Gain measurements of terahertz quantum cascade lasers using independent mode-matched emitters

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Recently, terahertz time domain spectroscopy (THz-TDS) has been shown to be a powerful tool for characterizing terahertz quantum cascade laser (QCL) gain media [1]. Typically, THz radiation is generated externally with a photoconductive antenna, focused onto the facet of a QCL with a single plasmon waveguide geometry, collected from the other facet, and sampled using photoconductive or electro-optic means. However, metal-metal waveguides have largely supplanted the surface plasmon waveguide in THz QCL research, as their tighter confinements of the optical mode and superior heat sinking abilities lead to increased temperature performance. [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 gain measurements of various types of metal-metal QCLs by integrating an independent terahertz pulse emitter with each device. The emitters are fabricated by lithographically etching a gap in a QCL ridge and cleaving the emitter section to be ~20 μm long. Near-infrared pulses from a ~100 fs Ti:Sapphire laser are focused onto the biased emitter to generate THz pulses, and collection of the pulses is aided by a silicon lens attached to the back facet of the device. Standard electro-optic sampling is used to measure the electric field as a function of time.

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. (Fig. 1(b) shows the difference of these two signals over a much longer delay range.) The QCL measured here is a five-level resonant-phonon design that that lases at 2.2 THz. 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. 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. As the bias is increased, the absorption at the lasing frequency yields to gain, and we observe laser action. In Fig. 2(b), the gain at 2.2 THz is plotted versus voltage bias. At 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.

Using this method, we can measure the properties of many types of gain media, and can get valuable information about electron populations, linewidths, and cavity losses. Such an improved understanding of QCL operation should eventually lead to improved temperature performance.

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[2] Kumar, S., Hu, Q. & Reno, J.L. "186 K operation of terahertz quantum-cascade lasers based on a diagonal design." Appl. Phys. Lett. 94, 131105 (2009).

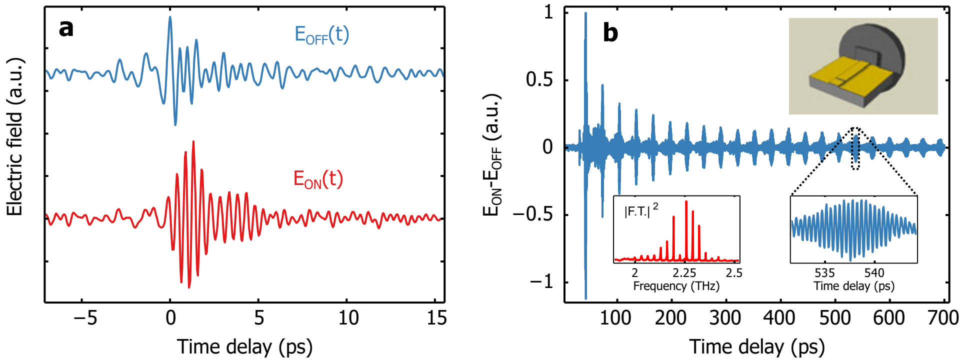

Fig. 1(a) THz pulse transmitted through QCL off and above threshold. (b) Difference in field generated by QCL over a 700-ps delay range. Top-right inset: schematic of device. Bottom-right inset: narrowband field oscillations resulting from laser action. Bottom-left inset: power spectrum of difference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

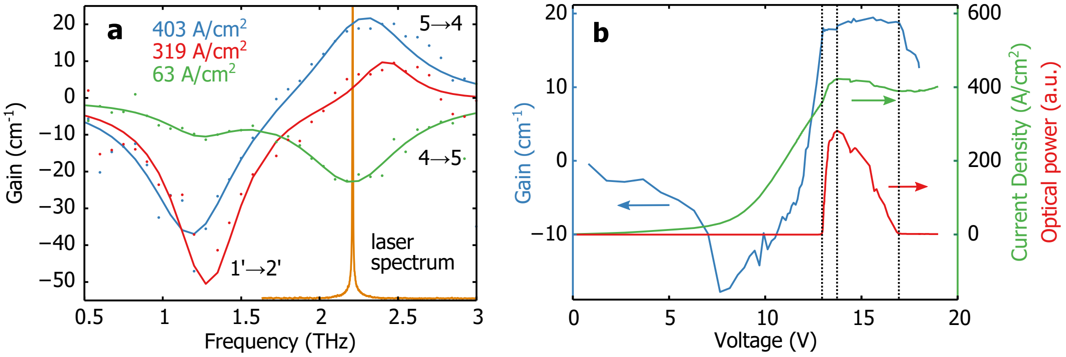

Fig. 2: (a) QCL gain measured as a function of frequency (dots), along with a double-Lorentzian fit (dashed lines). The three bias points shown are 63 A/cm^2 (far below threshold), 319 A/cm^2 (near threshold), and 403 A/cm^2 (above threshold). (b) Gain at 2.2 THz, light output, and current density as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