Metasurface-based terahertz quantum-cascade lasers operating beyond 5 THz

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***Abstract*—A terahertz quantum-cascade (QC) metasurface VECSEL that operates above 5 THz is demonstrated. The amplifying metasurface is loaded with a QC active material that was separately shown to lase in continuous-wave mode up to 5.71 THz at 45 K. The challenge of the VECSEL includes overcoming the net loss due to proximity to the *Reststrahlen* band, and the reduction in metasurface amplification at higher frequency designs. A metasurface in a tunable external cavity was observed to lase in single-mode operation from 5.40-5.71 THz in pulsed mode operation at 5 K heatsink temperature.**

***Keywords*— local oscillator, metasurface, quantum cascade laser, terahertz, VECSEL.**

I. Introduction

ONE of the key components to a successful heterodyne spectroscopic system is a stable local oscillator (LO) with sufficient power to pump the mixer. In the THz regime, Schottky diode multiplier chains have been the leading LO source for decades. But since their power output decays with frequency, they have not been featured as LOs above 3 THz. Quantum-cascade lasers (QCLs) are an alternative LO candidate at these high frequencies; they have been used in the GREAT spectrometer and GUSTO/STO-2 to observe [OI] lines at 4.74 THz. However, beyond 5 THz, there is a technological gap in LO candidates, despite the regime being populated by astrophysically interesting lines such as [NIII] (5.23 THz), [SI] (5.32 THz), [FeI] (5.52 THz), [OIII] (5.79 THz), and [FeIII] (5.8 THz) [1]. However, to design QCLs above 5 THz, it becomes important to address the increased losses and reduced gain due to proximity to the *Reststrahlen* band of GaAs. This band is a consequence of strong optical-phonon resonances in the 8-9 THz range. The first demonstration of a THz QCL operating in continuous-wave (cw) above 5 THz was in 2022, with a maximum operating temperature of 15 K at 5.26 THz [2]. Since then, a metal-metal (MM) ridge waveguide operating up to 5.71 THz with a maximum operating temperature of 68 K was demonstrated [3]. This demonstration motivates the work to realize a metasurface-based external-cavity laser at these frequencies — a necessary progression to realize a technology more suitable for a local oscillator, as the novel architecture comes with the benefits of single-mode operation, scalable power output, high beam-quality, and frequency tunability [4].

II. Results

Initial results of the MM ridge waveguide were obtained by careful design of a GaAs/AlGaAs quantum-cascade active region, as well as the waveguide itself to minimize losses. Fig. 1 shows its power-current-voltage characteristics operating in cw at various temperatures. The device showed a maximum output power of 1 mW at 45 K, which was the lowest temperature able to be achieved using a Stirling cooler.

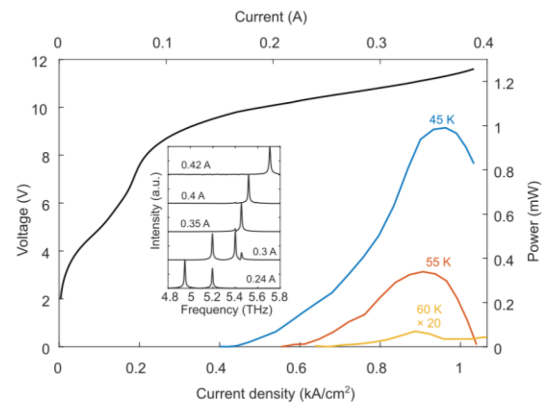

Fig. 1. Power-current-voltage data for a 0.5 mm x 75 µm metal-metal waveguide operating in continuous-wave mode at various heatsink temperatures. The inset shows the measured spectrum from an FTIR at various bias points, with modes spanning from 4.95 to 5.71 THz.

Additionally, the device demonstrated broadband gain with various lasing modes observed spanning from 4.76 – 6.03 THz in pulsed mode operation, and 4.95 – 5.71 THz in cw.

