

3–4.5 μm continuously tunable single mode VECSEL

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Abstract We present continuously tunable Vertical External Cavity Surface Emitting Lasers (VECSEL) in the mid-infrared. The structure based on IV–VI semiconductors is epitaxially grown on a Si-substrates. The VECSEL emit one single mode, which is mode hop-free tunable over 50–100 nm around the center wavelength. In this work, two different devices are presented, emitting at 3.4 μm and 3.9 μm , respectively. The lasers operate near room temperature with thermoelectric stabilization. They are optically pumped, yielding an output power $>10 \text{ mW}_p$. The axial symmetric emission beam has a half divergence angle of $<3.3^\circ$.

1 Introduction

The mid-infrared (MIR) wavelength region is highly interesting for spectroscopic applications due to strong absorption lines of many gases. Despite the potential, only few applications are commercially realized up to date, mainly caused by the lack of available and affordable laser sources.

Lasers based on III–V semiconductors cover the whole MIR. The maximum wavelength reached with edge emitting diode lasers based on III–V QW structures is up to 3.7 μm [1]. The spectroscopically interesting wavelength region above 3 μm is also covered by cascade lasers. Quantum cascade lasers (QCL) work best at wavelengths around 4–10 μm . Although QCL with emission wavelengths around

3 μm are reported [2], they are not commercially available. Interband cascade lasers (ICL) on the other side emit at wavelengths from 3 to 5.7 μm at RT.

But aside from emission wavelengths, lasers suited for spectroscopic absorption measurements should provide a narrow linewidth, sufficient output power, operation near room temperature (RT) and a wide tuning range. A broad wavelength tuning allows the detection of large molecules like propane as well as the detection of background absorption, leading to higher sensitivities and robustness in a not perfectly controlled environment. Because broad wavelength tuning for edge emitting lasers is achieved with an external cavity, this leads to a significant price increase, which hinders the commercial realization of many spectroscopic applications.

We present an alternative laser technology to access the wavelength region above 3 μm . The continuously tunable Vertical External Cavity Surface Emitting Lasers (VECSEL), based on IV–VI semiconductors, emit a single mode in a wavelength range between 3.0–4.5 μm . This single emission-mode is continuously tunable without mode hops over 50–100 nm at constant operation temperature. The pulsed output power at RT is $>10 \text{ mW}_p$. The far field emission is of almost perfect Gaussian shape with an half divergence angle of $<3.3^\circ$.

2 Structure

Our VECSEL are based on narrow gap IV–VI semiconductors. PbTe and PbSe have a direct band gap of approximately 300 meV at RT. Due to direct band transitions no complicated layer structures are needed as used for QCL. The structure of the VECSEL is shown in Fig. 1. On a silicon substrate, a 4 pair PbEuTe/EuTe Bragg mirror followed by the

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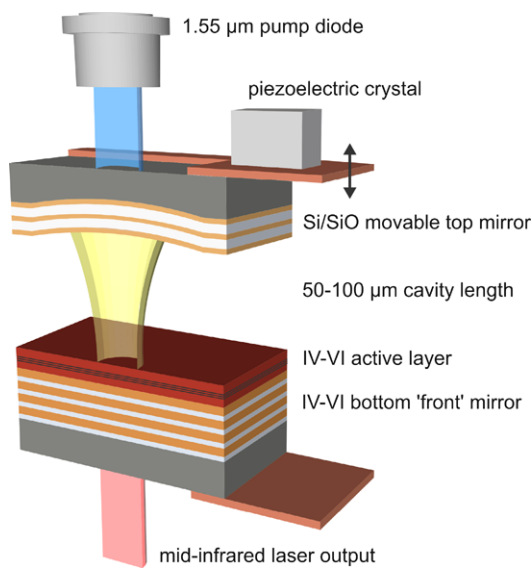


Fig. 1 Structure of the continuously tunable VECSEL without polyimide or chromium aperture

