test (Fig. 4).

The second alignment procedure is necessary in order to assure temporal indistinguishability between the photons arriving at the BSA. In the case of a BS-BSA this can be assured by performing a Hong-Ou-Mandel dip type experiment [27], which is to say, make a scan in a delay for one of the incoming photons and look at a decrease in the number of coincidences as a result of photon bunching (Fig. 5). The position where the minimum is obtained corresponds to the point with maximal temporal overlap of the two photons.

In the case of an interferometer-BSA (IF-BSA) this procedure becomes more complicated. We can no longer look at a mandel dip because the second beamsplitter will probabilistically split up the photons that bunched on the first beamsplitter. However, the photon bunching remains and it can still be seen by a different method. Consider the situation where two single photons, both in the state \( |0\rangle \), are send to the different inputs of an IF-BSA (Fig. 6). If the photons are not temporally indistinguishable there are three possible output differences between detection times, corresponding to “10”, “00&11”, and “01”. If the photons are indistinguishable they bunch at the first BS and therefore the difference in arrival time between the photons has to be zero. This means that “10” and “01” are not possible anymore and the possibility for “00&11” is larger. If the inputs are arbitrary qubits instead of the simple example above there will be more coincidence possibilities and some of them will be subject to single-photon interference and/or photon bunching. It is possible to see an increase in the coincidences for “00” and “22”, which is not affected by a single-photon interference, for similar reasons as the increase that was explained above. These coincidences can be measured in a straightforward way with our setup. A more rigorous calculation and explanation of this alignment procedure is given in the Appendix. A typical result of an experiment in which the count rate is measured while changing a delay is shown in Fig. 5 and clearly shows the expected increase in count rate.

The measured antidips have a net visibility of 32±3 % and 26±2 % after noise subtraction. The maximal attainable value is \( \frac{1}{2} \) due to undesired but unavoidable double-pair events (see appendix). The large visibilities mean that the temporal indistinguishability is very good, this will thus not
be limiting for our experiments. The noise substraction for this estimation is justified because in a teleportation experiment the noise will be reduced since one will consider only three-photon events. The difference in height of the two coincidences is related to an electronic loss of signal in an electrical delay line.

C. Experimental results

Two different types of teleportation experiments were performed. Namely a standard BS-BSA teleportation in order to benchmark our equipment followed by the IF-BSA experiment. For the BS-BSA, the main difference with regards to previous experiments [9,23] was that the interferometers now all had an active stabilization. This allows for large stability and long measurement times. The experiment consisted of Bob scanning of his interferometer phase while the other interferometers where kept constant, we therefore expect to find an interference curve of the form $1 + V \sin(\beta + \alpha)$ where $\alpha$ is kept constant. The results of the experiment (Fig. 7) clearly shows the expected behavior. The visibility measured was $V = 0.57 \pm 0.03$ ($F = 0.79 \pm 0.02$). After conservative noise substraction we find $V = 0.83 \pm 0.04$ ($F = 0.91 \pm 0.02$). This clearly is higher than the strictest threshold that has been associated with quantum teleportation of $F = \frac{\sqrt{2}}{2}$ [28,29]. The limiting factors of this experiment are the detectors and the fiber coupling after the LBO crystals.

After this experiment the setup was changed to the IF-BSA. The count rates in this experiment with regards to the previous one is reduced due to two reasons. The introduction of the BSA interferometer and its stabilization optics means an additional 3 dB of loss which reduces count rates. Another difference is that now the counts are distributed over three different Bell states, whereas before there was only one. Therefore an overall reduction of counts per state will occur. Combined these effects result in a large reduction of the count rate per Bell state. This problem was overcome by, on the one hand, an overall increase of the BSA efficiency by $\frac{1}{4}$ (from 25\% for the BS-BSA to 31.25\% for the IF-BSA) and, on the other hand, by integrating data over longer time periods. During the teleportation experiment scans were made in the interferometer of Alice rather than Bob. This was done since the most important noise is dependent of the phase of Bob’s interferometer but not of Alice’s (more details are given in the next subsection). The experiments were performed with approximately 4.4 h per phase setting in order to have low statistical noise.

For this IF-BSA all the different unambiguous results (Table II) were analyzed both separately (for example, “02”) and combined as a Bell state (for example, $|\psi_\perp\rangle = |02\rangle + |20\rangle$). For the separate results it is expected that each BSA outcome will have count rates depending on the phases of the

FIG. 5. (Color online) Top, IF-BSA: Graph showing the number of measured coincidences as a function of a change in the delayline. Both “00” and “22” clearly show an antidip at the same location. The net visibilities are $V_{00} = 32 \pm 3\%$ and $V_{22} = 26 \pm 2\%$. Bottom, BS-BSA: Graph showing the decrease in the number of measured coincidences 00 as a function of a change in the delayline [27]. The net visibility is $V = 29 \pm 3\%$.

FIG. 6. The simple experiment on the left (one photon in each input of an IF-BSA) will have the following property. If the photons are not temporally indistinguishable one will find three different coincidence peaks: “10”, “00& 11”, and “01” (dotted curve), however, if the photons are indistinguishable there will be only one peak: 00 and 11 (plain curve). This is caused by photon bunching.

FIG. 7. (Color online) The result of the one-Bell state teleportation experiment (a beamsplitter instead of the interferometer) with $F_{\text{raw}} = 0.79 \pm 0.02$ and $F_{\text{net}} = 0.91 \pm 0.02$. 
interferometers as $R[1 + V \cos(\alpha + \rho)]$. Here $R$ is dependent of the overall efficiency of the experiment and is different for each BSA outcome and $\rho$ is a combination of the constant phases of the interferometers of Bob and Charlie and is different for different BSA results:

$$|\psi_\alpha\rangle, |01\rangle, |10\rangle, |12\rangle, |21\rangle \rightarrow \rho = \beta,$$  \hspace{1cm} (9)

$$|\phi_\alpha\rangle, |11\rangle \rightarrow \rho = - \beta - 2\delta,$$  \hspace{1cm} (10)

$$|\psi_\alpha\rangle, |02\rangle, |20\rangle \rightarrow \rho = \beta + \pi.$$  \hspace{1cm} (11)

As is evident from the differences in $\rho$ we expect that fringes corresponding to one particular Bell state are in phase with each other, but have a well-determined phase difference with fringes corresponding to another Bell state.

The measured count rates as a function of the phase of Alice’s interferometer are shown in (Fig. 8). Note that, due to experimental restrictions, the absolute phases of the interferometers are not known and therefore all phase values have an unknown offset. The results clearly show that each of the outcomes has the expected interference behavior. Furthermore, the fringe corresponding to “01” is in phase with the fringe “21”. The same is true for the fringe “10” with “12” and for “02” with “20”. It is expected that all four of the fringes corresponding to $|\psi_\alpha\rangle$ (“01”, “10”, “12”, and “21”) are all in phase with each other, but there is a clear phase shift between the first two and the last two. The average phase of these four fringes is different by 180° from the fringes corresponding to “02” and “20” as expected. The fringe corresponding to “11” is in phase with the fringes of “02” and “20” as was expected since for this measurement we had arranged $2(\beta + \delta) = \pi \text{mod} 2\pi$. The results of the fits to these fringes is shown in Table III. The differences in phase and visibility are in part due to noise (see next subsection).

The results corresponding to each of the three possible Bell states can be found by adding the measurements of the constituent parts. When doing this one would expect coincidence fringes of the form $R[1 + V \cos(\alpha + \rho)]$ with $R$ and $\rho$ as above. This corresponds to three distinct interference fringes, with $|\phi_\alpha\rangle$ and $|\psi_\alpha\rangle$ in phase and $|\psi_\alpha\rangle$ with a 180° phase difference with respect to the other two.

In Fig. 9 we show the raw coincidence interference fringes between the detection rate at Bob and a successful BSA as a function of a change of phases in Alice’s interferometer. As expected fringes for $|\psi_\alpha\rangle$ and $|\phi_\alpha\rangle$ have a 180° phase difference due to the phase flip caused by the
teleportation. On the other hand, the fringe for $|\phi_+\rangle$ is in phase with the $|\phi_+\rangle$ as expected. The raw visibilities obtained for the projection on each Bell state are $V_{\psi}=0.38\pm0.05$, $V_{\phi}=0.22\pm0.01$, $V_{\phi}=0.43\pm0.03$ which leads to an overall value of $V=0.34\pm0.06$ ($F=0.67\pm3$). In order to check the dependence of $|\phi_+\rangle$ on $\delta$ we also performed a teleportation with a different value for $\delta$ and we clearly observe the expected shift in the fringe (Fig. 10) while measuring similar visibilities.

Note that Bob is able to derive the phase value $\delta$ of the BSA interferometer just by looking at the phase differences between the fringes made by $\psi_+$ and $\phi_+$ and his knowledge about $\beta$. It is important to know $\delta$ since this allows Bob to perform the unitary transformation $\sigma_{2\delta}$ on the teleported photon. Since the count rates were quite low we expected to have an important noise factor, an analysis of the noise follows in the next subsection.

D. Noise analysis and discussion

In the case of the BS-BSA the noise analysis is straightforward. All of the important noise counts are completely independent of the phase, since they concern situations in which there is no single-photon interference possible. The most important sources of noise were estimated and then measured. The estimated signal-to-noise ratio was 2.6, measurements find a SNR of approximately 2.2\pm0.5. The largest source of noise are darkcounts at one detector combined with two real detections.

