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Low divergent, high-power, single-mode terahertz wire lasers

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Abstract – We devise arrays of surface emitting THz QCLs exploiting two novel lithographic configurations: a) a dual periodicity slit architecture and b) corrugated sinusoidal wire laser cavities. Extremely low divergent optical beams, with up to 85 mW of emitted optical powers and 245 mV/A slope efficiencies have been reached.

Quantum cascade lasers (QCLs) operating at terahertz (THz) frequencies have undergone a rapid development in performance since their first demonstration, showing their potential as high power, broadly tunable, high spectral purity, ultra-broadband gain sources for a number of fields including astronomy, security screening, biomedicine, and cultural heritage.

Most applications for THz technology require radiation sources with a low divergent spatial profile in the far-field as well as a fine spectral control of the emitted radiation. However, double-metal waveguides, conventionally employed to maximize the THz QCL operating temperature, suffer from a lack of efficient extraction and a poor collimation of the output radiation, owing to the sub-wavelength dimensions of the resonant cavities. Also, the strong longitudinal confinement provided by the micro-strip waveguide configuration typically induces the laser to operate in a multimode regime.

The difficulty of achieving controlled spectral and spatial beam patterns from THz QCLs has recently been addressed by engineering two-dimensional photonic crystal lasers¹, one-dimensional graded heterostructures² and edge-emitting third-order (periodic) distributed feedback lasers (DFB)³, the latter showing superior performance in terms of emission profiles and power conversion efficiencies. Despite their clear advantages, there are some challenges associated with third order DFB THz QCLs: a perfect phase-matching condition must be established lithographically through deep dry etching processes and, being highly dependent on the lasing frequency, this requires high precision, which is extremely demanding.

Here we report on the development of THz QCLs exploiting two novel lithographic configurations to address simultaneously the need for: i) low divergence; ii) single-mode emission; iii) high power; and, iv) high power conversion efficiency. We devised arrays of surface emitting, 1D wire lasers exploiting: a) a dual periodicity slit architecture; and, b) corrugated sinusoidal wire laser cavities. In both cases, a broadband resonant-phonon QCL active region design was exploited to provide a sufficiently wide flexibility in tuning the central frequency.

In the first geometry (Fig. 1a), the emitted frequency and the beam angular divergence were tailored independently. Two sets of 2- μ m-wide slits were superimposed with different

periodicities by exploiting the following refractive index modulation function:

$$n(\mathbf{z}) = n_1 + (n_2 - n_1) f(\mathbf{z}, k_{fb}, k_{ex}(\theta)) \quad (1)$$

where the generating function f , consists of two superimposed square gratings with different periodicities:

$$f(\mathbf{z}) = H(S_d(2\pi k_{fb}\mathbf{z}) + S_d(2\pi k_{ex}\mathbf{z})) \quad (2)$$

Here, n_1 and n_2 are the minimum and the maximum values of the refractive index, respectively. The resulting feedback wave-vector is $k_{fb} = 2\lambda_1 n/c$, while the extraction wave-vector is $k_{ex} = \lambda_1 n/c + x\lambda_1 n/\sin(\theta)$, where λ_1 is the lower band-edge and x has been varied along the DFB array sequence, in regular steps, spanning a 10% range around the light cone edge. $H(x)$ is the Heaviside step function, $S_d(x)$ is a square wave with duty cycle d , defined as $S_d(x) = 1$ for $-d/2 < x < d/2$, and $S_d(x) = 0$ otherwise.

The second architecture (Fig. 1b) exploits a wire laser cavity, laterally corrugated following a sinusoidal function depending on the feedback wave-vector, k_{fb} . Holes with 5–10 μ m diameter, significantly smaller than the emitted radiation wavelength, have been periodically patterned onto the top surface with a periodicity equal to the extraction wave-vector k_{ex} , to allow efficient point-like isotropic vertical extraction. The rationale here is to employ a feedback grating weakly coupled into free-space, and avoid interference effects with the extraction grating. The sinusoidal corrugation is, therefore, providing the required feedback condition. 2D simulations of the laterally corrugated DFB lasers showed a clear dependence of the photonic bandgap on the ridge width, which we progressively varied in our array sequence to shrink the bandgap width within the QCL bandwidth. Furthermore, we tuned the extraction wavevector k_{ex} along the array sequence, in regular steps, spanning a 10% range around the light cone edge. In both architectures, the waveguide openings (slits or holes), behaving as localized emitters, ensure that light can be efficiently out-coupled, resulting in low divergent far-field emission patterns.

Figures 1a and 1b show the current-voltage and light-current characteristics of a prototypical dual-slit and corrugated wire quantum cascade laser emitter, respectively. Peak optical powers of ~ 85 mW (Fig. 1a) and ~ 25 mW (Fig. 1b) were achieved with slope efficiencies of 245 mV/A and 211 mV/A for the dual-slit and corrugated DFB. Both devices show single frequency emission at the lower band edge mode (Figs. 1c and 1d).

The measured far-field emission patterns provide experimental evidence of collimated emission with optical beam divergencies within 10° for both the dual-slit and corrugated DFB devices (Figs. 1e and 1f). The proposed

geometries open the way for development of a new class of in-plane emitting THz DFB QCLs, exploiting different feedback grating concepts to achieve single-mode, high power and highly collimated emission, based on an easy-to-implement phase matching approach.

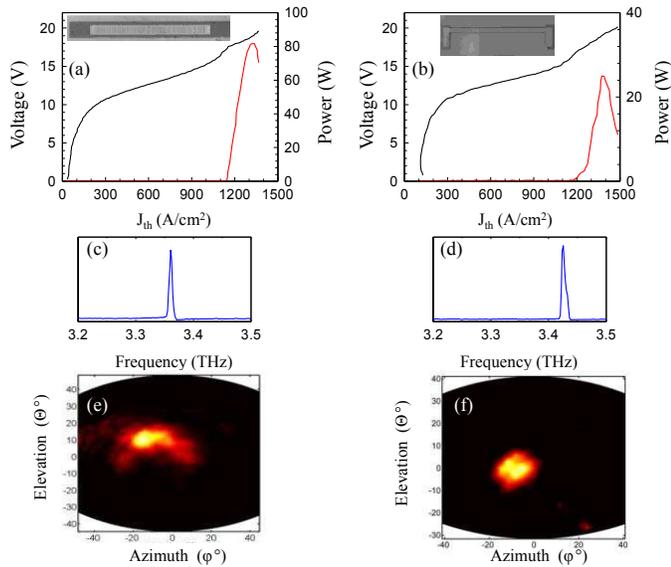


Fig.1: (a-b) Current-voltage and light-current characteristics of (a) a dual-slit DFB, and (b) a laterally corrugated DFB wire laser, both measured at 10 K while driving the QCL at a 10% duty cycle. Insets: Scanning electron microscope images of the laser bars. (c-d) Emission spectra of (c) the dual-slit DFB, and (d) the laterally corrugated DFB wire laser, acquired in rapid scan mode with a resolution of 0.125 cm^{-1} using an FTIR spectrometer. (e-f) Far-field emission pattern of (e) the dual-slit DFB, and (f) the laterally corrugated DFB wire laser, collected at a distance of 4 cm from the laser facet.

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