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Wavelength-tunable, GaSb-based, cascaded type-I quantum-well laser emitting over a range of 300 nm

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***Abstract*—We present a wavelength-tunable, external-cavity GaSb-based quantum-well laser operating near 3.2 µm. The laser setup consists of an intra-cavity grating in Littman-Metcalf configuration and a cascade pumped GaSb-based gain chip with a narrow-ridge waveguide. The narrow-ridge waveguide has a length of 2 mm and width of 7.5 µm. Cascade pumping is realized with three type-I quantum-wells, using one quantum-well per cascade stage. The laser provides continuous-wave output powers up to 8 mW and slope-efficiencies of 13 % at room temperature. Laser operation is demonstrated over a wavelength range of more than 300 nm, using continuous-wave and pulsed operation regimes.**

***Index Terms*—Semiconductor lasers, quantum well lasers, laser tuning, mid-infrared.**

I. Introduction

WAVELENGTH tunable, continuous wave (CW) lasers operating in the mid-infrared (mid-IR) range have been actively investigated in the last two decades. A wide range of commercial devices is available and used for various applications in industry and science, including medical diagnostics, molecular spectroscopy, and industrial process control. Tunable mid-IR lasers are most extensively used for trace-gas sensing applications, such as environmental monitoring, clinical breath analysis, and atmospheric sensing [1], [2]. Several approaches to extend wavelength-tuning ranges, increase output powers, and access new wavelength regions have been demonstrated, including nonlinear frequency conversion, Cr-doped crystal lasers, fluoride fiber lasers, quantum-cascade lasers, and GaSb-based diode lasers [2]–[9].

GaSb-based type-I quantum-well (QW) diode lasers are promising sources for the realization of tunable mid-IR lasers. They extend the wavelength range accessible with diode-based laser systems and allow for straightforward integration into compact, portable devices for mid-IR applications. The laser emission at room temperatures is adjustable from 1.9 µm to 3.7 µm [8], [9] and is suitable for the detection of water vapor, methane, and carbon dioxide. The wavelength range of 2.9 µm to 3.7 µm covers the stretching region of C-H bonds and is of particular interest for spectroscopy. In this wavelength region, cascaded GaSb-based lasers provide significantly higher output powers than quantum-cascade laser counterparts [2]. CW output powers of up to 960 mW at room temperature have been demonstrated from GaSb-based, multi-mode edge-emitters [9].

The recent demonstrations of cascade pumping in GaSb-based quantum-well lasers have resulted in improved efficiencies and a more than two-fold increase in achievable output powers [9], [10]. Cascade pumping of GaSb-based type-I quantum wells allows for efficient carrier recycling between QW stages and results in internal efficiencies of more than 100 %, thereby increasing output powers and slope-efficiencies.

In this publication, we investigate the wavelength-tunability of a cascade-pumped, GaSb-based, type-I quantum-well laser emitting around 3.2 µm. We demonstrate laser emission over a wavelength range of more than 300 nm under CW and pulsed regimes of operation. This is the broadest wavelength-tuning range achieved with a GaSb-based laser, so far. It is three times broader than the tuning ranges obtained with comparable quantum-cascade-lasers emitting at wavelengths near 3 µm [6].

II. Experimental setup

The wavelength-tunable laser setup uses an edge-emitting, cascade-pumped, GaSb-based, type-I QW laser. The heterostructure of the cascade quantum well laser (CQW) is illustrated in Fig. 1(a). In the cascade pumping scheme, the free-carrier electrons are recycled after each QW to improve laser efficiency. This is realized with compositionally graded AlGaAsSb sections and chirped InAs/AlSb superlattices between the QWs. After each QW, superlattices transfer the electrons from the valence band of one QW to the conduction band of the following QW. The graded AlGaAsSb sections between QWs act as electron-barriers and confine electrons inside the QWs. Further details on the heterostructure design and its impact on laser performance are discussed in [9], [10].