<table>
<thead>
<tr>
<th>Result 3BSA</th>
<th>$V_{raw}$</th>
<th>$V_{net}$</th>
<th>$\rho_{raw}$</th>
<th>$\rho_{net}$</th>
<th>$P_{raw}$</th>
<th>$P_{net}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>01\rangle$</td>
<td>35\pm3</td>
<td>61\pm6</td>
<td>278\pm4</td>
<td>279\pm5</td>
<td>13\pm1</td>
</tr>
<tr>
<td>$</td>
<td>10\rangle$</td>
<td>43\pm3</td>
<td>72\pm13</td>
<td>339\pm4</td>
<td>338\pm8</td>
<td>11\pm1</td>
</tr>
<tr>
<td>$</td>
<td>12\rangle$</td>
<td>18\pm3</td>
<td>64\pm7</td>
<td>340\pm7</td>
<td>340\pm4</td>
<td>14\pm1</td>
</tr>
<tr>
<td>$</td>
<td>21\rangle$</td>
<td>13\pm2</td>
<td>36\pm2</td>
<td>227\pm9</td>
<td>278\pm1</td>
<td>17\pm1</td>
</tr>
<tr>
<td>$</td>
<td>\phi_+\rangle$</td>
<td>43\pm3</td>
<td>55\pm2</td>
<td>136\pm3</td>
<td>136\pm10</td>
<td>29\pm1</td>
</tr>
<tr>
<td>$</td>
<td>\phi_+\rangle$</td>
<td>40\pm5</td>
<td>83\pm13</td>
<td>126\pm12</td>
<td>126\pm8</td>
<td>8\pm1</td>
</tr>
<tr>
<td>$</td>
<td>\phi_+\rangle$</td>
<td>39\pm4</td>
<td>62\pm10</td>
<td>153\pm4</td>
<td>153\pm8</td>
<td>9\pm1</td>
</tr>
</tbody>
</table>

Fig. 9. (Color online) Uncorrected teleportation fringes found when scanning the interferometer at Bob. The fitted curves have visibilities of 0.22, 0.43, and 0.38 for $|\phi_+\rangle$, $|\phi_+\rangle$, and $|\phi_+\rangle$. The average visibility of the BSA is $V_{avg}=0.34$ ($F=0.67$).

Fig. 10. (Color online) Teleportation fringes measured in two distinct measurements with a $\delta$ which had changed by $70°\pm10°$. In the measurement a clear shift is visible of the fringe $|\phi_+\rangle$ by $74°$ with regards to the other fringes.
The situation for the IF-BSA is more complicated. The additional interferometer has an unfortunate side effect. There are now possibilities for noise to depend on the phases of the interferometers. In other words, while measuring interference fringes there are also noise fringes. It is obviously important to be able to distinguish between the two. The most important fluctuating noise is caused by false coincidences that involve one or more photons coming from Alice and no photons from the EPR source at the BSA. These noise sources depend on the phases and since the photon coming from Alice experiences a single-photon interference. Since during the experiment the phase change is the same as for teleportation, however, there is a \( \pi \) phase shift between “01” (“21”) and “10” (“12”) that is not present in the teleportation signal. Such a noise influences the results of our measurements in different ways, first of all, the visibilities are altered and are smaller for “01” and “21” but larger for “10” and “12”. Secondly, when the fringe is not in phase with the teleportation signal there is a phase shift in the opposite direction for “01” and “21” with regards to “10” and “12”. In our measurements the phases were arranged in such a way that this second effect would not take place since the fringes would be completely in or out of phase with the teleportation signal. This noise was measured and the result (Fig. 11) clearly shows the expected fringes and phase shifts.

Other possibilities for fluctuating noise sources are when no photons from Alice arrive at the BSA. In this case single (or multiple) photon pairs from the EPR source combined with dark counts will give coincidences that depend on the phases and . This corresponds to a combination of a Franson-type Bell test with a dark count. The fluctuation of this noise was avoided in our experiment since we only changed the phase of Alice’s interferometer.

Not all possible sources of noise depend on the phases of the interferometers, there are also stable sources of noise, which are different for each of the BSA possibilities. The average value of the most important noise sources are shown in Table IV, which shows that by choosing to scan Alice instead of Bob a large fluctuating noise was avoided. It also shows that the fluctuating noise from Alice is only a small part of the total noise and therefore its effect will only be limited. Another source of errors that is different for each coincidence combination is electronical loss. These losses are caused by long (up to 100 ns) electronical delays that are required in the treatment of the coincidence signals.

The results, after noise subtraction and correction for electronical transmission differences for the individual coincidence combinations, are shown in Table III. There is a clear agreement with theory, for example, the probability of finding a “11” is approximately 4 times larger than the probability for any of the other possibilities (Fig. 12).

There are a few differences worth noting between the results and theory. First of all there are small differences in visibility, these are probably caused by several small unmeasured noise sources and partially they are real physical differences which are caused by imperfect interferometers, an indication of these imperfections is given by the quality of the alignment experiments. Second, the phases of the curves

<table>
<thead>
<tr>
<th></th>
<th>01</th>
<th>02</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>20</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Alice blocked</td>
<td>70±4</td>
<td>60±4</td>
<td>60±4</td>
<td>88±6</td>
<td>147±6</td>
<td>46±3</td>
<td>157±5</td>
</tr>
<tr>
<td>EPR to Bob blocked</td>
<td>2.7±0.1</td>
<td>1.0±0.1</td>
<td>3.5±0.1</td>
<td>5.3±0.1</td>
<td>4.3±0.1</td>
<td>1.7±0.1</td>
<td>4.2±0.1</td>
</tr>
<tr>
<td>EPR to BSM blocked</td>
<td>13±1</td>
<td>7±1</td>
<td>12±1</td>
<td>15±1</td>
<td>11±1</td>
<td>7.8±1</td>
<td>13.07±1</td>
</tr>
</tbody>
</table>

FIG. 11. (Color online) Measurements of the noise for a interferometer-BSA teleportation experiment. Top: “01” and “10” are in antiphases as expected and have visibilities of \( V_{01} =0.77±0.12, \ V_{10}=0.65±0.12 \) Bottom: “12” and “21” have a \( \pi \) phase shift as expected and have visibilities of \( V_{12}=0.66±0.14, \ V_{21}=0.91±0.13 \).
show an interesting phase difference between “01” and “10”. The reason for this shift is unknown, but the average value of the two phases corresponds with the phase that is expected from the curve for “02” and “20”. This suggests that this effect is caused by a fluctuating noise that is out of phase with the teleportation fringe.

When the different possibilities of the BSA are summed, in order to have the Bell states, the noise will no longer have any fluctuations. This is because the different noise possibilities had a π phase difference. After summing the different parts of the noise of a Bell state the result will be constant. For example, the noise of “01” combined with “10” is approximately constant. The overall resulting noise is in practice independent of the phase. The results after noise subtraction and correction for electronic transmission differences are shown in Fig. 13 and Table III. The results show excellent correspondence between theory and experiment. The visibilities are similar within their errors. The difference in phase between \(|\psi_+\rangle\) and \(|\psi_-\rangle\) (189° ±9°) corresponds with theory (180°). Also, since the phases were arranged in such a way that \(\beta = -\delta \mod 2\pi\), the fringe of \(|\phi_+\rangle\) is in phase with \(|\psi_-\rangle\) (phase difference of 4° ±9°). The normalized probabilities of a measurement (Fig. 12) show that \(|\psi_+\rangle\) and \(|\phi_+\rangle\) have the same probability (43%, respectively, 41%) and these values correspond with the theoretical value of 40%. The probability of \(|\psi_-\rangle\) is 15% with a theoretical value of 20%. These excellent agreements with theory suggest that the discrepancies as seen for the individual results are caused by differences in noise that cancel out when they are added to each other.

IV. CONCLUSIONS

In conclusion we have shown experimentally that it is possible to perform a three-state Bell analysis while using...
only linear optics without the use of ancilla photons. In principle, this measurement can reach a success rate of 50%. We have shown some of the techniques that have to be used to align a teleportation experiment which uses this BSA. Our teleportation experiment shows a noncorrected overall fidelity of $F = 67\%$, after noise subtraction we find $F = 76\%$. Also, we performed a teleportation experiment with a one state BSA which exceeded the cloning limit.

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APPENDIX: TEMPORAL ALIGNMENT

For a BSA to work it is important to have complete indistinguishability of the incoming qubits. This includes a indistinguishability in time. In order to align the path lengths in an experiment it is useful to perform photon bunching experiments, since photon bunching only occurs for indistinguishable photons. In the case of a teleportation experiment using a BS-BSA it is possible to perform a Mandel-dip experiment [27] by looking at the coincidence rate “00” or “11”. A decrease in the number of coincidences between the BSA detectors is observed when the photons from Alice’s source and the EPR source are indistinguishable. When an IF-BSA is used it is not trivial to directly measure such an effect, without having to make significant changes to the optical setup (such as replacing the interferometer by a beamsplitter) in between two teleportation experiments. In order to avoid any changes to the setup another method of checking indistinguishability was used. An increase in the number of coincidences “00” or “22” is dependent on indistinguishability, as was explained in the main text of the paper. The difference is clearly seen by calculating the probability to find “0” in both D0 and D1 for indistinguishable photons $[P(00|\text{aligned})]$ and distinguishable $[P(00|\not{\text{aligned}})]$ photons:

\[
P(00|\text{aligned}) = \frac{1}{2},
\]

(A1)

\[
P(00|\not{\text{aligned}}) = \frac{1}{8},
\]

(A2)

The maximum visibility when measuring the difference between aligned and nonaligned can be calculated by taking into account the probability of creating two photons in Alice $[P(00|(a')^2)]$ or at the EPR source $P[(00|(a')^2)]$.

\[
V = \frac{P_{\not{\text{out}}}-P_{\text{in}}}{P_{\not{\text{out}}}},
\]

(A4)

\[
P_{\text{out}} = \frac{1}{8} + 2 \times \frac{1}{8} = \frac{3}{8},
\]

(A5)

\[
P_{\text{in}} = \frac{2}{8} + 2 \times \frac{1}{8} = \frac{4}{8},
\]

\[
V_{\max} = \frac{1}{3}.
\]

Note that when measuring measurements of “antidips” the photons at Bob are completely ignored.

