Widely tunable high-power external cavity quantum cascade laser operating in continuous-wave at room temperature

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A grating-coupled external cavity quantum cascade laser operating in continuous-wave at room temperature is reported. Single-frequency operation tunable over more than 160 cm^{-1} around the centre wavelength of 4.6 μm has been observed at a chip temperature of 300 K. The maximum optical power at the gain peak was 300 mW, corresponding to a wall-plug efficiency of 6%. Observed power output at the gain bandwidth edges was in excess of 125 mW.

The performance of quantum cascade lasers (QCLs) has recently undergone significant improvement with demonstration of output powers in excess of 1 W and wall-plug efficiencies of the order of 10% in continuous-wave (CW) at room temperature [1, 2]. However, such performances have so far been reported only for multimode Fabry-Pérot devices. To utilise these lasers in spectroscopic applications, it is important to control their output spectrum to provide single-frequency, tunable radiation. In this Letter, we report a tunable external cavity (EC) QCL [3–5] combining high performance and broad, continuous, single-frequency tuning.

The gain chip of our EC-QCL is based on a highly strained $In_{0.67}Ga_{0.33}As/Al_{0.64}In_{0.36}As$ active region grown by MOVPE on an InP substrate and processed in buried heterostructure geometry as described in [2]. The full width at half maximum of its gain spectrum was measured to be 265 cm^{-1} [2]. Selection of the chip dimensions resulted in a trade-off between output power and reliable tuning. To avoid lasing on multiple transverse modes, which would result in undesirable mode hops during single-frequency tuning, a 4.8 μm-wide ridge was chosen. According to our two-dimensional waveguide simulations, ridges of this width support only two transverse magnetic (TM) modes and the second one is strongly suppressed because of its weak confinement factor (0.55 against 0.72 for the fundamental mode). In addition, to ensure reliable selection of one single longitudinal mode at every grating position, we chose a 3 mm-long device the free spectral range of which was 0.51 cm^{-1}. The gain chip was mounted epi-side down on an AlN submount as described in [6] and its facets were left as cleaved.

Bias voltage, total optical power (including both facets), and wall-plug efficiency of the free-running gain chip, measured in CW operation at 300 K are displayed in Fig. 1. The threshold current was 230 mA, corresponding to a threshold current density $J_{th} = 1.60$ kA/cm^2, and the maximum power was 370 mW. The laser spectrum of the free-running chip, measured in CW at 300 K at a current of 400 mA, is displayed in the inset of Fig. 1.

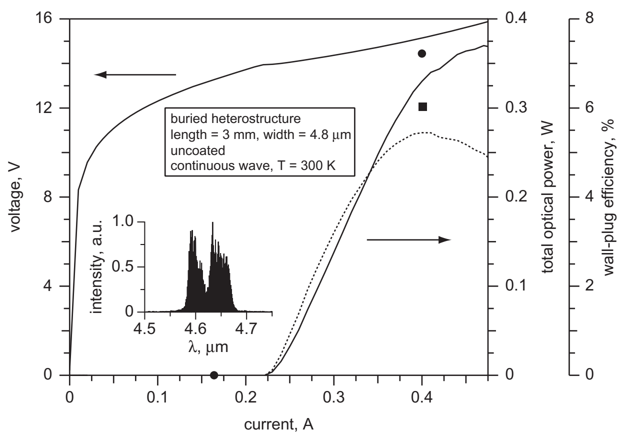

Fig. 1 *Voltage, total optical power, and wall-plug efficiency (dashed line) against injection current in CW mode at 300 K of gain chip used in study*

Solid disks mark threshold current and maximum optical power of EC-QCL at current of 400 mA. Solid square marks maximum wall-plug efficiency of EC-QCL at 400 mA. Optical power and wall-plug efficiency of EC-QCL corrected for lens collection efficiency

