Gain measurements of a metal-metal terahertz quantum cascade laser using an integrated terahertz pulse emitter

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Abstract: A terahertz pulse emitter is fabricated alongside a quantum cascade laser with a metal-metal waveguide. Terahertz pulses are used to measure the gain of the laser ridge, which is clamped above threshold to 18 cm^{-1}.

OCIS codes: 140.5965, 300.6495, 300.6500

In the past few years, terahertz time domain spectroscopy (THz-TDS) has been demonstrated as a powerful tool for characterizing terahertz quantum cascade laser (QCL) gain media, on account of its unique ability to identify both the amplitude and phase associated with intersubband transitions [1]. Typically, THz radiation is generated externally with a photoconductive antenna, focused onto one QCL facet, transmitted through the waveguide, collected from the other facet, and detected through either photoconductive or electro-optic means. Because this process leads to low coupling efficiencies from the external pulse generators, only single plasmon waveguide geometries—which have large mode profiles and a Fresnel-like impedance mismatch to free space—have been successfully characterized in this manner. However, metal-metal waveguides have largely supplanted the surface plasmon waveguide in THz QCL research, as their tighter confinement of the optical mode leads to a near-unity overlap with the active region and reduced mirror losses [2]. On the other hand, these very properties make coupling efficiencies to and from the waveguide low, thereby making TDS difficult to perform.

Here, we demonstrate the monolithic integration of an independent terahertz pulse emitter with a QCL based on a metal-metal waveguide, thereby overcoming the challenge of coupling efficiency. The emitter is fabricated by lithographically etching a 4 μm gap in a QCL ridge and cleaving the emitter section to be ~20 μm long. The QCL measured here is 1.21-mm long and 80-μm wide, and has an active region with a resonant-phonon design that lases at 2.2 THz. It has two wells in the injector region and is similar to the design described in Ref. [3]. Near-infrared pulses from a ~100 fs Ti:Sapphire laser were focused onto the biased emitter to generate THz pulses, a silicon hyperhemispherical lens was attached in order to collect THz that had propagated through the waveguide [4], and standard electro-optic sampling was used to measure the electric field as a function of time [5].

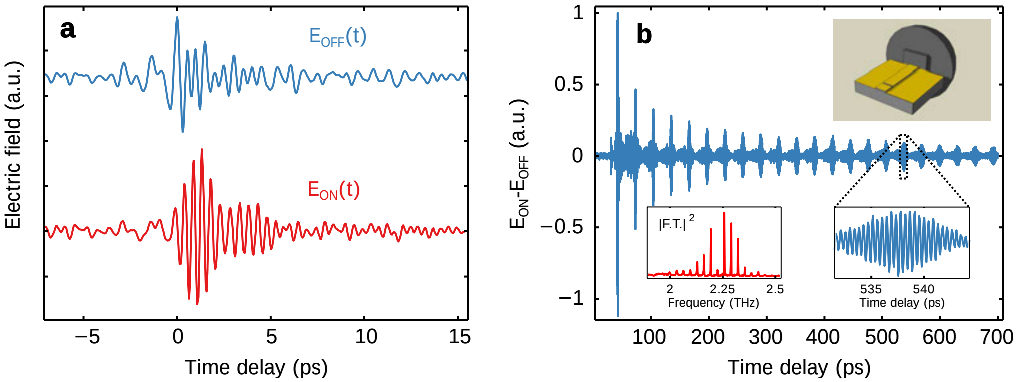

Fig. 1: (a) THz pulse transmitted through QCL off and above threshold. (b) Difference in field generated by QCL over a 700-ps delay range. Top-right inset: schematic of device. Bottom-right inset: narrowband field oscillations resulting from laser action. Bottom-left inset: power spectrum of difference field.

Fig. 1(a) shows the time-domain results for one of the pulses collected from such a device, with the QCL both biased and unbiased. When the laser is off, a broadband transient is generated that quickly decays away. However, when the laser is biased above the threshold current, a long-lasting narrowband oscillation is observed that corresponds to gain at the lasing frequency. Fig. 1(b) shows the difference of these two signals over a much longer delay range. The signal at the lasing frequency should in principle suffer zero loss while the signal at nearby frequencies does not, and so the initial pulse generated by the emitter gives rise to dozens of echoes that correspond to the round-trip time of the cavity, 31 ps, and narrow to the lasing frequency as they continue to circulate. In addition, the power spectral density of the difference field shows a uniformly-spaced comb, indicating that only one lateral mode was excited by the THz pulse. This is advantageous from an analysis perspective, because it helps to ensure that individual echoes can be windowed for gain calculations. In addition, note that the frequency range in which longitudinal modes are visible is the same range that has appreciable gain (see Figure 2(a)).