The antidips discussed above are not the only method of aligning the setup. It is also possible to look at a dip. For example, there will be a decrease in the number of “01” depending on whether there is photon bunching or not. During measurements of such a decrease the interferometers are not stabilized for experimental reasons. Since the coincidence rate is dependent on single-photon interference it is very difficult to clearly see the decrease in counts (Fig. 14).

One way to avoid this problem is to use a baby peak as a normalization. Baby peaks are coincidences with one (or more) laser pulses of difference between the creation time of the detected photons. For example, laser pulse $n$ creates a photon in Alice and this photon goes to detector D0, while laser-pulse $n+1$ creates a photon in the EPR source which goes to D1. The amount of coincidences measured for these

\[
\begin{array}{|c|c|c|}
\hline
\text{BSA} & \text{Indistinguishable} & \text{Distinguishable} \\
\text{“01”} & 1 + \cos(\alpha + \beta) & 1 + \cos(\alpha) \\
\text{“02”} & 1 - \cos(\alpha + \beta) & 1 \\
\text{“10”} & 1 + \cos(\alpha + \beta) & 3 - \cos(\alpha) \\
\text{“11”} & 4[1 + \cos(\alpha + \beta - 2\delta)] & 2[2 + 2 \cos(\alpha - \delta)] \\
\text{“12”} & 1 + \cos(\alpha + \beta) & 3 - \cos(\alpha) \\
\text{“20”} & 1 - \cos(\alpha + \beta) & 1 \\
\text{“21”} & 1 + \cos(\alpha + \beta) & 1 + \cos(\alpha) \\
\hline
\end{array}
\]

TABLE V. Theoretical interference for different projections made by the BSA. Two different cases are shown: indistinguishable photons (teleportation) and distinguishable photons (noise).
pulses will depend on the single-photon interference but there will clearly not be any photon bunching. Since such coincidences have the same interference effects as for the real coincidences it can be used to normalize a measurement and in this way a dip can be found (Fig. 14). Since this normalization method is much more complicated and less accurate it was not used for alignment, only antidiabatic alignment was used.

If temporal alignment is not accomplished in a BS-BSA teleportation experiment the resulting coincidence rates will not depend on the phases of the interferometers and therefore a fringe with \( V = 0 \% \) is found. When using an IF-BSA this is not the case since the presence of the extra interferometer leads to a single photon interference when changing the phase \( \alpha \). It is clearly important to be able to distinguish between these interferences and the interference fringes caused by teleportation. The behavior of the nonaligned setup can be readily calculated and the fringes that will be found are shown in Table V. One important fact clearly stands out straight away: there is no interference for “02” and “20” if the photons are distinguishable but there is when the photons are indistinguishable. The visibility of these fringes are an important indication whether or not there was temporal alignment during the experiment. In the experiment presented here a visibility of \( V = 55 \% \pm 3 \% \) was found which indicates that there was temporal indistinguishability.

Other indications whether there is good temporal alignment can be found when simulating the result of an unaligned experiment. Such a simulation is shown (Fig. 15) for the case of \( \delta = -\beta \) as was used during our experiments. The simulation clearly shows differences between the two cases which are readily identifiable in an experiment, such as the phaseshift of \( \pi \) between the fringes for “01” and “10”. These differences make it possible to see after an experiment whether or not the alignment was good and remained good.

Quantum teleportation over the Swisscom telecommunication network

Olivier Landry, J. A. W. van Houwelingen, Alexios Beveratos, Hugo Zbinden, and Nicolas Gisin

Group of Applied Physics, University of Geneva, 20 rue de l’École-de-Médecine, 1205 Geneva, Switzerland

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We present a quantum teleportation experiment in the quantum relay configuration using the installed telecommunication network of Swisscom. In this experiment, the Bell-state measurement occurs well after the entanglement has been distributed, at a point where the photon upon which data are teleported is already far away, and the entangled qubits are photons created from a different crystal and laser pulse than the teleported qubit. A raw fidelity of 0.93±0.04 has been achieved using a heralded single-photon source. © 2007 Optical Society of America

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1. INTRODUCTION
Quantum teleportation, or the ability to transfer information in the form of qubits between two locations without a direct quantum channel, has many practical applications in addition to its fundamental significance. In quantum communication protocols, such as quantum key distribution,1,2 the maximum distance one can reach is limited by channel losses and detector noise. When the signal-to-noise ratio gets lower than a certain limit that depends on the choice of protocol and experimental details, no secure information can be retrieved. While the losses in optical fibers cannot be decreased with current technologies, a suitably designed communication channel making use of quantum relays3,4 or quantum repeaters5 can reduce the noise and therefore increase the distance limit. Quantum relays use quantum teleportation and entanglement swapping to perform a kind of quantum non-demolition measurement at some points within the channel, in effect measuring the presence of a photon without measuring the qubit it carries. Detectors can then be opened only when a photon is certain to arrive, reducing dark counts, the main source of noise. Quantum repeaters perform the same task but also use quantum memories and entanglement purification.

In previous experiments, teleportation was demonstrated inside a laboratory6–8 or in the field but without prior entanglement distribution.9 The Bell-state measurement (BSM) always took place before the third photon was distributed to Bob. On the other hand, in all these experiments, the same laser pulse was used to create both the entangled pair and the photon to be teleported. These two points limit the feasibility of a practical quantum relay and open conceptual loopholes. Here we present an experiment where teleportation occurs long after entanglement distribution and the photons involved originate from two crystals excited by different pulses from the same laser.

2. PROTOCOL
The quantum teleportation protocol9 (schematically described in Fig. 1) requires that Bob (the receiver) and Charlie (a third party) share an entangled state, which in this case is a $|\phi^+\rangle$ state. Alice (the sender) needs to send a qubit over to Bob, but does not possess a direct quantum channel. She sends it to Charlie who performs a BSM10 using a beam splitter and classically announces the result to Bob.

Time-bin qubits12 have proved to be very robust against decoherence in optical fibers13 and several long-distance experiments have been demonstrated.7,14,15 In this experiment, time-bin qubits lying on the equator of the Bloch sphere are created using an unbalanced interferometer. For a review of time-bin qubits see Tittel and Weihs.16

3. SETUP
The experimental setup is shown in Fig. 2. A mode-locked Ti:sapphire laser (Mira Coherent, pumped using a Verdi laser) creates 185 fs pulses with a spectral width of 4 nm at a central wavelength of 711 nm, a mean power of 400 mW, and a repetition rate of 75 MHz. This beam is split in two parts using a variable coupler ($\frac{1}{2}$ and a polarization beam splitter).

The transmitted light is sent through an unbalanced Michelson interferometer stabilized using a frequency-stabilized HeNe laser (Spectra Physics 117A) and then on a lithium borate (LBO) nonlinear crystal (NLC) cut for type-I phase matching, which creates a time-bin entangled photon pair in the $|\phi^+\rangle$ state by spontaneous parametric downconversion. The created photons have wavelengths of 1310 and 1555 nm and are easily separated using a wavelength division multiplexer (WDM). A Si filter is used to remove the remaining 711 nm light.
A. Charlie's Photon
The 1310 nm photon is sent in a 179.72 m spool of fiber. This spool serves as a rudimentary quantum memory (QM). While Charlie's part of the entangled qubit pair is waiting in this spool, Bob's part leaves the laboratory.

B. Alice's Photon
Alice prepares her photon using the light reflected from the variable coupler. A pair of photons is created in the same type of crystal as above, then separated. The 1555 nm photon can either be discarded or detected by an InGaAs avalanche photodiode (APD) in order to herald the photon to be teleported.\(^{17,18}\) If it is not detected, teleportation still occurs without other changes in the setup.

The 1310 nm photon is stored in a 177 m spool of fiber. The 2.72 m difference with Charlie's QM corresponds exactly to the spacing between two subsequent pulses of the laser. This means that Alice's photon upon which the qubit to be teleported will be encoded is produced from a different pulse of the laser than Charlie's and Bob's photons. This is a conceptually important step toward completely independent laser sources.\(^{19,20}\)

To encode a qubit on her photon, Alice sends it after the spool to an unbalanced fiber interferometer independently and actively stabilized\(^7\) by a frequency-stabilized laser at a wavelength of 1552 nm (Dicos OFS-2123). Only then is Alice's qubit created. Note that at this point, Bob's photon is already 177 m away from the laboratory. Once Alice's photon has been encoded, Charlie performs a BSM jointly with his photon and the photon Alice prepared.

C. Alignment and Stabilization
Alice's and Charlie's photons need to arrive at the beam splitter within their coherence time and be indistinguishable for the BSM to be successful. Charlie's photon passes through a polarization controller to make both polarizations equal at the beam splitter. Chromatic dispersion is negligible at the 1310 nm wavelength. Charlie filters both photons down to 5 nm of bandwidth, which corresponds to a coherence time of \(\tau_c=500\) fs or a coherence length of \(L_c=150\) \(\mu\)m, approximately three times more than the excitation pulse. The easiest way to control the distance traveled by the photons with this precision is to add a variable delay consisting of a retroreflector mounted on a micrometer step motor placed right after the variable coupler, which can move with a precision of 200 nm.

