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# Continuous-wave highly efficient low-divergence terahertz wire lasers

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*Abstract*—**In recent years, Terahertz (THz) quantum cascade lasers (QCLs) have undergone a fast development, showing high power, ultra-broadband gain and quantum-limited linewidth. For many applications, THz QCLs need to operate in continuous-wave (CW), with a tight control of the emission spectrum and highly collimated beam profiles. These requirements are usually addressed by exploiting distributed feedback (DFB), photonic crystals or micro-cavity architectures, which can allow tailoring either the laser beam divergence or the emission frequency, and eventually both of them simultaneously, as in the case of third-order DFBs. Here we report on an original design in which a wire DFB THz QCL, engineered with a lateral sinusoidal corrugation providing feedback and frequency control, and an array of surface hole provides light outcoupling. This new photonic structure has led to the achievement of low-divergence beams (10°), single-mode emission, high slope efficiencies (250 mW/A), and stable CW operation.**

## I. INTRODUCTION

TERAHERTZ (THz) science and technology have undergone a dramatic surge in the last decade, bringing new fundamental and technological insights and showing a disruptive potential in many application fields as astronomy, security, high-resolution spectroscopy and sensing, metrology and biomedicine, amongst others. The quantum cascade laser (QCL) has been central to this development, paving the way to compact THz sources whose electronic and optical properties can be accurately engineered via a combination of quantum engineering and photonic patterning [1].

Nanofabrication techniques combined with new resonator concepts, recently allowed to address the challenge of controlling the spectral and spatial properties of laser beams from THz QCLs, with a number of solutions, such as two-dimensional photonic-crystal lasers [2], bi-periodic distributed feedback (DFB) gratings [3], plasmonic lasers [4] and edge-emitting 3rd-order DFBs [5]. This latter approach has demonstrated superior performances in terms of beam divergence and power conversion efficiency, but required critical lithographic and etching steps to obtain the perfect phase-matching condition, which is also dependent on the desired emission frequency.

Here we report on a new photonic architecture for THz QCLs which simultaneously shows: i) high-power output and wall-plug efficiency, ii) robust single-mode emission, iii) low divergence and iv) continuous-wave operation [6].

## II. RESULTS

The devised resonator architecture exploits a one-dimensional wire laser cavity, appropriately designed to achieve in-plane emission, and exploiting a double-metal laser cavity with a lateral sinusoidal corrugation to provide optical feedback (fig. 1.a).

Light extraction is separately controlled by a periodic array of 10 µm-wide holes, lithographically patterned on the top metal cladding. The extraction array periodicity is set to match the proper spatial wavevector $k_{ex}$ and achieve the desired extraction direction, while optimizing the output efficiency.

By tuning $k_{ex}$ in discrete steps with an extraction parameter $\eta$ in a ±10% range around the theoretical optimal value, it was possible to explore the matching condition for the scattering of the light wavevector with the feedback and extraction wavevectors. This can be represented by means of a one-dimensional light-cone diagram (fig. 1.b), but further investigation of the resonator were performed using band structure calculation and fully three-dimensional finite-element models (FEM). These highlighted the coexistence of multiple photonic bandgaps (fig. 1.c) associated with fundamental modes or higher-order lateral excitations with clearly distinguishable spatial envelopes.

