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5-μm vertical external-cavity surface-emitting laser (VECSEL) for spectroscopic applications

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Abstract Mid-IR tunable VECSELs (Vertical External-Cavity Surface-Emitting Lasers) emitting at 4–7 μm wavelengths and suitable for spectroscopic sensing applications are described. They are realized with lead-chalcogenide (IV–VI) narrow band gap materials.

The active part, a single 0.6–2-μm thick PbTe or PbSe gain layer, is grown onto an epitaxial Bragg mirror consisting of two or three $Pb_{1-y}Eu_yTe/BaF_2$ quarter-wavelength layer pairs. All layers are deposited by MBE in a single run employing a BaF_2 or Si substrate, no further processing is needed. The cavity is completed with an external curved top mirror, which is again realized with an epitaxial Bragg structure. Pumping is performed optically with a 1.5-μm laser.

Maximum output power for pulsed operation is currently up to >1 W_p at -173°C and >10 mW at 10°C. In continuous wave (CW) operation, 18 mW at 100 K are reached. Still higher operating temperatures and/or powers are expected with better heat-removal structures and better designs employing QW (Quantum-Wells).

Advantages of mid-IR VECSELs compared to edge-emitting lasers are their very good beam quality (circular beam with $<1°$ cone diameter), simple structure, and their easy tunability without mode-hopping. Wavelengths ranging from <3 μm up to >15 μm are accessible with $Pb_{1-y}X_yZ$ (X = Sr, Eu, Sn, Z = Se, Te) and/or including QW.

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1 Introduction

Vertical external-cavity surface-emitting lasers (VECSEL) are currently of high interest and exhibit attractive properties like narrow beam divergence and wavelength tunability [1–3]. They are often optically pumped, and their high power and power scalability are unmatched by other techniques. Most VECSEL described up to now emit in the 800–2400 nm IR-region and are realized with GaAs or GaSb based lattice-matched structures. GaSb based interband cascade lasers [4] as well as quantum cascade lasers are suited for still longer wavelengths [5], however, they are edge emitters with corresponding very astigmatic high divergence angles.

We recently reported optically-pumped VECSELs emitting at wavelengths up to as long as 5.5 μm [6–9]. The devices were realized with narrow bandgap IV–VI (lead-chalcogenide) materials. The structures consisted of a flat bottom 2–3 pair Bragg mirror with $Pb_{1-y}Eu_yTe$ quarter-wavelength ($\lambda/4$) layers for the high-index, and BaF_2 ($n = 1.45$) or EuTe ($n = 2.4$) for the low-index material, a curved top mirror, and a PbTe or PbSe based active layer. Note that an optical design has always to be done for a certain temperature range of operation due to the considerable shift of emission wavelength with temperature T (the wavelengths, unlike III–V materials, decrease with increasing T).

Here, we describe three improved structures. Two of them lase up to or even above RT, and one is designed with QW. Growth on a Si-substrate (which is even lattice- and thermal expansion-mismatched) yields to a record emission power of >1 W_p.

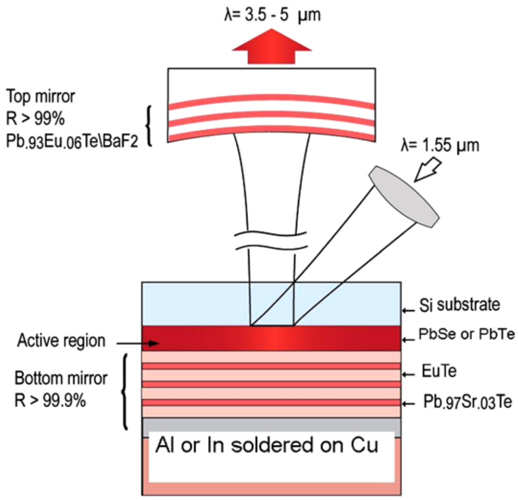

Fig. 1 Schematic representation of a IV–VI (lead chalcogenide) mid-IR VECSEL with resonant design

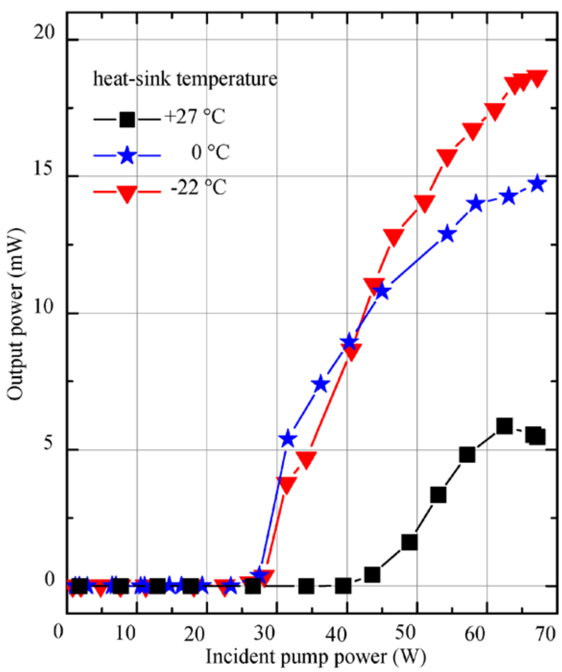

Fig. 2 Light in/light out characteristics at three different temperatures for a *RT* PbSe mid-IR VECSEL when pumped with a 1.55 µm wavelength laser. Note that the absorbed pump power is only about 60% of the incident power