A Mandel dip\(^{21}\) experiment (Fig. 3) is performed in order to measure the degree of temporal indistinguishabili-
ity between the two incoming photons. The registered raw visibilities are \( V_{11} = 0.266 \) and \( V_{00} = 0.255 \), respectively. These visibilities are close to the theoretical maximum net visibility of \( 3/2 \). The width of the Mandel dip, which corresponds to the coherence length of the photons, is 144 \( \mu \text{m} \) as expected for filters of 5 nm. Since the fiber spool at Alice's side is longer by one pulse period, the two photons that experience photon bunching have not been created by the same excitation pulse but from subsequent ones.

Unfortunately, the alignment of the different paths is not inherently stable. Temperature fluctuations in the laboratory will affect the length of the fibers and the repetition rate of the laser. To avoid length fluctuations of the fiber spools, they have been placed in a common insulated box so that any fluctuation will apply equally to both. The fluctuation in the length difference of the nominally equal 177 m spools of fiber has been measured in a Mach–Zender setup to be less than 10 \( \mu \text{m} \). Longer fibers similarly insulated show larger fluctuations: spools of 800 m showed fluctuations of up to 60 \( \mu \text{m} \) over less than an hour, which would have destroyed complete indistinguishability in the long term.

There remain two effects that have to be compensated for. First, the thermal expansion of the additional 2.72 m of fiber on Charlie's side is not compensated for by an equal length on Alice's side as for the other fibers. This 2.72 m will undergo a thermal expansion of \( \sim 100 \mu \text{m/K} \). Second, the laser repetition rate fluctuates in a seemingly random fashion by up to 400 Hz/h in the worst cases, a fluctuation that would cause a change of 15 \( \mu \text{m} \) in the additional length needed to skip exactly one period of the laser. These phenomena combined mean that Alice's photon and Charlie's photon will not stay indistinguishable for more than a few hours, not enough to perform a teleportation experiment.

The squares curve in Fig. 4 demonstrates this instability. A Mandel dip experiment is performed to find the minimum of the curve as in Fig. 3. The motor moves to this point at time zero and is not moved afterward. It can clearly be seen that the number of coincidences registered increases with time. After a few hours, a plateau is reached where no bunching occurs anymore.

Numerous experiments have shown that the departure from the minimum of the Mandel dip is very well correlated with the repetition rate of the laser, which is registered using an external counter (Agilent 53131A). This is because the only parameter involved is the temperature of the laboratory; the laser can then be used as a very sensitive thermometer. It is therefore possible to link the step-motor movement with the measured repetition rate using a LABVIEW program such that the motor moves at an empirically derived rate of 0.07 \( \mu \text{m/Hz} \). In this way, the step-motor position is constantly adjusted for optimal indistinguishability. The results are also shown in Fig. 4 in circles.

Another way of stabilizing the length difference would have been to measure the number of coincidences when inside the Mandel dip and move the motor accordingly in a feedback loop. However, due to the low count rate, the integration time would have been longer than the observed fluctuation time, making such a system inefficient.

### D. Bell-State Analyzer and Electronics

Both 1310 nm photons are sent to a Bell-state analyzer (BSA) consisting of a beam splitter and two detectors...
An electronic signal is generated for each photon detection. These signal time arrivals are electronically compared as shown in Fig. 5. A $|\Psi^-\rangle$ detection occurs when two photons arrive on different detectors with a time difference of one time bin, or 1.2 ns in our setup. To reduce dark counts, only those photons that are coincident with a clock signal from the laser are considered. In total, the electronic circuit is able to make a decision whether the clock signal from the laser are considered. In our setup, the dark counts, only those photons that are coincident with a clock signal from the laser are considered. In total, the electronic circuit is able to make a decision whether the signal is a $|\Psi^-\rangle$ in approximately 220 ns. This time corresponds to the physical cable lengths and various delays that had to be implemented to trigger the active detectors and synchronize and transform the electric signals. When the conditions for a $|\Psi^-\rangle$ are not fulfilled, no information about the state is available. When a $|\Psi^-\rangle$ has been successfully detected, the information is sent to Bob over a second optical fiber (the classical channel) and by means of an optical pulse.

E. Bob’s Photon

Bob is at a Swisscom substation at a flight distance of 550 m from the laboratory, but an optical fiber distance of 800 m. Losses in the these fibers are smaller than 2 dB. To minimize chromatic dispersion and reduce spurious detections, the photon is filtered down to a 15 nm width.

Upon receiving the qubit, Bob stores it in a very basic QM consisting of a fiber spool of 250 m waiting for the BSA’s information to arrive. Once the confirmation of a successful $|\Psi^-\rangle$ measurement reaches Bob, he opens his InGaAs APD (IdQuantique Id 200) and detects the incoming photon after sending it through an analyzing interferometer. Photons that do not correspond to a successful $|\Psi^-\rangle$ measurement from Charlie are discarded. Arrival times of the photons with respect to the classical signal are measured by means of a time-to-digital converter. Timing jitter between the classical information and the qubit is negligible and much smaller than the timing resolution of the InGaAs detector. By scanning the analyzing interferometer, Bob measures the visibility of the interference in order to extract the fidelity of the teleported state. Bob actively stabilizes his interferometer with a frequency-stabilized laser at a wavelength of 1533 nm (Dicos OFS-320).

It is important to note that Bob is a completely independent unit, with its own local interferometer stabilization and controls. A LABVIEW program developed in-house allows an operator to control Bob, Charlie, and Alice from the laboratory using a dedicated TCP/IP channel that uses the third fiber indicated in Fig. 2. In particular, the detectors have to be closed when the interferometers are being stabilized; synchronization of the stabilization and measurement periods are made through this channel. Cross talk between this fiber and the quantum channels is negligible, even at the single-photon level.

F. Difference between the Three-Photon and Four-Photon Setup

The laser light does not need to be separated equally between the two NLCs, and the ratio can be adjusted to minimize noise. When the 1555 nm photon from Alice’s NLC is not detected, double pair creation in the Einstein–Podolsky–Rosen (EPR) source can create a false signal even if there is no photon created in Alice’s NLC, since it is possible that one photon from the double pair will find its way to the Ge APD and the other one to the InGaAs APD. On the other hand, double pair production in Alice’s NLC will not be recorded if there is no corresponding photon at Bob’s. Therefore in this case, it is usual to use less power on the EPR source than on Alice’s source to minimize the number of false counts. However, when the fourth photon is also detected, no false signal will be recorded unless there is also a pair created at Alice’s source; therefore we can use equal power on both sources. The resulting noise reduction allows a greater signal-to-noise ratio.

4. RESULTS

A. Teleportation without a Heralded Single Photon

A first experiment was performed without detecting the fourth photon to allow for a greater count rate. We first performed a Mandel dip to adjust the variable delay and linked its position to the repetition rate of the laser as described before. We locked the phases of the bulk and Alice’s interferometer and slowly scanned Bob’s interferometer phase. Each point was measured for 53 min to accumulate statistics. The results are shown in Fig. 6.

The power on the entangled photon source was lowered compared to the power on Alice to reduce noise. The probability of creating a pair of photons per pulse on Alice’s NLC was $P_A=0.19$ and the probability of creating a pair of entangled photons per pulse was $P_B=0.07$.

The presence of two complete periods shows that the expected cosine is well reproduced. The visibility of the curve and the fidelity $F=(1+V)/2$ are good measures of the quality of the teleportation. The raw visibility $V_{\text{raw}}=0.46\pm 0.06$ ($F_{\text{raw}}=0.73\pm 0.03$) is higher than the classical limit $V=\frac{1}{2}$ ($F=\frac{3}{5}$). The difference with a perfect visibility comes mainly from known sources of noise such as double pair production in the NLC and dark counts in the detectors. This noise can be measured by running the same ex-

![Fig. 6. (Color online) Teleportation experiment: as we scan the phase of Bob’s interferometer, the number of coincidences oscillates, which shows that the qubit is in the expected superposition state. When subtracting noise, the near-perfect visibility $V_{\text{net}}=0.92\pm 0.13$ shows that decoherence is minimal. The raw visibility of $V_{\text{raw}}=0.46\pm 0.06$ is still higher than the classical limit.](image)
experiment but blocking different parts of the signal. When these sources of noise are measured and subtracted, we get a net visibility of \( V_{\text{net}} = 0.92 \pm 0.13 \) (\( F_{\text{net}} = 0.96 \pm 0.06 \)). We can conclude that decoherence is minimal.

B. Teleportation with a Heralded Single Photon

Even though the sources of the reduced visibility are known and understood, for practical applications a high raw visibility is needed. We performed a second experiment where we detected the fourth photon to transform Alice into a heralded single-photon source. In this case, the probability of creating a pair was set to be roughly equal in both NLCs at \( P = 0.13 \). The efficiency of the detector and additional losses induced by the additional optical components meant that the overall signal was reduced by a factor of 15, and each point necessitated 6 h of data accumulation. However the noise reduction meant that the raw visibility was much higher at \( V_{\text{raw}} = 0.87 \pm 0.07 \) (\( F_{\text{raw}} = 0.93 \pm 0.04 \)), which is higher than the cloning limit \( V = \frac{2}{3} \) (\( F = \frac{3}{4} \)). The results are shown in Fig. 7.

In this case, the noise is so low as to be unmeasurable by conventional means. Therefore, we did not measure the net visibility. We should point out that in this case, the raw visibility is as high (within uncertainties) as the net visibility. We should point out that in this case, the noise is so low as to be unmeasurable by conventional means. Therefore, we did not measure the net visibility. We should point out that in this case, the raw visibility is as high (within uncertainties) as the net visibility. We can conclude that the main sources of noises can be eliminated by using a heralded single-photon source.