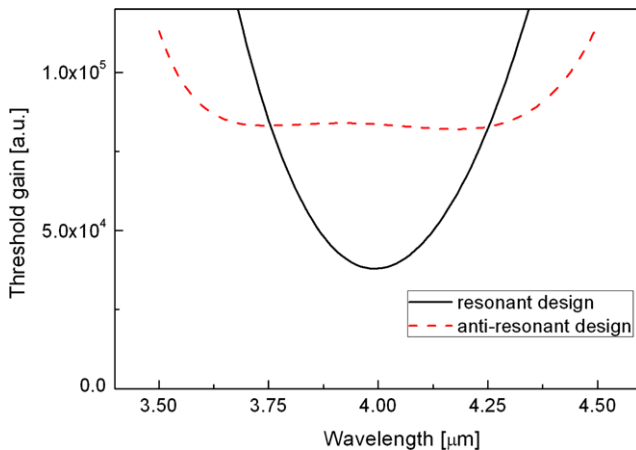


Fig. 2 Threshold gain for resonant and antiresonant design (with antireflection layer on the active layer). Due to favorable lasing conditions in a narrow wavelength region, the resonant structure is chosen

active layer are grown by Molecular Beam Epitaxy (MBE). The active layer consists of PbSe QW in PbSrSe. The center emission wavelength is determined by the thickness of the QW and the material composition of the host. A total wavelength range from 3.0 to 4.5 μm is covered at RT. The top curved Bragg mirror is made of 6 pairs of alternating Si/SiO layers. The VECSEL is optically pumped on axis through this external mirror. By alternating the thickness of individual Si/SiO layers, the transmission at the pump-wavelength of 1.55 μm is optimized without an observable decrease of the reflectivity at the output wavelength. The flat bottom Bragg mirror is used as the output coupler.

To reach single-mode emission, only one longitudinal mode must be supported by the gain. This is done by in-

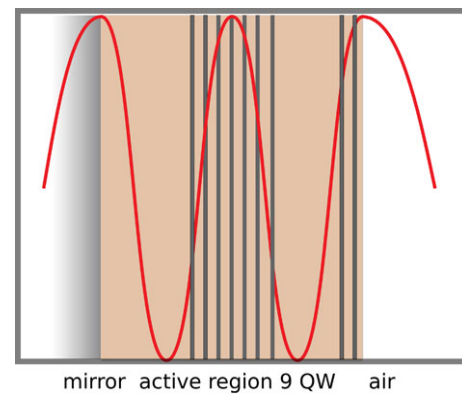


Fig. 3 Schematic drawing of $|E|^2$ along the active layer. The QW are placed at the center and near the surface, where the intensity of the electric field is high

creasing the free spectral range, the distance between two longitudinal modes, with a ~ 50 μm short cavity.

To suppress additional transversal modes, the surface of the active layer is covered with a structured polyimide or chromium layer. These apertures precisely define the lasing region and increase losses for higher order transversal modes due to their larger beam diameter. As a result, a single TEM₀₀ mode is emitted.

Continuous tuning is achieved by mounting the top curved mirror on a movable piezo driver. By applying a voltage, the cavity length, and thus the emission wavelength changes. This mechanic tuning allows full spectral scans at a kHz repetition rate.

3 Active layer

The first continuously tunable single-mode VECSEL realized in our group was based on a homogeneous bulk PbTe layer [5]. It is cryogenically cooled with a maximum operation temperature of 170 K. A large wavelength range from 4.7 to 5.6 μm is covered with just one laser device. Its single emission mode is tunable over more than 100 nm around 5.2 μm. By using active layers based on PbSe QW in PbSrSe host material, single-mode operation near RT has been achieved [6]. The maximum operation temperature for multimode emission so far is >50 °C [7].

The active layer of the VECSEL described in this work is one optical wavelength thick. No anti-reflection (AR) coating is employed. This resonant design increases the intensity of the standing electric field inside the active layer and leads to decreased threshold power values [3, 4]. But this favorable condition is only valid over a narrow wavelength range, as shown in Fig. 2. There the threshold gain (without internal losses) is shown as function of wavelength. The narrow minimum of g_{thr} is caused by the subcavity formed by the active layer. If the optical thickness of the active layer matches