Inset: Fabry-Pérot spectrum of free-running gain chip

The gain chip was then incorporated in an external cavity setup consisting of an appropriately antireflection (AR) coated aspherical ZnSe lens with a clear aperture diameter of 4 mm and a 300 grooves/mm diffraction grating mounted in Littrow configuration. The output power was extracted from the facet opposite to the grating and collimated with a similar lens. The QCL threshold current decreased from 230 to 164 mA ($J_{th} = 1.14$ kA/cm^2) in the presence of the grating feedback. In spite of the strong mode selection of its narrow waveguide, the chip lased on a combination of transverse modes in the current range from ~420 mA to roll-over (470 mA). This behaviour was indicated by a current-dependent beam steering in this current range, a phenomenon which happens only in the presence of more than one transverse mode [7, 8]. Since beam steering was not observed for the free-running chip, we conclude that the grating feedback reduced mirror losses sufficiently for the second mode to reach threshold at high current. For this reason, tunability studies were performed at currents smaller or equal to 400 mA. The optical power against wavelength of the EC-QCL in CW at 300 K is displayed in Fig. 2. The total tuning range was 163 cm^{-1}, corresponding to a wavelength tunability from 4.48 to 4.83 μm. The measured optical power was ~300 mW at the centre of the gain curve, near 4.65 μm, and remained in excess of 125 mW over the entire tuning range. The maximum power and wall-plug efficiency of the EC-QCL at a current of 400 mA are plotted along the same quantities for the gain element in Fig. 1. For better comparison, the EC-QCL power was corrected for the measured collection efficiency of 83% for the collimation lens, resulting in an optical power of 360 mW and a wall-plug efficiency of 6%.

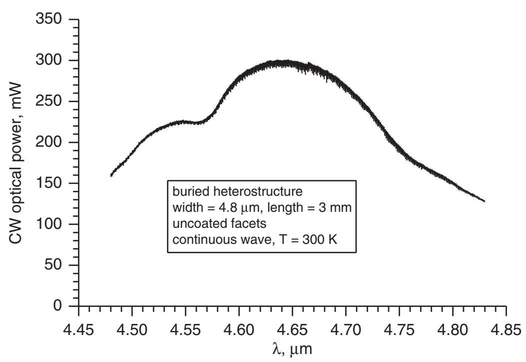

Fig. 2 *Optical power against wavelength of external cavity laser operated in CW mode at room temperature (data not corrected for lens collection efficiency)*

The maximum wall-plug efficiency of the present device is significantly lower than what we previously reported for 9.5 μm-wide ridges [2]. However, according to our simulations, narrower ridges have significantly better thermal conductance and only slightly lower overlap factor, which should result in equal or higher wall-plug efficiency. We attribute the lower performance to the fact that narrower ridges are more affected by waveguide sidewall roughness, which leads to higher threshold current and lower slope efficiency [9].

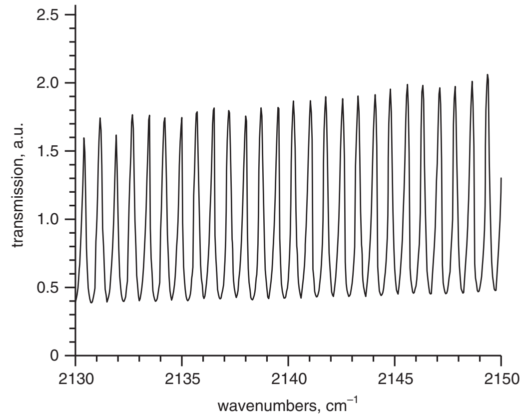

Fig. 3 *Transmission of Fabry-Pérot etalon measured with EC-QCL*

Etalon free spectral range 0.77 cm^{-1}, scan resolution 0.04 cm^{-1}

Because of the absence of AR coatings on the chip facets, our EC-QCL behaves as a coupled-cavity resonator. Continuous tuning thus requires a simultaneous adjustment of both the chip and extended cavity phases as the the grating angle is changed. In our setup, this is realised by varying the gain chip drive current and adjusting the extended cavity length by means of a piezo-electric actuator following the algorithm described in [3]. To demonstrate continuous tuning of our laser, laser power transmission through a Fabry-Pérot etalon was recorded during a frequency scan. A part of this mesurement is displayed in Fig. 3. The etalon free spectral range was $0.77\ cm^{-1}$ and the frequency spacing between measurement points was $0.04\ cm^{-1}$. As can be seen in Fig. 3, the measured data reproduce very well the Fabry-Pérot transmission curve, demonstrating that the frequency accuracy of our laser is better that $0.04\ cm^{-1}$. Similar continuous tuning was observed over nearly the entire tuning range of the device.

Conclusion: We have demonstrated an external cavity quantum cascade laser operating in continuous-wave mode at room temperature with a tuning range in excess of $160\ cm^{-1}$ and an output power in excess of 125 mW. Continuous tuning with an accuracy better than $0.04\ cm^{-1}$ has been demonstrated over nearly the entire tuning range. In future work, we expect to be able to demonstrate wider tuning range using AR coated gain chips.

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