5. CONCLUSION

In summary, we have performed a teleportation in conditions that are close to field conditions. Bob was a completely independent setup and was remotely controlled. Alice's qubit was created only after the entanglement distribution took place. The necessary optical delays were stabilized using the variations of the repetition rate of the laser, an easily obtainable information. The qubits were created using different pulses of this laser. In the future, using truly independent lasers will enable the construction of a teleportation machine that will have the ability to receive and transport information from another independent machine, an ability that would be helpful in quantum networks, for example. Using a heralded single-photon source, we were able to obtain a raw fidelity of \( F = 0.93 \pm 0.04 \).

REFERENCES

Synchronized and independent picosecond photon sources for quantum communication experiments

J.A.W. van Houwelingen†, O. Landry, A. Beveratos, H. Zbinden, and N. Gisin

Group of Applied Physics, University of Geneva,
rue de l’École-de-Médecine 20,
1211, Genève, Switzerland

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An essential requirement for the future of quantum communication is the capability to create indistinguishable photons at separate locations. The biggest challenge is temporal-indistinguishability because there exist many sources of jitter which cause distinguishability. This article reports a system that creates a large tolerance against such jitter by using synchronized sources of photons with large coherence lengths.

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Introduction

Quantum communication and information has seen a lot of development in photon sources in recent years. Most of this research focuses on increasing either the rate and/or the quality of the entanglement produced. Also many different types of sources have been implemented [1, 2, 7, 10–12]. Such sources are essential for the construction of a quantum repeater (QR) [3, 6]. A QR allows distribution of entanglement over large distances. It consists of a large number of entangled pair sources, quantum memories and Bell-state analyzers (BSA) in order to perform a cascaded entanglement swapping which will eventually create entanglement between the first photon and the last (Fig. 1). The BSA is an essential part of this protocol and is responsible for a lot of the experimental constraints. It requires that both of the analyzed photons are completely indistinguishable.

Amongst all possible sources of distinguishability one is of a particular difficulty, temporal distinguishability. If the two photons for the BSA arrive at different times the BSA does not function, and therefore neither does the entanglement swapping. Several methods can be conceived to assure temporal indistinguishability. Recently a new method was proposed and tried which uses cw-sources [8]. This method is an interesting approach but has its own set of of problems. In this paper we will focus on the second, and more common, method of achieving temporal indistinguishability. It consists in using pulsed lasers as a ‘clock’ for the experiment. Unfortunately it is difficult to synchronize two different laser. Experiments have been done that circumvent this problem by using a single pulsed laser for both sources.

Using pulsed lasers means that the times at which photons are created are strictly correlated. In order to assure equal time of arrival on the BSA all that is then required is an alignment of path lengths to a difference less than the coherence length of the photons. Also it is required that this alignment stays stable during the experiment. Entanglement swapping performed in this manner has proven to function for a variety of systems [5, 13]. However all these experiments have a common fault, it is impossible to separate the photon sources by any significant distance. This is a direct result of the fact that the pump-pulses cannot be easily distributed. In order to simulate independent sources experiments have been done that use different pump pulses and different nonlinear crystals, but what is really needed is the use of different lasers altogether. Because of the requirements of the BSA such lasers have to be synchronized to a very high degree. Few experiments have investigated the problems associated with such systems, they will be discussed further below.

As mentioned above another important point for temporal indistinguishability is the stability of the path lengths that the photons will take to get to the BSA. When using optical fibers at telecommunication wavelengths these path lengths can fluctuate up to the order of several millimeters per day [14]. In terms of jitter this corresponds to several picoseconds. Therefore either an active control of path length is required or the system must have tolerances for such fluctuations.

FIG. 1: Graphic representation of a quantum repeater. The squares represent quantum memories and the stars photon-pair sources. At the position where the arrows meet a Bell-state analyzer (BSA) is used which ‘swaps’ the entanglement. The synchronization is required for the BSA.

†email: jeroen.vanhouwelingen@physics.unige.ch
Innovative experiments have been done[9, 15] that have shown that in principle it is possible to use independent lasers to perform a BSA. Neither of the techniques used in these experiments can be easily used to truly make a QR. In the first case the two independent sources had a common optical element, making it impossible to physically separate both sources. And both experiments are very sensitive to path length fluctuations and drifts of repetition frequency because of the use of photons with short coherence lengths. This means that a big effort has to be made to assure temporal indistinguishability in the presence of picosecond path length fluctuations. The second experiment consisted of two laser that can be physically separated but a active correction for delay drifts of the synchronization was required.

In this paper we will show a system that can be both physically located at different places and is highly tolerant against path length drifts. It consists of using very narrow bandwidth photons which means photons with long coherence lengths. Such photons have the advantage that the BSA is a lot more tolerant to a difference in arrival time. In order to create a large number of such photons it is useful to use ps-pulsed sources instead of the fs-pulsed sources used up to date. Furthermore two different types of laser will be used to show the versatility of the scheme. One laser will be a mode-locked Ti-sapphire (MIRA) pumped by a diode pump-laser (VERDI). In the long term it is important for QR to be able to work with ‘cheap and simple’ sources. In order to approach such a source the second laser source will be an electrically pumped pulsed diode laser (PICOQUANT). Also the essential requirement to send our synchronization signal over large distances will be investigated.

Theory

An important parameter for the quality of synchronization is jitter. One can easily imagine that the quality of a BSA is greatly reduced if one or both sources have a large jitter because this introduces temporal distinguishability between the created photons (Fig. 2). If we assume the use of pulsed lasers and parametric-downconversion to create photon-pairs several different sources of jitter can be identified. First of all there is the intrinsic jitter. Every laser has a certain uncertainty in the time of emission of a pulse, this jitter is minimal in a free-running modelocked-laser but can be important in pulsed diode lasers. Second, there is a timing jitter which is created by the synchronization system itself. Finally there is the path-length jitter. As explained above, fluctuations in path-length will influence the time of arrival on the BSA. Obviously an effort has to be made to limit all of these quantities, but one method to overcome them all is to increase the coherence length of the photon-pairs (Fig. 2) since this will effectively reduce the jitter per pulsewidth.

The result of such a change is best illustrated with the visibility of a Hong-Ou-Mandel(HOM) dip: Consider the probability P of photon bunching when two identical photons arrive at a different time on a beamsplitter.

\[ P_{\text{bunch}} = \frac{1}{2} \left( \int f^*(t) f(t+\tau) dt \right)^2 + 1 \]  

where \( f(t) \) is the amplitude of the temporal distribution function of the photon and \( \tau \) is the difference of arrival time. When assuming a gaussian distribution for the photons we find:

\[ f(t) = \sqrt{Ne^{-8\ln(2) (\frac{t}{\tau})^2}} \]  

\[ P_{\text{bunch}} = \frac{1}{2} \left( N \int e^{-\frac{4\ln(2) \tau^2}{\tau^2}} \right)^2 + 1 \]

\[ = \frac{1}{2} \left( e^{-\frac{4\ln(2) \tau^2}{\tau^2}} + 1 \right) \]

here \( N \) is a normalisation factor and \( w \) is the FWHM of \( f(t) \). It is convenient to rewrite this last formula in dimensionless units:

\[ \Delta \equiv \frac{\tau}{w} \]

\[ P_{\text{bunch}} = \frac{1}{2} \left( e^{-4\ln(2) \Delta^2} + 1 \right) \]

where \( \Delta \) is the amount of FWHMs the photons arrive apart. When considering jitter the time-of-arrival difference will fluctuate, there is a probability \( P_j \) to find the photon at a delay \( \Delta \) of:

\[ P_j(\Delta, w_j) = \frac{2}{w_j} \sqrt{\ln(2) \pi} e^{-\frac{4\ln(2) \Delta^2}{\tau^2}} \]

where we assumed a gaussian distribution with FWHM \( w_j \). When performing a standard HOM dip experiment with these parameters the average visibility of the system equals

\[ \nabla = \int P_j(\Delta, w_j)V(\Delta)d\Delta \]
are desired extremely narrow filters are required. The spectrum generated by the source i.e. use spectral filters enough when having mm-range pathlength fluctuations. To coherence lengths of the order of 10\(^{-}\lambda\) wavelengths (SPDC usually creates a large spectrum which can easily exceed several dozens of nm. At telecom wavelengths (\(\lambda_0 = 1550\)nm) such a spectrum corresponds to coherence lengths of the order of 10\(^{-}\lambda\)m which is not enough when having nm-range pathlength fluctuations. One obvious approach is to use only a small part of the spectrum generated by the source i.e. use spectral filtering. However if coherence lengths of the order of a cm are desired extremely narrow filters are required. The filters used for our experiment are a combination of a fiber bragg-grating(FBG) and a phase-shifted FBG (more in the next section). In order to have a well defined total energy of the photon-pairs it is also required to filter the pump-photons. Furthermore the coherence length of the created photon-pairs must be larger than the length of the pulse that generated them [16] but shorter than the difference between two time-bins.

The HOM dip as explained above is a good method to show the usefulness of our sources for QRs. A method that can be used to directly show that two lasers are synchronized is to perform a cross-correlation measurement. One way of doing this is to by passing light form both sources through a non-linear crystal (NLC) cut for type II phasematching. When both pulses arrive at the same time in the NLC there will be frequency-doubling with an intensity dependant on their overlap. Assuming gaussian spectrums and Fourier limited pulses this means that the length of the frequency-doubled light is equal to \(w_{fd} = \sqrt{w_{s1}^2 + w_{s2}^2 + w_j^2}\) where \(w_{fd}, w_{s1}, w_{s2}\) and \(w_j\) are the widths for the frequency-doubled light, first laser, second laser and the synchronization jitter respectively. In order to find the value of \(w_j\) it is required to first measure the pulse lengths \(w_{s1}\) and \(w_{s2}\) using an auto-correlation measurement. This is similar to the cross-correlation but both sources are one half of a single pulse.