The layer structure and waveguide design of the CQW laser are illustrated in Fig. 1(b). The CQW laser is grown on a Tellurium-doped GaSb substrate using solid source molecular beam epitaxy. The waveguide cladding is realized with two $Al_{0.80}Ga_{0.20}As_{0.07}Sb_{0.93}$ layers with thicknesses of 2 µm. The waveguide core consists of a 300 nm thick GaSb layer, three GaInAsSb QWs, and a 350 nm thick $Al_{0.30}Ga_{0.40}In_{0.30}As_{0.28}Sb_{0.72}$ layer. The QWs have a thickness

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of ~13 nm, indium composition of ~55 %, and compressive strain of ~1.5 %.

The straight-ridge waveguide has a length of 2 mm, a width of 7.5 µm, and is etched down to the interface between p-cladding and waveguide-core. An SEM-image of the cleaved waveguide-facet is shown in Fig. 1(c). One waveguide-facet is anti-reflection (AR) coated with a triple-layer Al_2O_3/Si/Al_2O_3 coating, resulting in a reflectivity of ~0.3%. The opposite waveguide-facet is coated with a single Al_2O_3 layer, providing a reflectivity of ~32 %. The CQW lasers used for this work were fabricated as described in [7].

The external-cavity setup used for investigation of wavelength-tuning is illustrated in Fig. 2. The CQW gain chip is mounted epi-side-up on a temperature stabilized copper heat sink. The reflecting waveguide-facet acts as 68 % output coupler. The laser light from both waveguide-facets is collimated with aspheric lenses (4.0 mm focal length, 0.56 NA). The lateral beam diameter after the collimating lens is estimated to 1.4 mm (assuming a slow-axis beam divergence of ~20°). Wavelength-tuning is realized with a 450 grooves/mm intracavity grating in Littman-Metcalf configuration (V-shaped cavity with arm lengths of ~25 cm), providing an estimated spectral feedback bandwidth of ~1.5 nm. The Littman-Metcalf configuration has been chosen to suppress side-lobes and modulations arising from the Fabry-Perot formed by the CQW waveguide-facets. The wavelength-tuning range of the laser was extended by variation of the operating temperature from 15 °C to 25 °C.

The laser spectra have been measured with a Horiba iHR550 monochromator and an amplified PbSe-detector in combination with a lock-in amplifier. The CW spectra have been recorded with a wavelength increment of 0.1 nm, sub-0.5 nm resolution (~0.5 cm^{-1}), and 30 dB signal-to-noise ratio. The pulsed operation spectra have been measured with sub-1 nm resolution. In all spectra, the contributions from self-lasing in the CQW waveguide (around 3200 nm) remained at relative power densities below -10 dB.

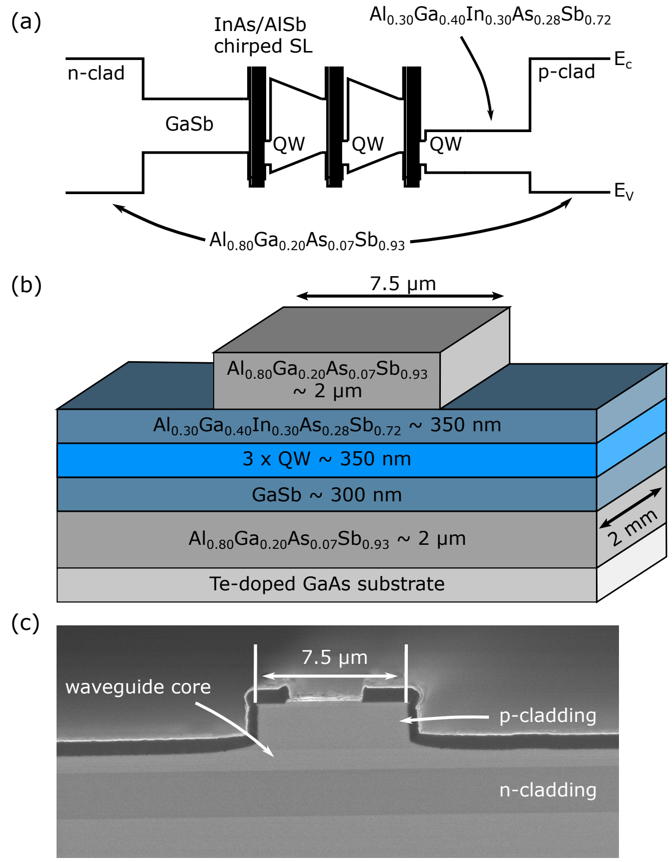

Fig. 1. Cascaded GaSb-based QW laser: (a) energy band schematic of the CQW heterostructure, (b) layer structure of the narrow-ridge waveguide, and (c) SEM-image of cleaved waveguide facet.