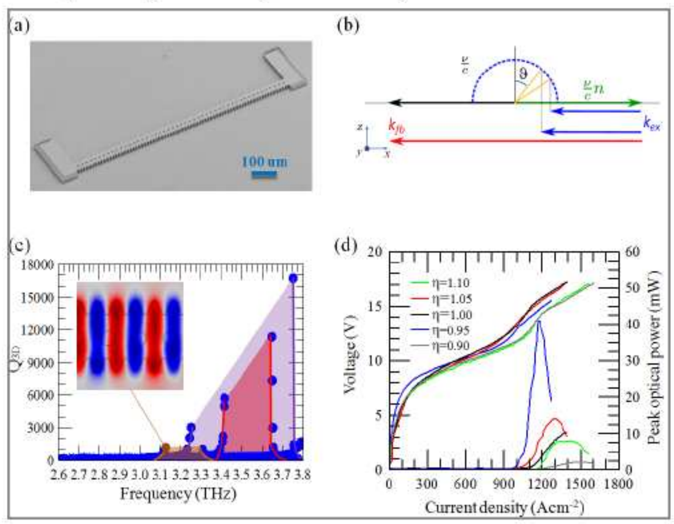


**Fig. 1. a)** Scanning electron microscope image of a fabricated corrugated wire-laser. **b)** Light cone diagram describing the scattering process between the light wavevector in the material (green line), the feedback wavevector (red line) and the extraction wavevector (blue line). Since the latter is tuned, a different matching with the free-space propagating wavevector is obtained (dashed cirlce). **c)** Quality factor of the eigenmodes as a function of frequency in the sinusoidal feedback geometry. The photonic bandgaps associated with the fundamental mode (brown), the 1st-order lateral excitation (magenta) and the 2nd-order lateral excitation (red) are highlighted. The inset reports the real part of $E_z(x,y)$ in the corrugated device with extraction holes patterned on top, from FEM simulations. **d)** Current-voltage and light-current characteristics of a set of corrugated QCL with different extraction parameter $\eta$, operated at 10 K in pulsed regimes with duty cycle of 2%.

Based on the designed architecture, a set of devices with different extraction parameters were fabricated and measured, featuring a 40 µm-wide ridge with sinusoidal width modulation of ±10 µm. Maximum peak optical power of ≈ 45 mW (fig. 1.d) and slope efficiencies of ≈ 250 mW were achieved. The fabricated wire lasers showed a robust single-mode spectral emission (fig. 2.a) around 3.4 THz and beam divergence of about 10° (fig. 2.b), in good agreement with the simulated lower-band edge of the second-order lateral excitation.

Moreover, stable CW regime was achieved with devices specially devised to operate at very low current densities, showing a divergence (fig. 2.c) comparable to that of the lasers in pulsed regime, while reaching a maximum CW output power of nearly 6 mW (fig. 2.d). Tight control over the emission spectra was demonstrated as well, with an intense spectral peak at ≈ 3.1 THz (fig. 2.e), which correlates well with the predicted fundamental lower-band edge mode.

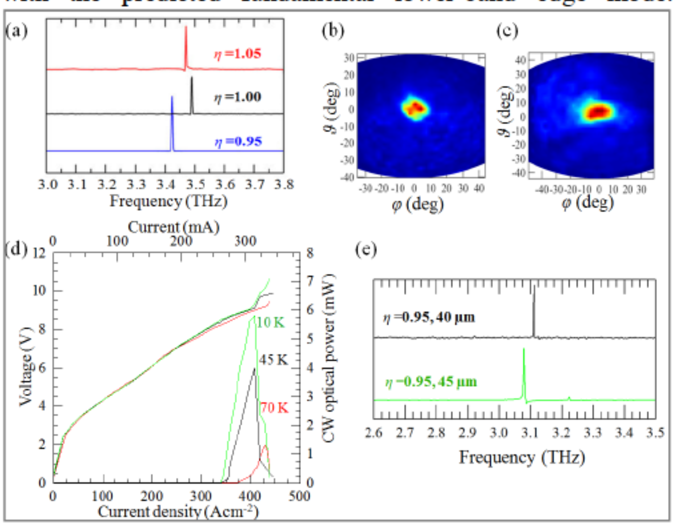


**Fig. 2. a)** Fourier transform infrared (FTIR) emission spectra of corrugated devices with different extraction parameter $\eta$. **b)** Far-field pattern of a wire-laser with $\eta$ = 0.95 operated in pulsed regime and emitting at ≈ 3.4 THz. **c)** Far-field pattern of a QCL with $\eta$ = 0.95 operated in CW mode and emitting at 3.1 THz. **d)** Current-voltage and light-current characteristics of a corrugated wire-laser with $\eta$ = 0.95 and ridge width of 45 µm, measured at different operating temperatures. **e)** FTIR emission spectra of corrugated wire-lasers with same $\eta$ = 0.95 and different average ridge width, measured at a temperature of 15 K.

## III. Summary

The proposed wire DFB THz QCLs demonstrate the possibility of separately controlling the optical feedback and the light outcoupling, exploiting a lateral sinusoidal corrugation and an array of surface holes, respectively. By carefully tuning the extraction hole array periodicity, the optimal scattering condition has been investigated, leading to the achievement of tightly controlled single-mode emission, highly-collimated beams (≈ 10°), high slope efficiencies (≈ 250 mW/A), and stable CW operation

The proposed resonator concept paves the way to a new generation of high-power, single-mode and low-divergence THz QCLs in both pulsed and CW modes, which can be extended to a broad frequency range in the far-infrared region, promising important impacts for the development of portable THz sources for applications in sensing, imaging and security.

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