**Experiments**

As mentioned in the introduction it is important for quantum communication to have simple entanglement sources. With this in mind we developed a source based on a pulsed laserdiode, instead of the more common mode-locked lasers. The diode produces pulses with a FWHM of about 25ps at a wavelength of 1550nm. The power of the diode 20\(\mu\)W. A higher output power is possible but this increases the length of the pulse. In order to amplify the power several Er-doped fiber amplifiers are used. First the light passes two pre-amplifiers. The output is filtered with an FBG in order to remove the amplified spontaneous emission (ASE). After the filter the light is once more amplified by the main-amplifier. The resulting pulses have a power of 200mW with a narrow spectrum. These pulses are then send trough a PPLN crystal which through frequency doubling generates 2mW of the desired light at 775nm with a spectral width of 0.4nm (Fig. 4).

The other source used for the experiments is a more conventional mode-locked-laser generating picosecond pulses with a wavelength of 775nm, bandwidth of 1.1nm and a pulse length of about 5ps. The power of this laser was matched to the diode laser by using gray filters.

The synchronization of these two sources was performed using a master-slave configuration. A part of the
light emitted by the MIRA is send to a fast diode. This signal is then used to directly trigger the diode laser. In order to test the jitter of the synchronization a cross-correlation measurement (Fig. 5) was performed. It consisted of combining the two lasers using a polarizing beamsplitter. The mode-locked laser had a large variable optical delay-line which was adapted to assure the same time of arrival of the two sources on the PBS. Behind the PBS there was an BBO-crystal cut for type II parametric downconversion. Such a crystal is also efficient for upconversion of two 775 photons to a single 387.5nm photon. The blue light was separated from the other wavelengths with a prism and measured using a Si-APD. The delay was scanned while recording the countrate. The result of this measurement (Fig. 6) shows a FWHM of 8.3mm (28ps). This length corresponds to a combination of jitter and pulse widths so in order to measure the jitter it is also required to measure the pulse lengths. This was done with a setup similar to the cross-correlation but the two inputs of the PBS now came from the same source. The measured pulse widths are 1.5mm (5.0ps) for the mode-locked laser and 6.2mm (20.7ps) for the diode laser (Fig. 6). Using these measurements it is possible to calculate the jitter, which is found to be 18ps (5.9mm).

The jitter found in the cross-correlation experiment puts a limit minimal limit on the pulse width required to find a high visibility in a HOM-dip. From its value it is possible to conclude that if a visibility greater than 95% is desired pulse lengths of about 20mm (67ps) are required. The visibility of the HOM-dip directly gives the maximum quality of any quantum communications protocol. One practical method of creating such pulses is to filter out a small spectrum of the generated photons. In this experiment a 30pm filter was used. This filter consisted of several parts, one standard fiber Bragg-grating(FBG), reflecting the desired wavelength at a large bandwidth, one circulator and one phase-shifted FBG, which has a very narrow transmission peak in its otherwise large-banded reflection (Fig. 7). Two such filters were used and finetuned to match each other using temperature.

The setup for the HOM-dip (Fig. 8) consisted of the same two sources as used for the cross-correlation measurement. The light from these sources was send into PPLN-waveguides in order to produce pairs of pho-
In conclusion we have shown that it is possible to build pulsed photon-sources with pico-second pulse lengths using different techniques. It is possible to synchronize two sources too such an extend that the jitter and path length fluctuations are not a cause of loss of visibility. Such sources are required if one wants to build a QR with multiple locations for the photon sources.

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Semiconductor Waveguide Source of Counterpropagating Twin Photons


Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162, Université Paris 7-Denis Diderot, Case 7021, 2 Place Jussieu, 75251 Paris, France

Alcatel-Thales III-V Laboratoire, Route Départementale 128, 91767 Palaiseau Cedex, France

Université de Genève, GAP-Optique, Rue de l’Ecole de Médecine 20, 1211 Genève 4, Switzerland

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We experimentally demonstrate an integrated semiconductor source of counterpropagating twin photons in the telecom range. A pump beam impinging on top of an AlGaAs waveguide generates parametrically two counterpropagating, orthogonally polarized signal/idler guided modes. A 2 mm long waveguide emits at room temperature one average photon pair per pump pulse, with a spectral linewidth of 0.15 nm. The twin character of the emitted photons is ascertained through a time-correlation measurement. This work opens a route towards new guided-wave semiconductor quantum devices.

Momentum conservation is a general property that appears in various physical contexts such as classical dynamics, optics, x-ray diffraction, and elementary particle collisions. In the field of nonlinear optics, which is the framework of the semiconductor source of twin photons described in the following, momentum conservation results in the phase matching between nonlinearly radiating dipoles. In parametric fluorescence, where one pump (p) photon is annihilated into two signal (s) and idler (i) photons sharing its energy, the translational invariance of the crystal can match the photon momentum before and after the down-conversion: \( k_p = k_s + k_i \). This is indeed the most widely used process to produce entangled photon pairs, which are one of the most intriguing phenomena at the heart of quantum mechanics [1]. Entangled two-photon states have been used to demonstrate the violation of Bell inequalities and confirm the foundations of quantum mechanics [2–4]. They are now the building block of quantum information [5], including quantum-key distribution protocols, quantum computing [6,7], or teleportation [8].

Different approaches have been followed to produce entangled two-photon states: atomic radiative cascades [2] and parametric fluorescence in nonlinear dielectric birefringent materials [3,4,9]. Compared to them, semiconductor materials fulfill stability, robustness, and integration criteria, thus exhibiting a huge potential in terms of integration of novel optoelectronic devices. A semiconductor source of entangled photons based on the biexciton cascade of a quantum dot has recently been demonstrated [10]. With respect to this technique, parametric generation in semiconductor waveguides allows room-temperature operation and a high directionality of the emission, which dramatically enhances the collection efficiency and decreases the rate of broken pairs (where one of the two photons is not collected). Moreover, the high nonlinear susceptibility of AlGaAs along with its well-mastered growth technique makes it particularly attractive for this purpose [11]. Recently, counterpropagating phase matching has attracted some interest for its potential in twin photon experiments for quantum communication [12–14], but no experimental demonstration of the generation of counterpropagating twin photons has been reported to date.

In this Letter, we use parametric fluorescence to produce counterpropagating twin photons in an AlGaAs multilayer waveguide. In our geometry, a pump beam impinging on top of a waveguide generates parametrically two counterpropagating, orthogonally polarized signal/idler guided modes through a type II interaction [Fig. 1(a)]. Counterpropagation results from the translational invariance of the waveguide along the propagation direction (z), where the momentum difference between the generated photons of a pair equals the longitudinal component of the pump momentum, \( k_z = k_p \sin \theta \) [Fig. 1(b)]. In order to improve the efficiency of the nonlinear process, we implement quasiphase matching in the epitaxial direction (x) through an alternation of AlGaAs layers with different Al content and therefore different nonlinear coefficients \( d_{14} \) [15]. Important advantages result from such a geometry, in the aim of realizing quantum communication devices: absence of the pump beam in the guided direction, automatic separation of the down-converted photons and their possible coupling into two optical fibers (through standard pigtailting process), tunability through the angle of incidence of the pump beam, and the proximity of the generated photons to the Fourier transform limit [16]. Moreover, the narrow spectral bandwidth, a signature of counterpropagating processes, is beneficial in two respects: it allows long-distance propagation in optical fibers with a negligible chromatic dispersion, and most importantly for quantum optics experiments, it is well suited for the interaction with very thin transition linewidths encountered in atoms or ions.

Our sample is grown by molecular beam epitaxy on a GaAs (100) substrate; its planar structure consists of Al\(_{0.94}\)Ga\(_{0.06}\)As cladding (1080 nm)/ Al\(_{0.25}\)Ga\(_{0.75}\)As (110 nm)/4 × [Al\(_{0.8}\)Ga\(_{0.2}\)As (124 nm)/ Al\(_{0.25}\)Ga\(_{0.75}\)As (110 nm)]/Al\(_{0.94}\)Ga\(_{0.06}\)As cladding.
energy for the photon copropagating with the than the TE photon due to birefringence; (2) a higher energy for the TM photon, because it travels faster signal and idler results in two concomitant effects: (1) a higher angle $\theta$ are shown in Fig. 1(c): the additive interaction is responsible for the longest and shortest emitted wavelengths, whereas the subtractive interaction is responsible for the intermediate ones. We point out that the two effects discussed above (birefringence and pumping geometry) can cancel out exactly, giving rise to wavelength-degenerate twin photons. As can be seen in Fig. 1(c), this occurs for $\theta = 0.4^\circ$ in the subtractive interaction.

From an experimental point of view, the acquisition of the time-correlation spectra of the generated photon pairs is a crucial issue. In the related setup (Fig. 2) the pump beam is provided by a TE polarized, pulsed Ti:sapphire laser with $\lambda_p = 768.2$ nm and a 3 kHz repetition rate. The pulse peak power is $P_p = 100$ W and its duration is 100 ns. The pump beam is focused on top of the waveguide ridge using a cylindrical lens (focal length = 2 cm) with an angle $\theta$ in the $xz$ plane. The generated photons are collected with two 63× microscope objectives, sent through two monochromators, and then coupled into fibered InGaAs single-photon avalanche photodiodes. A time-interval analyzer records the delay ($t_s - t_i$) between the arrival times of the generated photons.

The same experimental setup lends itself to the measurement of the spectral profiles of the generated photons.