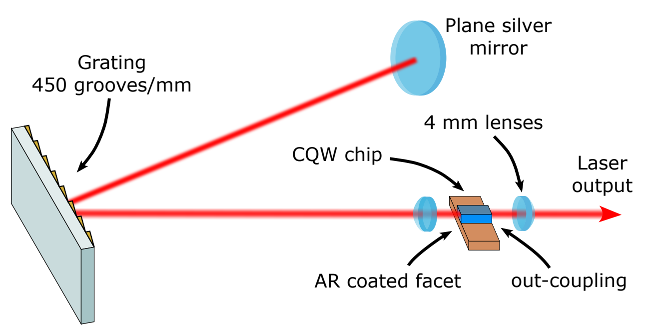

Fig. 2. Experimental setup of wavelength tunable GaSb-based QW laser.

III. Results

The LIV-characteristics of the CQW gain chip have been measured in an external-cavity without grating and spectral filtering. Fig. 3 shows the measured output power and forward voltage versus applied current at a constant temperature of 20 °C. The threshold for lasing is about 114 mA, output power saturation is observed for more than 360 mA of current, and the slope efficiency is 0.05 mW/mA. The CQW laser provides a maximum output power of 8.2 mW at a laser current of 360 mA and a voltage of 2.4 V. The inset in Fig. 3 show a typical output spectrum at the laser current of 360 mA. The spectrum has a bandwidth of more than 20 nm and is modulated with a period of ~0.7 nm. The modulation is caused by the Fabry-Perot filter formed by the waveguide facets.

Wavelength-tuning in CW operation is performed at a diode current of 360 mA. Fig. 4 plots the measured laser spectra and output powers over the achieved tuning range. At a constant operating temperature of 20 °C, the laser wavelength is tunable from 3065 nm to 3266 nm. The maximum output power of 8.0 mW is obtained at the wavelength of 3206 nm. The output power drops to 4.6 mW at 3065 nm and to 4.2 mW at 3266 nm. The tuning range is further extended by changing the operating temperature to 15 °C and 25 °C. At 15 °C, the laser wavelength can be tuned to 3051 nm with an output power of 3.4 mW. At 25 °C, laser emission at 3307 nm with an output power of 1.7 mW is achieved. In all measurements, the self-lasing of the CQW waveguide remained at relative power densities below -10 dB.

Fig. 5 shows the normalized laser spectra at 3056 nm, 3206 nm, and 3307 nm. The spectra have a sub-0.5 nm bandwidth (full-width at half-maximum), which is limit by the resolution of the measurement setup. The observed side-lobes

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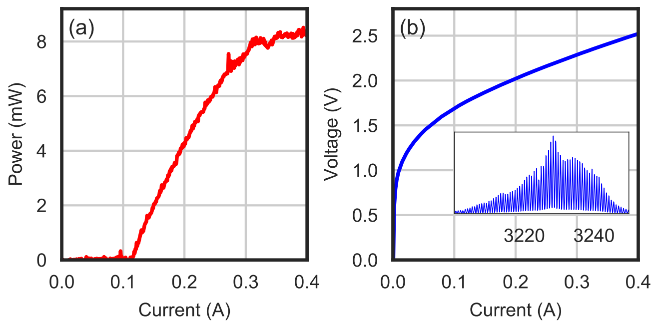

Fig. 3. LIV-characteristics of external-cavity CQW laser without intra-cavity grating: output power (a) and applied voltage (b) vs laser current. The inset shows the laser spectrum for a current of 360 mA.