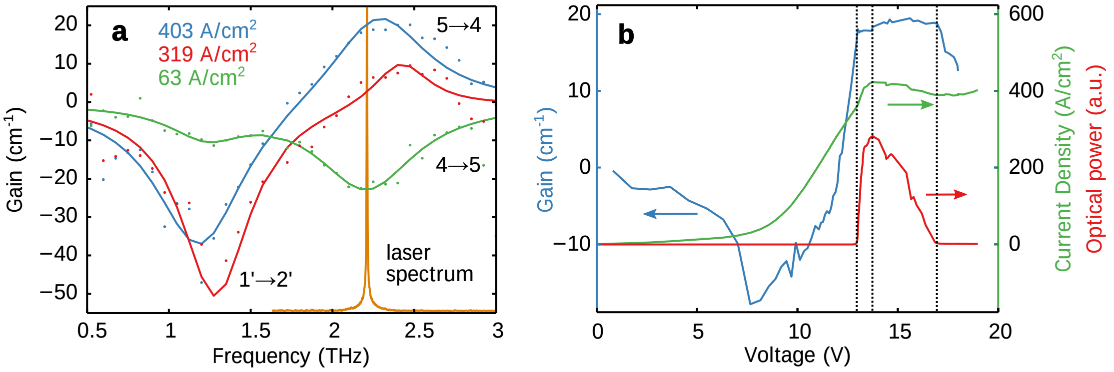

Fig. 2: (a) QCL gain measured as a function of frequency (dots), along with a double-Lorentzian fit (dashed lines). The three bias points shown are 63 A/cm^2 (far below threshold), 319 A/cm^2 (near threshold), and 403 A/cm^2 (above threshold). (b) Gain at 2.2 THz, light output, and current density as a function of voltage bias. Vertical lines indicate the onset of lasing, the onset of NDR, and the cessation of lasing.

Fig. 2(a) shows the resulting gain measured as a function of frequency and at several biases. Below laser threshold, absorption features are evident at 2.2 THz that corresponds to parasitic alignment of the injector levels to the lower laser level. We also observe an absorption feature at ~1.25 THz, which we attribute to absorption between the two injector states. As the bias is increased, the absorption at the lasing frequency yields to gain, and we observe laser action. This behavior is evident when the gain at 2.2 THz is plotted versus the voltage bias, shown in Fig. 2(b). At about half the design bias (corresponding to the bias where the injector aligns to the lower laser level), the absorption at the lasing frequency reaches its maximum. The gain then rapidly increases until lasing is reached, at which point it clamps to ~18 cm^{-1}, indicating the total losses of the cavity. When the QCL enters the negative different resistance (NDR) regime, electrical instability allows the gain to partially unclamp, and when the gain drops below threshold, lasing ceases.

In conclusion, we have successfully characterized the behavior of QCLs with metal-metal waveguides. The integration of a photoconductive emitter with the high-confinement waveguide should enable a wide range of possible experiments.

4. References

[1] J. Kröll, J. Darmo, S. S. Dhillon, X. Marcadet, M. Calligaro, C. Sirtori, and K. Unterrainer, "Phase-resolved measurements of stimulated emission in a laser," Nature 449, 698-701 (2007).

[2] B. S. Williams, S. Kumar, H. Callebaut, Q. Hu, and J. L. Reno, "Terahertz quantum-cascade laser at λ≈100 μm using metal waveguide for mode confinement," Appl. Phys. Lett. 83, 2124 (2003).

[3] B. Williams, S. Kumar, Q. Hu, and J. Reno, "Resonant-phonon terahertz quantum-cascade laser operating at 2.1 THz (λ≈141 μm)," Electronics Letters 40, 431-433 (2004).

[4] A. Wei Min Lee, Q. Qin, S. Kumar, B. S. Williams, Q. Hu, and J. L. Reno, "High-power and high-temperature THz quantum-cascade lasers based on lens-coupled metal-metal waveguides," Opt. Lett. 32, 2840-2842 (2007).

[5] Q. Wu and X. Zhang, "Free-space electro-optic sampling of terahertz beams," Appl. Phys. Lett. 67, 3523-3525 (1995).