(1080 nm). The lateral confinement is provided by a wet-etched ridge with 4 $\mu$m width and 2 mm length. AlGaAs is the material of choice to generate twin photons around 1.55 $\mu$m, compatibly to telecom devices; however, alternative materials can be used to realize a source for the silicon absorption band, for line-of-sight experiments in quantum-key distribution [17]. It is important to stress that two phase-matched processes occur simultaneously in our scheme: in the first one, the photon copropagating with the $z$ component of the pump beam is TM polarized and the counterpropagating one is TE polarized. In the second one, the vice versa occurs.

These two processes exhibit different output spectra due to the form birefringence induced by the multilayer geometry. The sharing of the pump photon energy between signal and idler results in two concomitant effects: (1) a higher energy for the TM photon, because it travels faster than the TE photon due to birefringence; (2) a higher energy for the photon copropagating with the $z$ projection of the pump beam, since it carries a supplementary momentum given by the pump. Additive contributions from these effects are thus obtained if the copropagating photon is TM polarized and the counterpropagating one TE polariz: this case shall hereafter be referred to as “additive” interaction. Conversely, the process with a TE copropagating photon and a TM counterpropagating photon will hereafter be referred to as “subtractive” interaction. The calculated tuning curves as a function of the pump incident angle $\theta$ are shown in Fig. 1(c): the additive interaction is responsible for the longest and shortest emitted wavelengths, whereas the subtractive interaction is responsible for the intermediate ones. We point out that the two effects discussed above (birefringence and pumping geometry) can cancel out exactly, giving rise to wavelength-degenerate twin photons. As can be seen in Fig. 1(c), this occurs for $\theta = 0.4^\circ$ in the subtractive interaction.

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FIG. 1. Parametric generation of counterpropagating twin photons in a multilayer waveguide. (a) A pump photon of frequency $\omega_p$ is converted in two counterpropagating twin photons with frequencies $\omega_s$ and $\omega_i$, with $\omega_s + \omega_i = \omega_p$ (energy conservation). (b) Momentum conservation is fulfilled in the longitudinal direction ($z$) for appropriate values of $k_s$ and $k_i$: (c) Calculated tuning curves as a function of the pump incident angle $\theta$ are shown in Fig. 1(c): the additive interaction is responsible for the longest and shortest emitted wavelengths, whereas the subtractive interaction is responsible for the intermediate ones. We point out that the two effects discussed above (birefringence and pumping geometry) can cancel out exactly, giving rise to wavelength-degenerate twin photons. As can be seen in Fig. 1(c), this occurs for $\theta = 0.4^\circ$ in the subtractive interaction.

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The same experimental setup lends itself to the measurement of the spectral profiles of the generated photons,
which are given by the count rate recorded by each detector versus wavelength. These are shown in Fig. 3 for $\theta = 3^\circ$, where sharp peaks are superposed to a flat background. The spectral structure nicely corresponds to the expected counterpropagating processes: the longest and shortest wavelengths result from the additive process, while the intermediate ones result from the subtractive interaction. Small secondary peaks are also observed, corresponding to counterpropagating photons reflected at the waveguide facets. A complete agreement is found between experimental values and numerical simulations of the generated wavelengths. For the additive interaction, for example, the measured wavelengths deduced from Fig. 3 are $1509.5 \pm 0.5$ nm and $1564.5 \pm 0.5$ nm, where the uncertainties stem from the resolution of the monochromators. The corresponding calculated values are $1508.9 \pm 1$ nm and $1564.8 \pm 1$ nm [Fig. 1(c)]. Here the uncertainties are mainly due to the uncertainty on two inputs of our simulations: the experimental values of the incident angle ($\pm 0.05^\circ$) and of the pump wavelength ($\pm 0.2$ nm). Such a good agreement reflects the robustness of the structure with respect to the tolerances on the ridge size (width and height) and to the fluctuations (thickness and composition of the layers) in the epitaxial process [18]. Apart from the above experimental uncertainties, the intrinsic full width at half maximum of the generated spectrum has been accurately measured by difference frequency generation and was found to be equal to 0.15 nm.

The flat background in the measured spectra arises from two contributions: (1) dark counts generated by the detectors in the absence of any incident photon, and (2) photoluminescence due to electron-hole recombination after pump absorption, resulting from below-band-gap deep levels embedded in semi-insulating GaAs substrates. In the future, both these contributions could be reduced: the former by employing state-of-the-art detectors and the latter by partially removing the substrate.

To further assess the twin character of the emitted photons, the time correlations between the detected counts have been analyzed. A histogram of the time delays is shown in Fig. 4, for the case of the additive interaction with $\theta = 3^\circ$. With a sampling interval of 43 ps, the histogram results from an acquisition time of 12 h. The emission level remained constant during this long integration time, which shows the remarkable robustness and stability of the device.

The peak observed for $t_s = t_i$ demonstrates unambiguously the twin character of the generated photons; the 750 ps full width at half maximum of the histogram...
corresponds to the timing jitter of both detectors. The flat background is produced by the uncorrelated coincidences with dark and below-band-gap luminescence counts: indeed, switching the pump polarization from TE to TM leads to the suppression of the $t_2 = t_1$ peak, without modifying this background. Finally, no time correlation is found between photons that are generated with different interactions: this agrees with the expectations, since these photons are not generated within the same nonlinear process.

The amount of detected coincidences, 0.15 pairs per second, allows deducing the brightness of our twin photon source. Taking into account the quantum efficiency of the detectors (5%), the transmission of the monochromators (50%), and the overall transmission along the setup optical path (40%), we estimate 1500 generated pairs per second. A similar level is obtained if the subtractive interaction is selected. Finally, this leads to an average generation rate of one pair per pump pulse (or $2.5 \times 10^{-14}$ generated pairs/pump photon), in good agreement with our numerical modeling. We emphasize that the above amount of average generated pairs per pulse is well suited for current standards in quantum-key distribution protocols.

Moreover, significant improvements in quantum efficiency and background noise suppression are expected with a structure including Bragg mirrors to enhance the light-matter interaction and by removing the GaAs substrate, source of spurious deep level emission events. These modifications (especially the microcavity immersion) will lower the pump power to standard pump sources below the Watt level. Before these improvements, the source reported in this Letter generates more pairs (one per pump pulse) than necessary for quantum information. Compared to the guided twin photon sources reported to date in periodically poled lithium niobate waveguides [19] and in photonic crystal fibers [20], our source exhibits room-temperature operation, very narrow bandwidth, no need for pump spectral cleaning (the pump is not guided), and easy separation of the generated photons. Finally, we emphasize the possibility of directly generating polarization-entangled states.

For example, the generation of a Bell state can be done by simultaneously pumping the sample with $\theta = \pm 0.4^\circ$ [see Fig. 1(c)], by illuminating the waveguide through a diffraction grating [13] or by inserting it in a bow-tie cavity.

Clearly, our twin photon source can be profitably integrated in innovative devices. On the one hand, one can, e.g., obtain an entangled light emitting diode thanks to the integration of an electrically pumped vertical cavity surface-emitting laser on top of the waveguide. On the other hand, forgetting entanglement but making use of simultaneity, an integrated heralded source of single photons is readily available by integrating or pigtailing a photon counter at one of the two waveguide facets.

These innovations can be envisaged because our source belongs to the domain of semiconductors, which is a major qualitative leap of our work. Because of all these advantages and perspectives, we candidate our twin-photon-source geometry as a novel archetype for future quantum information devices.

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*Corresponding author.
Electronic address: leo.giuseppe@paris7.jussieu.fr

We report an experimental test for the local causality of space-time assuming the influence of gravity in quantum state reduction. In a Franson-type test of Bell inequality, two energy-time entangled photons are sent through optical fibers and directed into unbalanced interferometers at two receiving stations separated by 18 km. At each station, the detection of a photon triggers the displacement of a macroscopic mass. The timing ensures space-like separation from the moment a photon enters its interferometer until the macroscopic mass, 18 km away, has moved. When scanning the phase in one of the interferometers, interference fringes with a visibility of up to 90.5% are obtained, leading to a violation of Bell inequality.

When is a quantum measurement finished? Quantum theory has no definite answer to this seemingly innocent question and this leads to the quantum measurement problem. Various interpretations of quantum physics suggest opposite views. Some state that a quantum measurement is over as soon as the result is secured in a classical system, though without a precise characterization of classical systems. Decoherence claims that the measurement is finished once the information is in the environment, requiring a clear cut between system and environment and arguments assuring that the system and environment will never re-cohere. Others claim that it is never over, leading to the many worlds interpretation [1]. Note that none describes how a single event eventually happens. And there are more interpretations and many variations on each theme. In practice this measurement problem has not yet led to experimental tests, though progress in quantum technologies bring us steadily closer to such highly desirable tests [2].

Another possibility, supported among others by Penrose and Diósi [3][4], assumes a connection between quantum measurements and gravity. Intuitively the idea is that the measurement process has to be finished before space-time gets into a superposition state of significantly different geometries. The latter would be due to superpositions of different configurations of massive objects. Penrose and Diósi independently proposed the same criterion (up to a factor of 2) that relates the time of the collapse (that terminates the measurement) to the gravitational energy of the mass distribution appearing in the superposition. Following Diósi equation [4], the time of the collapse is given by:

\[ t_D = \frac{3\hbar V}{2\pi G m^2 d^2} \]  

where \( V \) is the volume of the moving object, \( m \) is its mass and \( d \) is the distance it has moved.

Hence, according to Eq. 1, a typical measurement in quantum optics is finished once the alternative results would have led to displacements of a sufficiently massive object. This view differs strikingly from the one adopted in practice by most quantum opticians. Indeed, the common view in this community is that a quantum measurement is finished as soon as the photons are absorbed by detectors. But such an absorption, even when it triggers an avalanche photodiode and gets registered by a computer, only involves the motion of electrons, that is of insufficient masses to satisfy the Penrose-Diósi criterion.