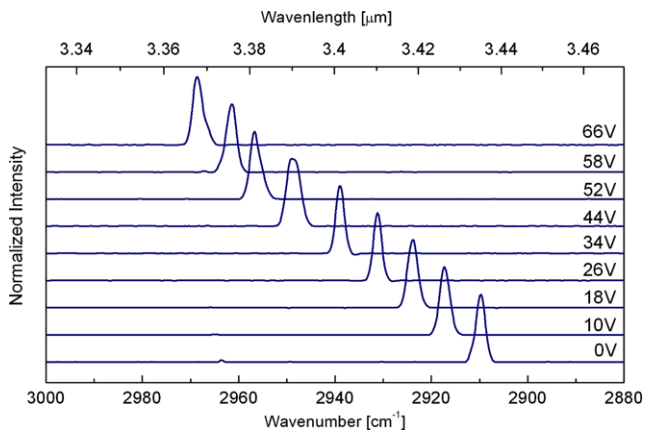


Fig. 4 Normalized emission spectra at different piezo-voltages for device I (4.5 nm thick QW). A wavelength-region of 60 nm is continuously covered around 3.4 μm

the output wavelength, the quality factor (Q -factor) of the whole cavity increases, leading to high electric fields inside the active layer and low g_{thr} . By changing the temperature, the bandgap energy of PbSe changes much stronger than the refractive index. Thus, the optical thickness of the active layer and the output wavelength don't match anymore. This leads to partially destructive interference of the cavities, to a decreased electric field and in consequence to deteriorated lasing conditions.

To further maximize the effective gain, the QW are placed where the standing electric field is high. This is at the center and the edges of the layer (see Fig. 3). Because of the optical pumping, the pump beam intensity and, therefore, the carrier generation rate is the highest near the front surface. Thus, the QW are located at the center and near the surface of the active layer to distribute the generated carriers evenly among the QW.

4 Results

Two different VECSEL designed for different emission wavelengths are presented. They differ in the number of QW and QW thickness. For device I, the QW are 4.5 nm thick. Seven QW are placed at the center and four near the surface of the active layer. Device II contains seven QW with 9.5 nm thickness. All QW are placed at the center of the active layer. For both devices, the PbSrTe barriers are 15 nm wide.

In Fig. 4, the normalized emission spectra of device I with 4.5 nm thick QW are shown. At a constant temperature of 250 K, the voltage applied on the piezoelectric-driver varies from 0 V to 66 V. This causes a change of the cavity-length, corresponding to a continuous shift of the emission wavelength from 3.44 to 3.37 μm .

Device II contains seven QW, each 9.5 nm thick. At 250 K, the emission wavelength is around 3.9 μm . The

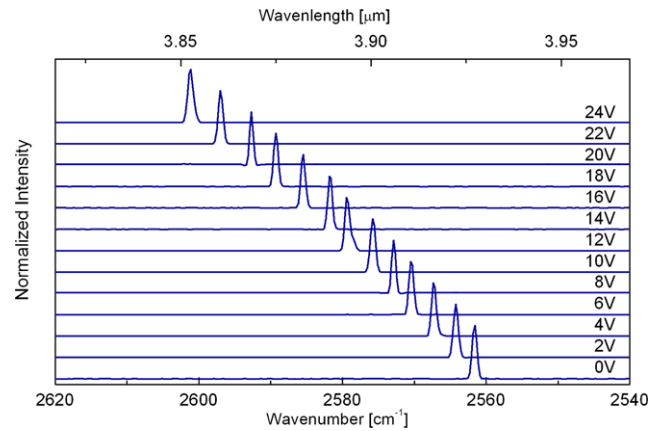


Fig. 5 Normalized emission of device II spectra around 3.9 μm for different piezo-voltages

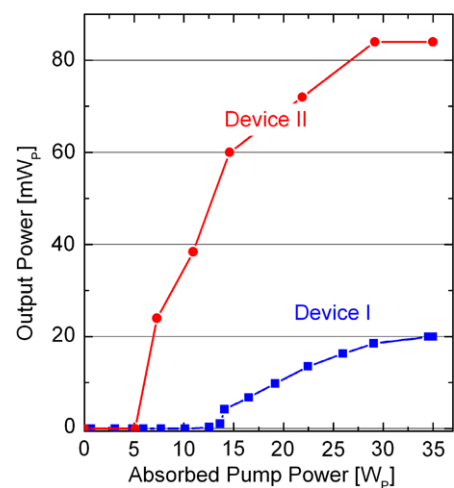


Fig. 6 Power in / power out measurements for device I with 4.5 nm thick QW and device II with 9.5 nm thick QW

normalized emission spectra at different piezo-voltages are shown in Fig. 5. The result is a 70 nm wide tuning range of one single mode around 3.9 μm , which can be further increased with a shorter cavity-length.