Following these MM waveguide results, metasurface-based QC-VECSELs were designed and fabricated using the same active region. The QC-VECSEL is enabled by a metasurface composed of a subwavelength array of elongated microstrip antennas loaded with the QC gain material. Fig. 2a shows an SEM image of such a metasurface. The dimensions of the antenna are chosen to operate at the TM_{01} cutoff frequency ($w = 6.5\ \mu\text{m} \cong \lambda_0/2n$), allowing for coupling to surface-incident radiation. In principle, scaling the metasurface to

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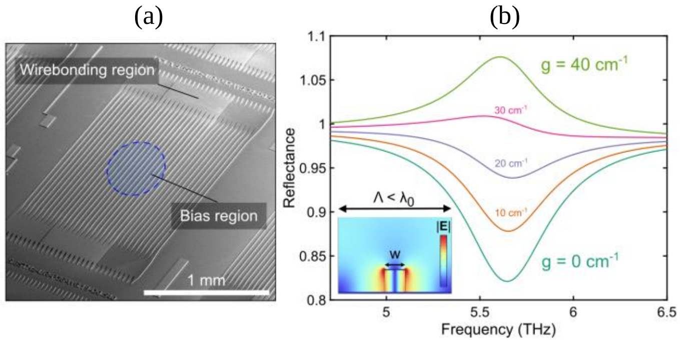

Fig. 2. (a) SEM image of a representative metasurface fabricated for operation above 5 THz. The blue circle corresponds to the region of the metasurface that is selectively biased to encourage lasing in the fundamental mode. (b) An FEM simulation of the metasurface reflectance as uniform gain is applied to the semiconductor. The inset shows the electric field profile of the corresponding eigenmode of a single unit cell of the metasurface with subwavelength periodicity. For the design in this work, $w = 6.5$ µm and $h = 7$ µm.

operate at higher frequencies is a straightforward matter of scaling the metasurface dimensions (e.g. width, period, height) by the wavelength. However, this is not necessarily true [5]. At higher frequencies, metallic loss makes it undesirable to scale down the metasurface active region thickness; however, if it is not scaled down, the quality factor of the metasurface drops significantly, which in turn reduces the effective gain interaction length. This results in a weaker metasurface amplification per reflection. An FEM simulation of the reflectance for varying levels of applied gain is shown in Fig. 2b. The results show a transparency gain of 28 cm^{-1}.

Initial results of the QC-VECSEL were successful in pulsed mode operation. Fig. 3a demonstrates broadband single-mode tuning from 5.40 – 5.72 THz as the output coupler is mechanically stepped outward via an intracryostat piezoelectric stepper motor, as illustrated by the VECSEL configuration in the inset. To achieve this, the cavity length was reduced to less than 500 µm to extend the free-spectral-range beyond the threshold gain-bandwidth. Fig. 3b shows a corresponding power-current-voltage plot at a particular lasing frequency of 5.69 THz operating at 5 K. The device lased up to a maximum heatsink temperature of 50 K. A high reflectance output coupler was needed (~99%), however this had the consequence of reducing the slope-efficiency due to the lower mirror-loss and the loss from the metals of the output coupler.

The initial results are promising and prove that QC-VECSELs can be made to operate beyond 5 THz. Additionally, these results inform subsequent designs to optimize the efficiency, power output, and achieve cw operation for LO candidates.

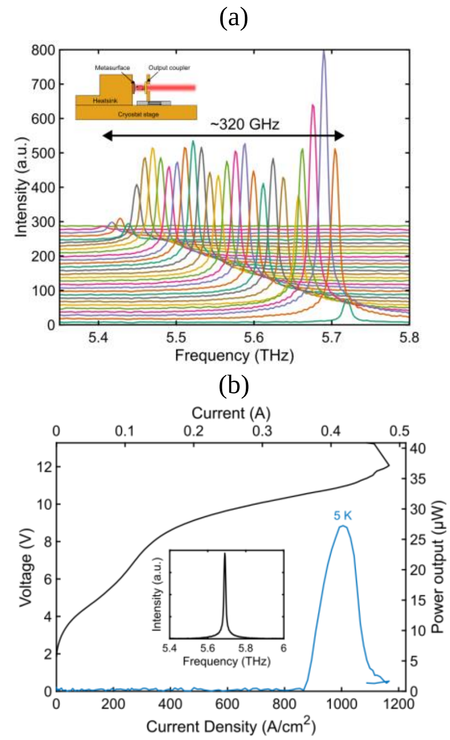

Fig. 3. (a) Stacked spectra of the QC-VECSEL output collected via FTIR that demonstrates single-mode tuning over a 320 GHz bandwidth. The spectra were collected in pulsed mode at 5 K. The inset shows a diagram of the VECSEL configuration, where the output coupler is mounted on a piezoelectric stepper motor to step the cavity length intra-cryostat (b) Power-current-voltage plot of the QC-VECSEL operating at 5.69 THz in pulsed mode.

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