Gain measurements of terahertz quantum-cascade lasers with metal-metal waveguides

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Quantum-cascade lasers (QCLs) are a promising source of radiation in the terahertz regime [1] and potentially have extensive applications in the astronomical, chemical, and biological sciences. To that end, much work has gone into the development of active region designs that can achieve high-temperature operation. Terahertz time-domain spectroscopy (TDS) has proven to be a useful tool for characterizing the properties of these devices [2]. In TDS, a broadband terahertz pulse —usually generated with a mode-locked laser and a photoconductive antenna — is passed through a QCL active region and probed on the other side.

In recent years, the metal-metal waveguide has become the waveguide of choice for the highest-temperature terahertz QCLs, thanks in part to its increased mode confinement and reduced mirror losses [3]. However, the very properties that make the metal-metal waveguide attractive for high-temperature performance also make TDS measurements more difficult, since subwavelength confinement of the optical mode ensures that the coupling efficiency of the probing pulse is low. We circumvent this problem and perform TDS on such devices by using one facet as an integrated pulse generator [4] and affixing a silicon hyper-hemispherical lens to the other [5].

Figure 1(a) shows the terahertz pulses that result from the measurement of a device below and above lasing threshold, while Figure 1(b) shows the corresponding frequency spectra. The device was illuminated with 200 mW of optical power from a mode-locked Ti:Sapphire laser tuned to 730 nm, and detection was performed using an electro-optic scheme with a ZnTe crystal. Because the short pump wavelength pumps electrons above the $Al_{15}Ga_{85}As$ barriers, the generated spectra should be relatively bias-independent (up to a constant factor). Below threshold, the frequency spectrum looks like that of a typical photoconductive switch; above threshold, a bump in the spectrum appears that we attribute to the gain of the active region. Using the low-frequency response as a calibration factor, we can estimate the gain, shown in Figure 2. The peak gain at this bias occurs at 2.9 THz and has a value of approximately 36 cm^{-1}, and the full-width-half-maximum (FWHM) of the transition is about 1 THz.

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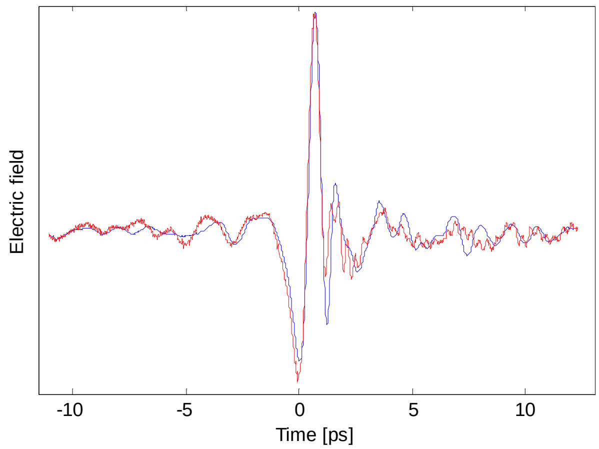

Figure 1(a): Pulse generated by device biased below threshold (5 mA, shown in blue) and above threshold (500 mA, shown in red). Gain medium is designated FL175M-M3, and has a two-well injector with a resonant-phonon depopulation scheme. Device is 80 microns wide and 1.5 mm long.

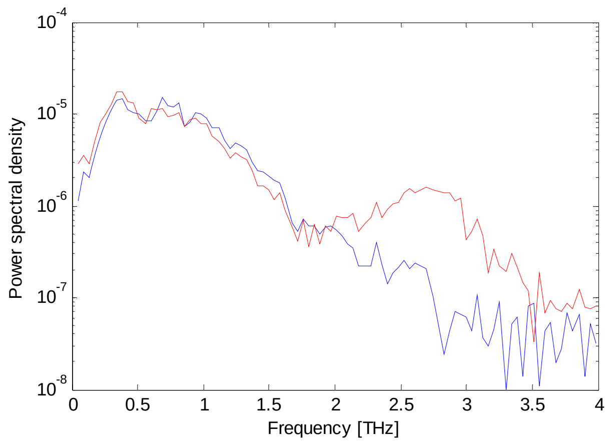

Figure 1(b): Frequency content of pulses. Two data points have been removed corresponding to atmospheric absorption lines not eliminated by purging; no additional scaling has been performed.

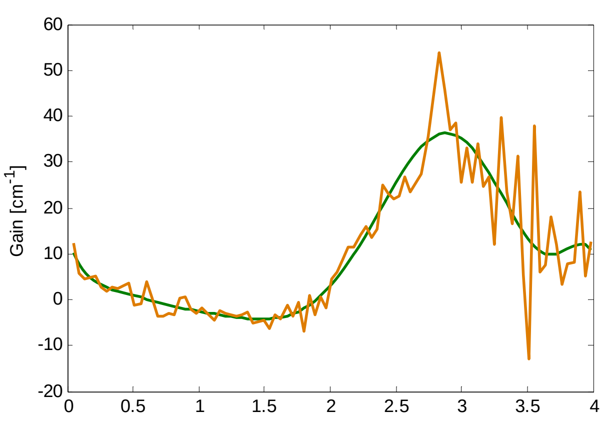

Figure 2: Gain spectra computed by dividing the logarithm of the ratio of the spectra by the device length. Green line is gain calculated from polynomial fits of data in Fig. 1(b).