Spectral engineering of terahertz quantum cascade lasers using focused ion beam etched photonic lattices

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Focused ion beam etching has been used to introduce one-dimensional photonic lattices, of periods 9.11, 9.24, 9.44 μm, between the cleaved facets of three 4.44 THz Fabry-Perot quantum cascade lasers. Singlemode lasing has been achieved at precisely defined wavelengths of 67.59, 68.48, 70.00 μm, respectively.

Introduction: Terahertz (THz) quantum cascade lasers (QCLs) [1] traditionally employ a Fabry-Perot (FP) cavity and are primarily edge-emitting. They, therefore, have a natural tendency to lase with multiple longitudinal modes across the envelope of the gain spectrum. The intermodal separation, $\Delta\lambda$, is determined by the length of the laser cavity between the two cleaved facets and the group index $n_g = n_{eff} - \lambda(\partial n_{eff}/\partial\lambda)$, where n_{eff} is the effective refractive index of the surface-plasmon optical mode and $\lambda(\partial n_{eff}/\partial\lambda)$ represents the dispersion of the active layer. Singlemode operation is observed only occasionally, normally for very short cavity lengths, at specific temperatures and over a limited range of injection currents. However, for a diverse range of applications, including absorption spectroscopy of gases and heterodyne mixing in astronomy, a stringent control over the wavelength and stability of the laser spectrum is needed. There is, therefore, an need for low-cost, straightforward techniques to realise robust THz laser sources with high quality spectral performance.

To achieve stable singlemode emission at a precisely designed wavelength, a spatially varying refractive index is often included in the form of a 'photonic lattice'. This photonic lattice acts as a filter for the unperturbed FP cavity modes, and can force the laser to operate at a specific wavelength. This idea is common in conventional interband semiconductor lasers, which use distributed feedback (DFB) cavities. These structures [2] tend to lase in a single mode and have both a high sidemode-suppression-ratio (SMSR) and a narrow linewidth. However, the complex etch and regrowth process required to define the photonic lattice, together with subsequent passivation and further device processing, make such DFBs expensive to manufacture compared to FP lasers. In the THz range, using a combination of wet chemical etching and ohmic-contact deposition, Mahler *et al.* [3] reported DFB QCLs emitting singlemode THz radiation at 69.1 μm. Ajili *et al.* [4] subsequently reported DFB QCLs manufactured using etching and refilling with hard-baked resist. Very recently, electron-beam lithography [5] has been used to fabricate periodic microstructures in a THz QCL. Although this latter technique is powerful, it requires several fabrication steps and is consequently time consuming.

Here, we report an alternative approach to fabricating periodic microstructures, based on focused ion beam (FIB) etching of very short photonic lattices. This 'Fabry-Perot modal sculpturing' [6], unlike in conventional DFBs, is based on only 19 lattice sites being introduced between the laser facets. The photonic band functionality originating from this short lattice allows achievement of singlemode lasing. It is notable that the THz FP QCLs can be post-processed using FIB etching once the waveguide metallisation is completed and even after the wafer is separated into individual dies. No resist is required and photonic microstructures can be fabricated with a high degree of flexibility.

Principle: The THz FP QCLs used for this work were based on a GaAs/AlGaAs chirped superlattice active region and a plasmon-based waveguide, and are described more fully in Kohler *et al.* [1]. Briefly, a buried 800 nm-thick highly doped (doping density $\sim 2 \times 10^{18}\,\mathrm{cm}^{-3}$) n^+ GaAs layer forms the boundary between the active medium and the undoped GaAs substrate and acts as a lower contact. A 200 nm-thick doped (doping density $\sim 5 \times 10^{18}\,\mathrm{cm}^{-3}$) n^+ GaAs layer and a Ti/Au layer on top of the active region confine the laser mode from the upper side with a standard low resistance ohmic contact being made to the GaAs layer. The lasers, having a 11.2 μm-thick active region, were 100 μm wide, 2–3 mm long, and soldered onto copper blocks for heatsinking.

To fabricate photonic lattices, the whole packaged laser was inserted inside an FIB etching system. Discrete reflection sites were then introduced into the lasing structure by etching narrow, sub-wavelength, slits through the top metal contact and upper n^+ GaAs layer into the first few layers of the active region. It should be noted that such reflection (or scattering) sites do not have to project deep into the active layer, but need only perturb the refractive index of the surface plasmon mode. For the case of a THz QCL, where the electromagnetic energy is confined by the surface plasmon waveguiding mechanism, a slit, opened in the metallic layer, acts as an optical barrier for the propagating electromagnetic mode as no surface plasmon is supported there [7]. The refractive index in the slit region will then be different from that of the surface plasmon waveguide. As a result, part of the electromagnetic energy tunnels through the slit (forward wave), part gets reflected and couples to the original field (reverse wave), and part is scattered out (scattering loss). If the optical barrier, i.e. the slit width, is thin enough, the scattering loss can be significantly reduced, and the so-called 'Bragg phase matching' between the forward and the reverse propagating waves occurs, given by $k_{BR} = G/2n_{eff}$, where k_{BR} is the wavevector of THz radiation and G is the available lattice momentum [8]. As a result of this, the photon density of states enhances around the Bragg wavelength λ_{BR}, given by $\lambda_{BR} = 2\pi/k_{BR}$, and this will force the QCL to lase around the Bragg wavelength λ_{BR}. Facet reflections, however, still remain the primary source of feedback necessary for lasing. In the simplest case of a periodic lattice with periodicity, Λ, we note that the existence of the dominant Fourier component at $G_{BR} = 2\pi/n_{eff}\Lambda$ provides a Bragg wavelength of $\lambda_{BR} = 2n_{eff}\Lambda$.

