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Continuous-wave operation of far-infrared quantum cascade lasers

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Continuous-wave operation of a terahertz quantum cascade laser is reported. Optical output powers ranging from 410 μW at 10 K to 124 μW at 35 K, at an emission wavelength of 66 μm are obtained.

Introduction: The quantum cascade laser (QCL) [1], is a unipolar semiconductor laser based on intersubband transitions in quantum wells. A fundamental property of the QCL is that the wavelength is not controlled by the material bandgap but by the layer thickness. For this reason, the emission wavelength of such a laser can be changed without using different semiconductor materials. Pulsed operation of an FIR-QCL was recently achieved at cryogenic temperature [2, 3]. However, for practical applications, such as local oscillators for sub-millimetre-wave astronomy, high resolution chemical sensing, the narrow line width obtained from a device operating in continuous wave is necessary. In this Letter, we report continuous-wave operation of a QCL in the terahertz frequency range (4.6 Thz). The device (see Fig. 1) is based on a chirped superlattice design [4] consisting of a three quantum well gain region followed by a four quantum well relaxation/injection region, realised in the $GaAs/Al_{0.15}Ga_{0.85}$ As material system. The structure was grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate and consists of 120 periods. The latter are embedded in a waveguide based on a single interface plasmon and a buried doped contact layer (see [3] for more details).

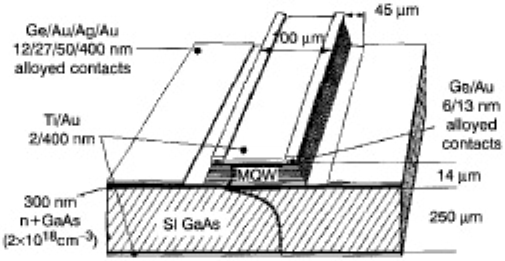

Fig. 1 *Schematic diagram of sample processing*
------ optical mode intensity in transverse direction

Sample processing: Device processing starts by etching the active region down to the buried contact layer, thereby creating 60–100–150–200 μm-wide ridges. Two bottom contacts are then evaporated on both sides of the stripes (Ge/Au/Ag/Au 12/27/50/400 nm alloyed at 400°C during 1 min). The top contact is provided by two 10 μm-wide stripes (Ge/Au 6/13 nm alloyed at 320°C for 1 min) deposited along the edges of the ridge. A Ti/Au confining layer is further evaporated completely covering the top of the stripe. Substrate thinning down to 250 μm, and backside metallisation (Ti/Au), complete the processing of the devices. They are then cleaved in laser bars of various lengths, soldered on a copper mount using indium and wire bonded. Back facet is then coated with 110/60 nm ZnSe/Au to decrease mirror losses. Compared to our previously published processing [3] several changes were introduced. The separation between the metal on the side and the edge of the ridge has been increased (45 instead of 15 μm) to reduce the overlap of the optical mode with the bottom contact. Evaporating the bottom contact layer before the top contact allows for a softer annealing of the latter.

Measurement results: A 1.85 mm-long and 100 μm-wide device was mounted and tested in pulsed mode. Threshold current density is $J_{th} = 235\ A/cm^2$ with a maximum power of ~18 mW at 10 K. At 58 K the threshold current density increased to a value of $540\ A/cm^2$; the maximum output power dropped to ~0.8 mW. The CW optical output power emitted from the front facet with a 20% collection efficiency was measured with a calibrated thermopile detector mounted directly in front of the cryostat window and is shown in Fig. 2. At 10 K the laser exhibited a threshold current of 460 mA ($j_{th} = 227\ A/cm^2$ at $V = 5.4$ V) and a slope efficiency $dP/dI =$ 1.48 mW/A (where P is optical power and I is current). A maximum optical power of 410 μW at 10 K was detected at a driving current of 855 mA. CW operation was observed up to 35 K, where the threshold current increased to 595 mA, while still more than 120 μW of output power was emitted at 850 mA. From a comparison of the pulsed and continuous-wave threshold currents, we extract an average thermal resistance of the device of 6 K/W.

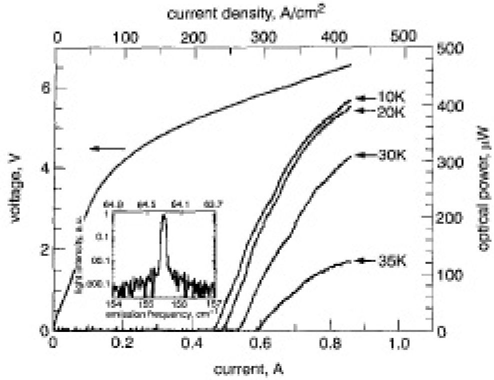

Fig. 2 *CW optical power from single facet and applied bias of 1.85 mm-long and 100 μm-wide laser stripe against drive current for various heatsink temperatures*
Inset: CW emission spectrum at drive current of 700 mA

The emission frequency ν of this far-infrared QCL can be tuned over a small range of a few cm^{-1} by changing the current and temperature. The CW spectral properties were analysed collecting the light by an off-axis parabolic mirror and sending it through an FTIR spectrometer (with a $0.09\ cm^{-1}$ resolution) operated in rapid scan mode. The emission spectra (see one example in the inset of Fig. 2) collected at a constant heatsink temperature of 10 K and at various currents between 510 and 700 mA reveal a frequency tuning from 156.8 to $155.2\ cm^{-1}$. From Fig. 3 we can observe that at higher injection currents the main emission peak shifts discontinuously towards smaller energies. The reason for this behaviour is that between 510 and 600 mA the laser heats while maintaining the initial longitudinal mode. Between 600 and 650 mA as well as between 650 and 700 mA, modehops take place to the adjacent longitudinal mode. From this data, we extract the current tuning rate ($0.3\ A^{-1}\ cm^{-1}$) and longitudinal mode spacing ($0.62\ cm^{-1}$). From the latter and the known cavity length, we can also compute an approximate value for the group effective refractive index in the laser cavity. This procedure yields an $n_{eff} = 4.33$, which is in reasonable agreement with the value reported in the literature [5] including the dispersion correction ($n = 4.1$). Tuning of the laser is studied against tempeature at a fixed current of 700 mA. As shown in Fig. 3, the mode tunes, as expected, towards the red with a tuning rate of $1/\lambda\Delta\lambda/\Delta T = 1.9 \times 10^{-5}\ K^{-1}$.

Fig. 3 *Peak position of CW spectra against injection current and temperature*

a Emission spectra measured at constant temperature of 10 K for various drive currents 510–700 mA

b Current kept at 700 mA and temperature varied between 20–35 K

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