2 Experimental

Figure 1 shows a typical cross section of a IV–VI mid-IR VECSEL. The active layer and one Bragg mirror are grown by solid-state molecular beam epitaxy (MBE) on a BaF_2 or Si substrate. The transparent substrate is located inside the cavity, and a heat spreader (evaporated Al, or, more efficient, a Cu-heat sink onto which the sample is In-soldered) is employed. A curved top mirror ($r = 25$ mm) completes the cav-

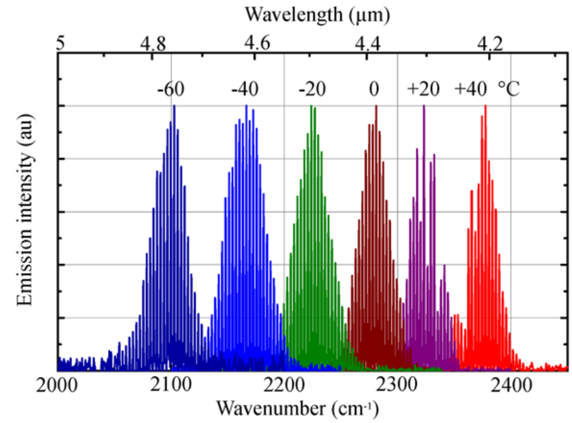

Fig. 3 Laser spectra at different temperatures for a *RT* PbSe mid-IR VECSEL. Each spectrum is individually normalized

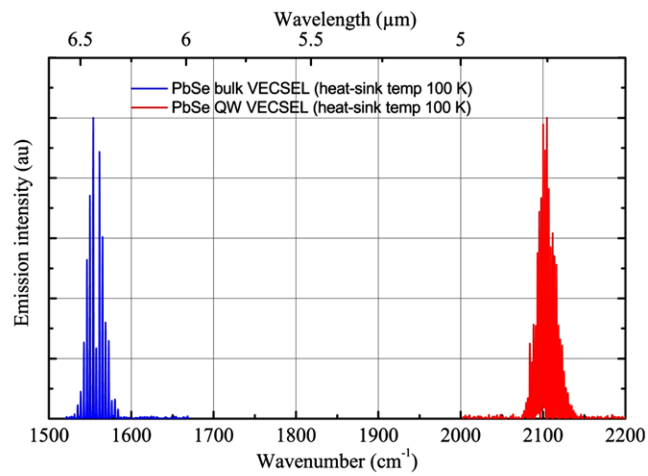

Fig. 4 Normalized laser spectra at 100 K for a QW PbSe mid-IR VECSEL (*right*) in comparison to a "bulk" PbSe active layer (*left*)

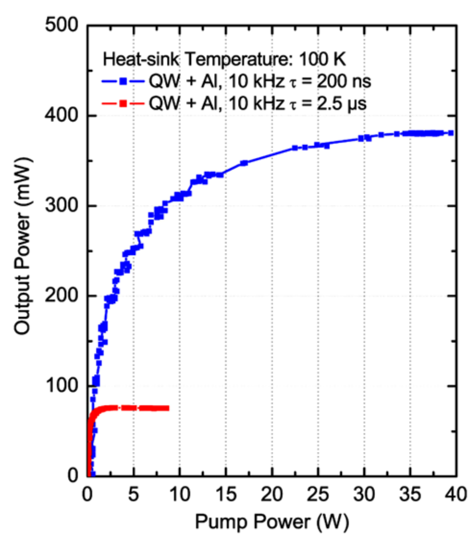

Fig. 5 Light in/light out characteristics for a QW PbSe mid-IR VECSEL when illuminated with a 1.55 µm wavelength laser. Note that the absorbed pump power is only about 60% of the incident power

ity. Pumping is done optically with a 1.55-μm or 2-μm pump laser with a beam focused to ∼200 μm diameter. While high-power 1.55-μm lasers are easily available, this is not yet the case for GaSb based 2-μm lasers. However, the quantum deficit is lower, leading to lower pump power at 2 μm pump wavelength. Spectra are recorded with a Bruker FTIR spectrometer.