To eliminate influences of the external Si substrate on the output power, a wedge with an angle of 2° is grinded into the bottom of the Si substrates. However, the output power is not constant over the whole tuning range. This is mainly caused by the gain profile, which height changes with energy. Aside of the inhomogeneous gain-profile, there are further variations of the output power. These fluctuations could be caused by interference effects with the substrate of the external mirror.

Power in / Power out measurements were done for both devices at the maximum of the gain profile at 250 K and shown in Fig. 6. For device II, a maximum output power of 90 mW_p is measured with a threshold power of 5 W_p . With device I, a maximum output power of $\sim 20 \text{ mW}_p$ is reached, while the threshold power increases to 13 W_p . The dete-

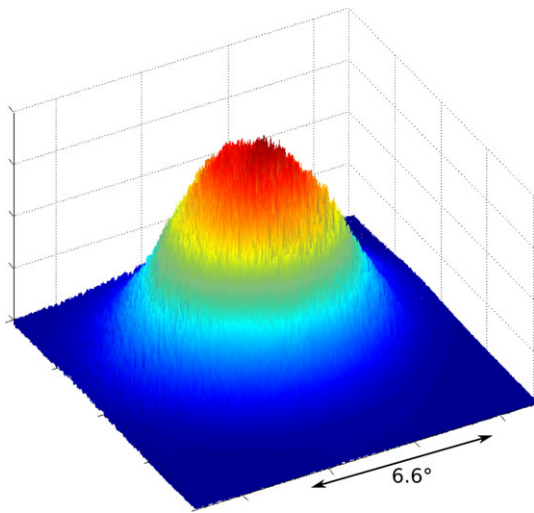


Fig. 7 Beam profile of the TEM₀₀ mode

rioration of the lasing characteristics with decreasing QW thickness was also observed for VECSEL with 25 mm long cavity and may be caused by:

1. Thermal leakage effect: the thinner the QW are, the stronger is the blueshift of the levels and the higher are the losses by thermal excitation of carriers. This can only partially be compensated by higher barriers, because a higher Sr content in the PbSrSe barrier decreases the crystalline quality noticeably [7].
2. Decreased total thickness of the gain medium: because the region, where QW are placed is limited, the total thickness of the gain medium $N \cdot d_{\text{QW}}$ (N is the number of QW, d_{QW} is the QW thickness) is reduced for thinner QW with comparable barrier thicknesses.
3. Decreased crystalline quality: With Sr content of 7 % in PbSrSe, the lattice constant changes by 0.1 % with respect to PbSe. Although the lattice mismatch is rather small, it could impede a high crystalline quality for very thin PbSe layers.

One of the advantages of the VECSEL structure is the circular output cone with low divergence angles [8]. Figure 7 shows the TEM₀₀ mode with half divergence angle $\Theta = 3.3^\circ$. With the parameters of the cavity (cavity-length = 66 μm , radius of the top curved mirror = 50 cm) an $M^2 = 4.3$ is estimated. This value is larger compared to earlier results ($M^2 = 1.14$ [5]) caused by the diffraction due to the aperture. However, the divergence angle is still low and therefore favorable for spectroscopic applications.

The linewidth of the laser was determined using the previous setup operating at low temperatures [5]. There the active region was just a bulk layer. No influence on the FWHM is expected compared to the here used QW structures. A sweep scan across a water line in ambient air at normal pressure was performed. Calculating back from the measured absorption spectrum a FWHM of $<0.05 \text{ cm}^{-1}$ was estimated. This value is an upper limit, as the features of the absorption line were reduced significantly due to the peak broadening at atmospheric pressure.

All of the results shown above are measured in pulsed mode. The reason is a short carrier lifetime of 0.1 ns. With an increased crystalline quality of the host material CW operation is within reach.

5 Summary

In conclusion, we presented a novel continuously tunable single-mode VECSEL. Based on PbSe QW in PbSrSe, any wavelength between 3.0 μm and 4.5 μm can be realized and, therefore, any absorption line in this wavelength region can be targeted. While keeping the operation temperature and the pump power constant, continuous tuning of the single emission mode is done by moving the external mirror. A tuning range of 50–100 nm is realized with a repetition rate of several kHz. The output power is in the mW_p range. The half beam divergence angle is below 4° . In addition with a compact setup and operation around RT, this VECSEL is especially well suited for spectroscopic applications.

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