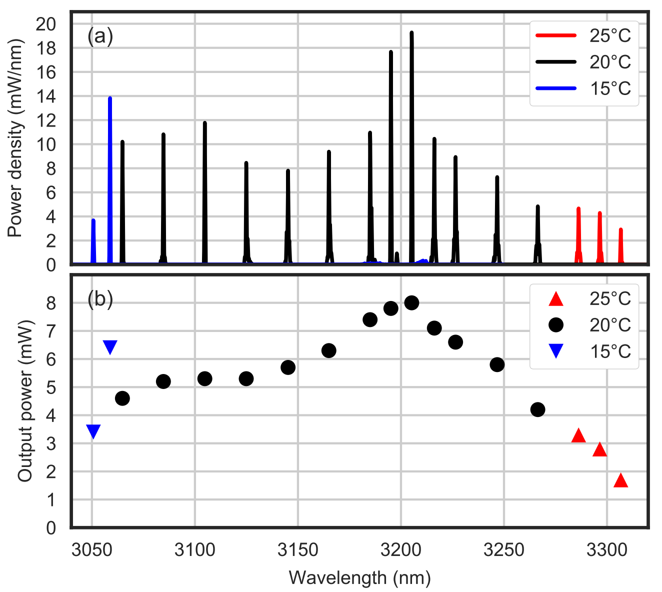

Fig. 4. Spectrum (a) and output power (b) at different laser wavelengths and operating temperatures.

result from Fabry-Perot modulations of the CQW waveguide, with an estimated modulation period of 0.7 nm.

Further temperature changes did not result in increased CW tuning-ranges in our setup. The laser operation range could be further extended to shorter wavelengths by use of pulsed operation. At 12 °C operating temperature, using 400 ns pulses with 1.8 A peak current and 10 kHz repetition rate, we obtained laser emission at 2986 nm. The corresponding spectrum is shown in Fig. 5 and has a bandwidth of 1.8 nm.

The presented results correspond to a CW wavelength-tuning range of 256 nm and laser operation over a range of 320 nm. The wavelength-tuning is limited by the onset of self-lasing in the CQW waveguide, indicating that broader tuning-ranges may be achieved by reducing the reflectivity of the AR-coated CQW waveguide facet.

IV. Conclusion

The wavelength-tuning of a cascade pumped, GaSb-based type-I QW laser in an external-cavity configuration has been investigated. A CW tuning range of 256 nm from 3056 nm to

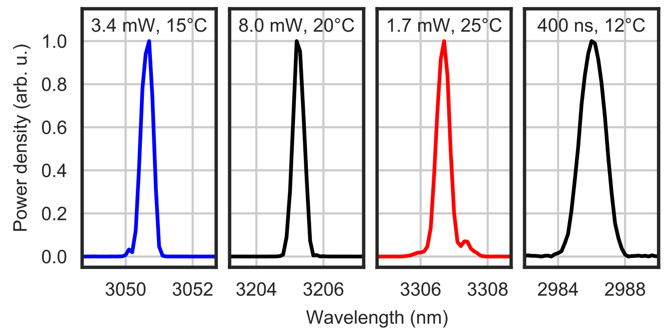

Fig. 5. Normalised spectra at the shortest CW wavelength, maximum output power, longest CW wavelength, and in pulsed operation (from left to right).

3307 nm, with output powers between 1.7 mW to 8.0 mW, has been demonstrated. Pulsed laser operation has been achieved at wavelengths down to 2986 nm, corresponding to laser operation (CW and pulsed) over a range of 320 nm. Further wavelength-tuning is limited only by the onset of self-lasing in the straight-ridge CQW waveguide. To the best of our knowledge, this is the broadest tuning range demonstrated from an edge-emitting, CQW laser, so far.

The achieved results highlight the potential of GaSb-based, cascade pumped, type-I quantum well lasers for the realization of broadly tunable mid-IR laser devices. Future work will be focused on the use of tilted ridge waveguide designs to reduce reflections from the AR-coated waveguide facet. This is expected to suppress self-lasing of the CQW waveguide, reduce spectral side-lobes, and further increase the wavelength-tuning range.

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