2.1 Above *RT* PbSe on BaF_2-substrate VECSEL

A resonant design with a one-wavelength thick active PbSe layer was employed. Contrary to our earlier designs, the design thickness was chosen for intended room-temperature operation (the design in Ref. [6] on a BaF_2 substrate was for cryogenic operation). Figure 2 shows light in/light out characteristics and spectra around *RT* when illuminated with 100 ns pulses with 10 kHz repetition frequency [8]. Emission is multimode with a spacing between the lines corresponding to the optical thickness of the substrate (Fig. 3). Note the broad temperature tuning range, 4.8–4.2 μm for heat sink temperatures of −60°C to +40°C. This is due to the huge temperature coefficient of the band gap of narrow gap lead chalcogenides.

2.2 QW PbSe on BaF_2-substrate VECSEL

Quantum wells (QW) have lower threshold with respect to bulk layers and blue-shift the emission wavelengths, the amount of the shift depends on the width of the wells. Figures 4 and 5 show an example. Five PbSe QW, each ∼8 nm thick, are embedded in a $Pb_{.95}Eu_{.05}Se$ host of (in total) one-wavelength optical thickness near the maximum value of the

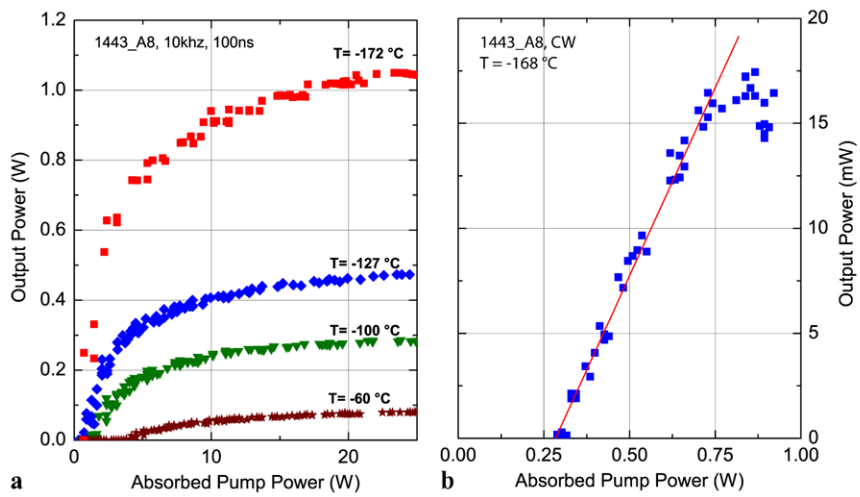

Fig. 6 Light in/light out characteristics at different temperatures for a PbTe-on-Si mid-IR VECSEL when pumped with a 1.55 μm wavelength laser (corrected for optical losses in the power measurement set-up). **a** Pulsed excitation with 100 ns pulses and 10 kHz repetition frequency, **b** CW excitation