Fabrication: The FIB system used for this work was a dual beam system (FEI Nova 200 NanoLab) comprising a high resolution ion beam column, which mills directly, and a high resolution field-emission gun scanning electron microscope (SEM), which allows precise positioning and inspection of the fabricated microstructures. For milling, a finely focused ($\sim$7 nm) beam of highly energetic (30 kV) gallium ions was scanned over the surface of the specimen at normal incidence. At high beam currents, the gallium beam rapidly sputters away the specimen surface. Using a 1 nA beam current, slits of 1.5 μm width were etched to an accuracy of ±160 nm, the width being chosen as the best compromise between increased reflection strength and increased diffraction losses. A similar compromise was made for the number of scattering sites (N). A higher N value provides fine tuning of the Bragg wavelength [8], but with increased loss. A value of $N = 19$ was chosen for this work, which (following [7]) is sufficient to saturate the reflectivity. Three THz QCLs of cavity length 3 mm were modified with periodic photonic lattices of lattice constants 9.11, 9.24 and 9.44 μm, distributed centrally along the FP cavity, with an etch depth of 1.5 μm ± 100 nm being used for each slit. SEM images of an FIB processed device, taken at normal incidence, are shown in Fig. 1, showing excellent sidewall smoothness. Such smoothness is required so as to limit scattering loss in the laser cavity.

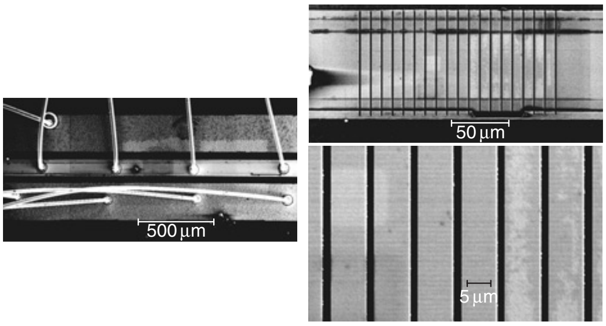

Fig. 1 *SEM images, at three different magnifications, of typical post-processed photonic lattice, engraved into QCL waveguide*

Completed devices were mounted onto the cold finger of a liquid-helium, continuous-flow cryostat equipped with polythylene windows. Spectra were recorded with a Bruker Fourier-transform infrared spectrometer in rapid scan mode with a resolution of $0.25\,\mathrm{cm}^{-1}$. A helium-cooled silicon composite bolometer was used for THz detection. The lasers were driven at 10 kHz with a 25% duty cycle.

Results: The QCL emission spectra, together with the electrical (V-I) and light-current (L-I) performance (see insets) of various QCLs are shown in Figs. 2 and 3. In both Figures, the estimated power from each facet of the laser is plotted, as estimated from the detector's responsivity. Similar V-I and L-I characteristics were observed against temperature for both patterned and unpatterned devices. Fig. 2 shows data from an unperturbed FP laser of 2.2 mm cavity length. The separation $\Delta\lambda$ between the neighbouring lasing modes at $\lambda = 68.4$ µm is ~0.243 µm, indicating a refractive index of 4.37. Fig. 3 then displays the pulsed emission spectra of three microstructured lasers of different photonic lattice constants Λ. For $\Lambda = 9.1$, 9.24, 9.44 µm, lasing takes place at $\lambda_{BR} = 67.59$, 68.48, 70.00 µm, respectively, with SMSR values of 25, 12 and 18 dB, respectively, demonstrating achievement of an 'engineered spectrum' for a QCL. An effective refractive index value of $n_{eff} \sim 3.71$ is calculated for the QCL waveguide, with thin air slits. This is in excellent agreement with the theoretical value (3.728) [3], as a slightly higher effective index is expected for an unperturbed waveguide. An interesting point to note, however, is that owing to the large structural dispersion factor ($\lambda\partial n_{eff}/\partial\lambda$) present in high index material systems (such as the surface plasmon waveguide), the group index (n_g) is actually larger than the effective index (n_{eff}), and it is n_{eff} that is responsible for the precise determination of λ_{BR}. This is evident from the measured value of $\Delta\lambda$ from the FP spectra (discussed above), which reveals a group index (n_g) value of 4.37 for the propagating surface plasmon mode.