This situation led Kent to observe that actually, according to the Penrose-Diósi criterion, none of all the many Bell inequalities tests that have been performed so far involve space-like separated events [5]. Indeed, in all these tests, no massive object moves, at least not in the microseconds following
the photon absorptions by the detectors. But then, none of these Bell tests strictly excludes the possibility that the observed violation of Bell inequalities is due to some hypothetical communication (of a type unknown of today’s physics). Given the importance of quantum nonlocality (i.e. violation of Bell inequalities), both for fundamental physics and for quantum information science, we present in this letter an experiment that closes this loophole.

In a Franson-type test of the Bell inequalities [6], pairs of entangled photons travelling through optical fibers are sent to two receiving stations physically separated by 18 km with the source roughly at the center. This distance breaks the previous record for this kind of experiments [7]. At each receiving station, the detected photons trigger the application of a step voltage to a piezoelectric actuator. The actuator is a ceramic-encapsulated PZT (lead zirconate titanate) block of 3x3x2 mm and weighs 140 mg (PI, PL033). We chose this actuator because it fulfills all the following criteria: it can move a measurable distance in a time of the order of microseconds and it can be triggered to repeat this movement several thousand times per second. Due to the converse piezoelectric effect, the applied voltage expands the actuator and, at the same time displaces a gold-surfaced mirror measuring 3x2x0.15 mm and weighing 2 mg that is attached to one of the piezo faces. We used this mirror as the movable mirror of a bulk optical interferometer (see Fig. 2) to confirm the expansion of the piezo (see Fig. 3).

To guarantee the space-like separation between the detection events, the time that the light needs to travel from one receiving station to the other must be significantly shorter than the time needed to perform all the measurement process ($t_M$). This time includes, not only the time of the collapse, but also the time between the moment the photons enter their respective analyzer (a 3-dB fiber coupler inside an interferometer), until the moment the mirrors move sufficiently to be certain that the measurement process is finished, according to the Penrose-Diósı hypothesis. The time between the moment the photons enter the analyzer to the moment the step voltage is applied it is just 0.1 µs. After the application of the voltage, the piezo starts to expand and displaces the mirror. This produces a change in the phase of the interferometer that is detected by the photodiode. The equivalence between the voltage variation detected by the photodiode and the mirror displacement has been calculated from the wavelength of the laser ($\lambda = 633$ nm) and the phase change produced by the displacement. If we consider that the phase change takes place in a node of an interference fringe, where the slope between the phase and the intensity is maximum, we will set a lower bound for the displacement distance. Hence, 6 µs after the step voltage is applied to the piezo, the voltage has already changed by 0.3 V meaning that the mirror has displaced a distance of at least 15 nm. Finally, we find that the time of collapse is $t_D = 0.7$ µs, using Eq. 1 [8] with d=15 nm and taking just the mass and volume of the mirror. The total time is then $t_M = 6.8$ µs, one order of magnitude shorter than the 60 µs the light needs to cover the 18 km between the receiving stations.

Fig. 2. Experimental set-up of the bulk interferometer used in each receiving station (Satigny and Jussy) to confirm the piezo expansion. Each interferometer is mounted inside a box that isolates it from atmospheric disturbances. The piezo actuator is glued to a fixed support with one mirror attached to its side. Each time a photon is detected by the single-photon detector, a step voltage of 4V is applied to the piezo, expanding it. When the piezo expands, the laser beam-path through the arm with the piezo shortens and the interference produces a variation in the intensity observed by the photodiode.

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Fig. 3. Step voltage applied on the actuator and the mirror displacement. This measurement confirms the piezo expansion. It was repeated in each receiving station before and after each run of the experiment. Grey line is the step voltage of 4 V (left scale) applied to the piezo actuator. Black line is the distance the mirror has moved represented as the voltage variation (right scale) detected by the photodiode. 6 µs after the voltage is applied, the mirror has already moved by 15 nm.

The scheme of the experimental setup is given in Fig. 4. A cw single mode external cavity diode laser (2.7 mW at 785.2 nm) pumps a PPLN (Periodi-
cally Poled Lithium Niobate) nonlinear waveguide that creates pairs of photons through the process of spontaneous parametric down-conversion. After the waveguide, a Silicium filter (F) blocks all the remaining light at 785.2 nm and the created photon pairs are coupled into an optical fiber. Two circulators and two fiber Bragg gratings (FBG) separate the pairs according to its wavelength. The first FBG reflects only the photons at 1573.0 nm (Δλ=1.0 nm) and allows for the rest of the photons to be transmitted, while the second FBG reflects the photons at 1567.8 nm (Δλ=1.0 nm). The rest of the photons are not transmitted. The photons are sent to their respective receiving stations through standard communication optical fibers. Although the photons wavelength was chosen to be very close to the third telecommunication window at 1550 nm, there were still around 8 dB of losses in each of the fibers linking the source with the detectors, concentrated mainly at the connectors between different fibers.

![Experimental setup](image.png)

Fig. 4. Experimental setup. See text for a detailed description.

The source is situated in Geneva and sends the pairs to two receiving stations situated in two villages (Satigny and Jussy) in the Geneva region, at 8.2 and 10.7 km, respectively. The beeline distance between them is 18.0 km. At each receiving station, the photons pass through a Michelson interferometer with a long arm and a short arm. The path-length difference is 1.3 ns and is the same in both interferometers. It is also smaller than the coherence length of the pump laser, so an entangled state can be detected when both photons pass through the short (or long) arms. Because the photons are entangled, the probability that pairs of photons choose the same output port can be affected by changing the phase in either interferometer. This will produce interference fringes in the coincidence count when the phase is scanned. To scan the phase, the temperature of one of the interferometers is changed while the other is kept stable.

To compensate for birefringence effects in the arms of the interferometers (i.e. to stabilize polarization), Faraday mirrors (FM) are used [9].

After passing through the interferometers, the photons are detected by single-photon InGaAs avalanche photodiodes (APDs) (id Quantique, id200). The photodiodes are operated in the gated mode with a repetition frequency of 1 MHz and a gate width of 100 ns. The quantum efficiency is 10% and the dead time is 10 µs. They are triggered in a synchronized way using the same signal sent out from Geneva through other optical fibers. This greatly improves the number of coincidences per unit of time.

Each time the single-photon APDs detect an event, an optical signal is sent back to Geneva, where it is detected by a p-i-n photodiode. For this, we used the same fibers that were used to send the trigger signal to the APDs. The lasers at both ends of the fibers had different wavelengths (1550 nm and 1310 nm) and Wavelength Division Multiplexers (WDM) were used to separate the signals. The detected events are sent to a time-to-amplitude-converter (TAC) that takes one of the signals as start and the other as the stop, measuring the difference in their arrival times. Coincidences in the arrival times between events coming from different detectors indicate that those photons passed either through the short-short or the long-long paths in the interferometers. Using a discriminator with a narrow window, the other two non-interfering possibilities (photons that passed through different arms − short-long or long-short paths) can be discarded.

We monitored the single photon count rates for each detector and the coincidence rate while scanning the phase δ in one of the interferometers. We make the temperature of one interferometer decrease slowly but regularly between 40°C and 21°C during a period of several hours. The coherence length of the single photons was 2.47 · 10^{-3} mm, 2 orders of magnitude smaller than the path-length difference in the interferometers (267 mm), so there was no single photon interference, and no phase-dependent variations in the single rates were observed. On the contrary, the coincidence rate showed a sinusoidal oscillation dependent of the phase change in the interferometers. The measured single count rates were 5.0 and 4.1 kHz, including 0.7 and 1.1 kHz of dark counts, for the detectors at Satigny and Jussy, respectively. A discriminator window of 600 ps placed around the coincidence peak gave us an average coincidence rate of 33 coincidence/min.

The Bell inequalities set an upper bound for correlations between particles that can be described by classical theories. One of the most frequently used forms is the Clauser-Horne-Shimony-Holt (CHSH)
Bell inequality [10], which has a Bell parameter
\[ S = |E(d_1, d_2) + E(d_1', d_2') - E(d_1', d_2) - E(d_1, d_2')| \leq 2 \]
(2)
where \( E(d_1, d_2) \) are the correlation coefficients and \( d_1, d_2 \) are values for the phase in the interferometers. Quantum mechanics predicts a maximum value of \( S = 2\sqrt{2} \). If the correlation coefficient \( E \) is described by a sinusoidal function like \( E = V \cos(\delta) \) where \( \delta \) is the relative phase in the interferometers and \( V \) is the visibility, the parameter \( S \) becomes \( S = 2\sqrt{2}V \). This implies that if the visibility is \( V \geq 1/\sqrt{2} \) the correlations between detected photons must be of quantum origin.

We are interested in the best visibility value obtained over a period of more than one fringe. To obtain an optimal visibility, it is important to have less than 0.1 pairs/window in order to reduce the probability of having a double pair. The number of photons pairs after the FBGs was 2.6 \cdot 10^7 \text{ pairs/s} or 0.0156 pairs/window. The raw data yields a visibility of \( V_{\text{raw}} = (90.5 \pm 1.5)\% \) (see Fig. 5) leading to \( S_{\text{raw}} = 2.56 \pm 0.04 \), surpassing the limit given by the Bell inequalities by 13 standard deviations (\( \sigma \)). We can conclude that the correlations between the photons remain well above the classical limit even when the gravitational field is being modified by the displacement of the masses.

5. A. Kent, gr-qc:0507045.
8. Diósi equation gives a value for \( t_D \) that is bigger by a factor of 2 with respect to the value given by Penrose equation.