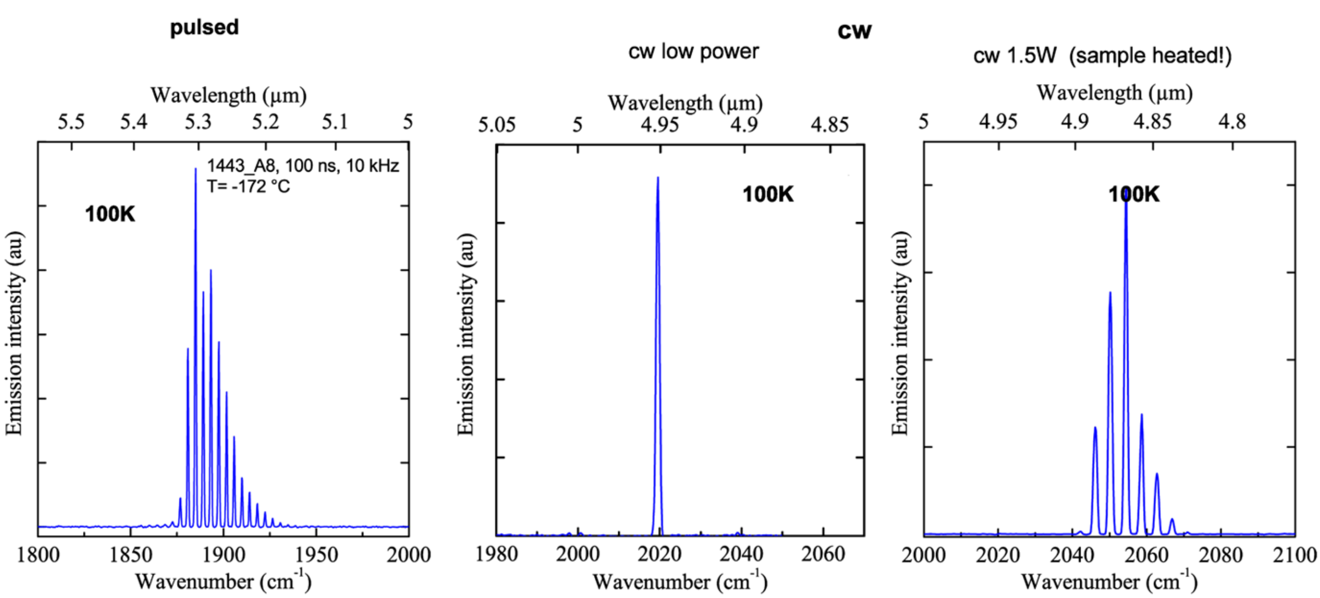

Fig. 7 Normalized laser spectra at 100 K for a PbTe-on-Si mid-IR VECSEL

standing electric wave (i.e. at half of the layer thickness). The structure is designed for 100 K operating temperature and grown on a BaF_2 substrate. Up to >600 mW_p output power is achieved at ∼ 100 K, while threshold pump power is as low as 200 mW. Laser emission is at ∼4.5 µm wavelength at this temperature. The corresponding wavelength for a VECSEL with "bulk" PbSe active layer at the same temperature is ∼6.5 µm (Fig. 4), the blue-shift therefore amounts to ∼1.7 µm. Threshold power is below ∼0.2 W, and lasing occurs up to 170 K heat sink temperature [9].

2.3 PbTe VECSEL on Si-substrate with 1.1 W output power

A better heat removal, leading to higher output power, is expected when growing on a Si substrate, which has much better heat conductance than BaF_2. PbTe was applied as active layer with an optical thickness of one wavelength at 130 K operation temperature [10]. Indeed, at 100 K operating temperature, emission power is up to 1.1 W_p when illuminated with 100 ns pulses (Fig. 6a). In CW operation, up to 18 mW are observed before thermal rollover occurs (Fig. 6b). Spectra are multimode with high-power excitation, but monomode for low power. Figure 7 (left) shows a spectrum at 100 K with pulsed excitation, while in Fig. 7 (right) spectra with CW excitation are shown. Note the blue-shift due to the increased heating (positive temperature dependence of the bandgap) when switching from pulsed to low power CW and (still more pronounced) high-power CW operation. The structure lases up to 0°C. In a similar structure, but with a thinner PbTe active layer corresponding to one wavelength at *RT*, lasing occurs up to 25°C (Fig. 8).

3 Conclusions

The first VECSELs for the mid-IR range are described. They emit at 3.6–6.5 µm, CW up to 170 K, and above *RT* in pulsed-mode operation. The devices are fabricated employing lead chalcogenides (IV–VI narrow band gap semiconductors) rather than III–V materials.

Advantages of VECSELs are their good beam quality (circular emission cone with ∼1° aperture angle), their very simple structure, easy and large wavelength tuning, and power scalability. This is in contrast to the well-known mid-IR quantum cascade lasers, which are edge emitters with corresponding very wide astigmatic emission angles and consist of a complicated arrangement of 100's of individual layers. Mid-IR VECSELs are therefore extremely well suited sources for spectroscopy.

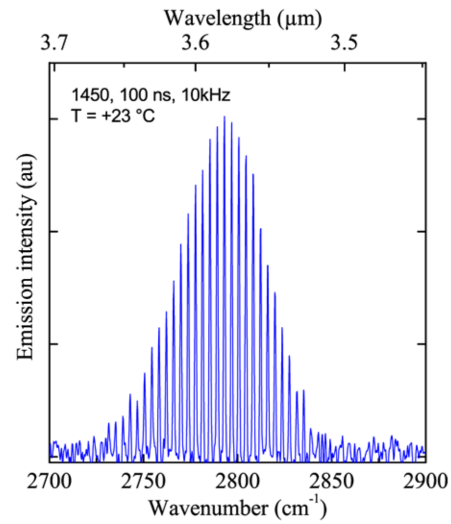

Fig. 8 Normalized laser spectra at *RT* for a PbTe-on-Si mid-IR VECSEL

RT CW operation is possible when employing improved heat spreaders like diamond. This technique is already developed for III–V based VECSELs with wavelength up to 2.*x* µm [2]. With the typical pump powers needed in the IV–VI samples shown above, a temperature rise of 20–40°C is calculated by stationary heat flow simulations when bonded to diamond substrates. Therefore, *RT* CW emission is expected when employing this technology.

Other wavelengths ranging from <3 µm up to >15 µm are accessible by using ternary active layers like $Pb_{1-z}X_zY$ (Y = Se or Te) where X = Eu or Sr for shorter, and X = Sn for longer wavelengths with respect to the binary compounds. As described above, QW blue-shift the emission and at the same time lead to still lower thresholds.

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