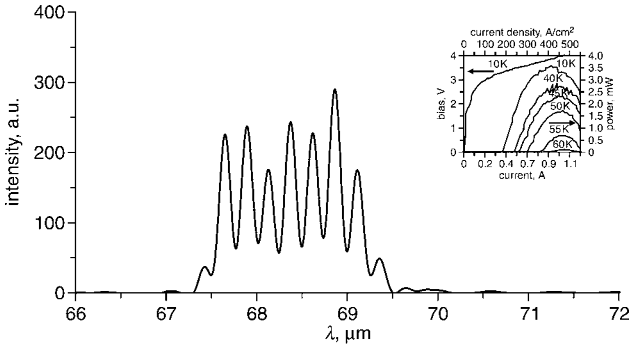

Fig. 2 *Emission spectrum (at 10 K) of unpatterned 2.2 mm-long, 4.44 THz FP QCL*

Measurements performed in pulsed mode at 10 kHz, 25% duty-cycle, 1 A drive current

Inset: Voltage-drive current and light-drive current characteristics

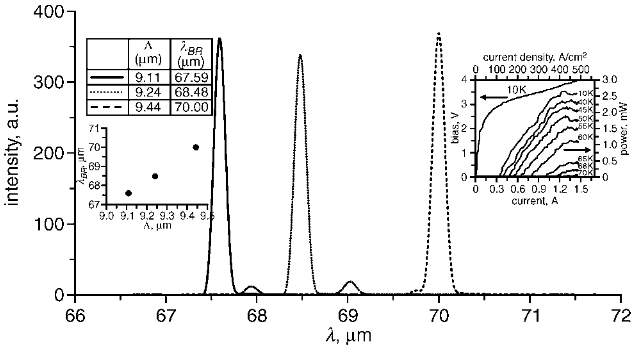

Fig. 3 *Singlemode emission spectra (at 10 K) of 3 mm-long FP QCLs microstructured, with periodic photonic lattices of three different lattice constants: 9.11, 9.24, 9.44 µm*

Spectra collected in pulsed mode at 10 kHz, 25% duty-cycle, 1 A drive current, close to maximum output power

Insets: (Left) measured Bragg wavelength against lattice constant ($n_{eff} = 3.71$ calculated from slope). (Right) voltage-drive current and light-drive current characteristics for 9.44 µm structure

Conclusion: We have shown that FIB etching can be used straightforwardly for direct writing of photonic lattices in THz QCLs. These microstructured QCLs show singlemode emission, and the lasing wavelength can be tuned within the envelope of the available gain spectrum.

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References

1 Kohler, R., Tredicucci, A., Beltram, F., Beere, H.E., Linfield, E.H., Davies, A.G., Ritchie, D.A., Iotti, R.C., and Rossi, F.: 'Terahertz semiconductor-heterostructure laser', *Nature*, 2002, **417**, pp. 156–159
2 Carroll, J.E., Whiteaway, J., and Plumb, R.G.S.: 'Distributed feedback semiconductor lasers' (IEE, London, 1998)
3 Mahler, L., Kohler, R., Tredicucci, A., Beltram, F., Beere, H.E., Linfield, E.H., Davies, A.G., and Ritchie, D.A.: 'Single-mode operation of terahertz quantum cascade lasers with distributed feedback resonators', *Appl. Phys. Lett.*, 2004, **84**, pp. 5446–5448
4 Ajili, L., Faist, J., Beere, H., Ritchie, D., Davies, G., and Linfield, E.: 'Loss-coupled distributed feedback far-infrared quantum cascade lasers', *Electron. Lett.*, 2005, **41**, (7), pp. 419–421
5 Mahler, L., Tredicucci, A., Kohler, R., Beltram, F., Beere, H.E., Linfield, E.H., and Ritchie, D.A.: 'High-performance operation of single-mode terahertz quantum cascade lasers with metallic gratings', *Appl. Phys. Lett.*, 2005, **87**, pp. 181101-1–181101-3
6 Kozlowski, D.A., Young, J.S., England, J.M.C., and Plumb, R.G.S.: 'Singlemode 1.3 µm Fabry-Perot lasers by mode suppression', *Electron. Lett.*, 1995, **31**, (8), pp. 648–650
7 Weeber, J.C., Lacroute, Y., Dereux, A., Devaux, E., Ebbesen, T., Girard, C., Gonzalez, M.U., and Baudrion, A.L.: 'Near-field characterization of Bragg mirrors engraved in surface plasmon waveguides', *Phys. Rev. B*, 2004, **70**, pp. 235406-1–235406-12
8 Chakraborty, S., Parker, M.C., and Mears, R.J.: 'A Fourier (k-) space design approach for controllable photonic band and localization states in aperiodic lattices', *Photonics Nanostruct. Fundam. Appl.*, 2005, **3**, (2–3), pp. 139–147