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Pump-Probe Measurements of Gain in a Terahertz Quantum Cascade Laser

David R. Bacon, Joshua R. Freeman, Reshma A. Mohandas, Lianhe Li, Edmund H. Linfield, A. Giles Davies, Paul Dean
School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds LS9 2JT, United Kingdom

Abstract - **The gain recovery time of a bound-to-continuum terahertz frequency quantum cascade laser, operating at 1.98 THz, has been measured using broadband terahertz-pump-terahertz-probe spectroscopy. The recovery time is found to reduce as a function of current density, reaching a value of 18 ps as the laser is brought close to threshold. We attribute this reduction to improved coupling efficiency between the injector state and the upper lasing level as the active region aligns**.

I. INTRODUCTION

In recent years active modelocking of a terahertz (THz) quantum cascade laser (QCLs) has been reported [1, 2]. However, it is difficult to form stable modelocked pulses from this type of device owing to the interplay of the inherent characteristic lifetimes, most notably the ratio of the gain recovery time (GRT) and round-trip time of the laser cavity. In this work [3], we measure the GRT of a bound-to-continuum THz QCL directly using a THz-pump-THz-probe technique, based on a THz time-domain spectroscopy (TDS) [4, 5], arrangement. The GRT of the THz-QCL is dependent on the applied bias and is found to reduce as the device approaches threshold, at which point a value of 18 ps is obtained.

II. EXPERIMENT

For this experiment, a Ti:Sapphire femtosecond laser was used, centred at 800 nm, it produced 100 fs pulses at an 80 MHz repetition rate and 2 W average power. This provided the optical excitation for a large-area photoconductive emitter and gated detection. The optical beam was split into three parts, for the 'pump', 'probe' and 'sampling' beams. The more powerful pump pulse passed through a delay stage to vary its arrival time on the emitter, thus providing control of the pump-probe delay (PPD), before being focused onto the same photoconductive emitter as the probe beam. The generated broadband THz pump and probe pulses were collected and focused into the QCL facet using parabolic mirrors. The QCL device consisted of a 14.2 μm thick active region confined with a single *plasmon* waveguide (4.4 mm-long and 200 μm-wide), and had a threshold current density of 124 Acm^{-2} at a heat sink temperature of 15 K. The THz pump pulse arrived first at the QCL input facet, causing stimulated emission from the population inversion within the active region, thereby depleting the population inversion and available gain. At a later time (equal to the PPD) the THz probe pulse entered the cavity and experienced amplification proportional to the population inversion in the active region. To determine the GRT of the QCL, the probe pulse was measured for different time-delays with respect to the earlier pump pulse. A modulation scheme consisting of two lock-in amplifiers was used to discriminate between the THz pump and THz probe signals.

III. RESULTS

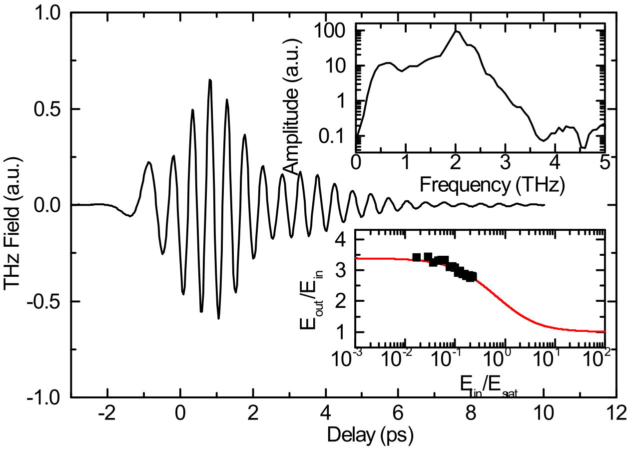

Figure 1: Time and frequency-domain measurements of a broadband pulse, after passing through the QCL biased just below threshold. The lower inset shows the relationship between QCL cavity gain and injected pulse power (black squares). A fit based on the Frantz-Nodvik equation has also been plotted (red line).

Figure 1 shows the signal obtained with the probe beam blocked and the QCL biased below threshold at a current density of 114 Acm^{-2}. In this case the signal corresponds to the pump pulse following relative amplification in the QCL cavity. The bias of the LT-GaAs emitter was then varied so that the dependence of this amplification on input THz power could be determined. The input power was estimated from the FFT of the signal, evaluated at a frequency of 2 THz, measured when the QCL was unbiased. These results, shown in the lower inset, reveal that the pump pulse is partly able to saturate the population inversion.

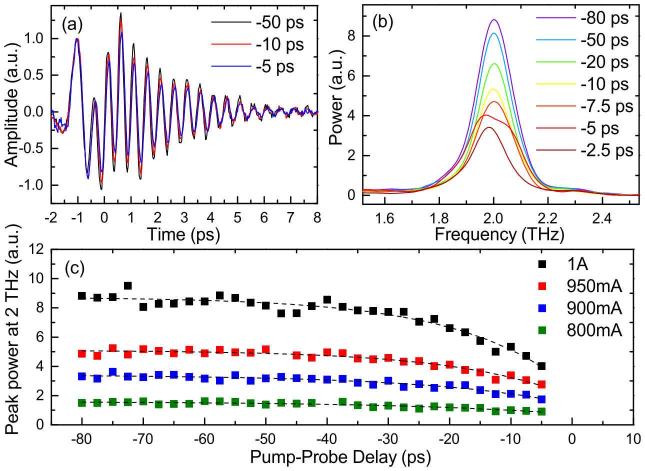

Figure 2: (a): Time-domain trace/ (b): Frequency spectrum of the probe pulse for various PPD times. (c): Peak of the probe spectrum at the QCL emission frequency of 2 THz, as a function of PPD, plotted for four different QCL current-densities (squares). An exponential fit has been applied to each curve (black lines).

This data has been fitted to the Frantz-Nodvik equation [6]. Next the probe beam was unblocked. Figure 2(a) illustrates the probe signal obtained for various PPD times, normalized to the peak of the incident THz probe pulse. As the PPD reduces, so does the relative gain at 2 THz, since the gain has less time to recover after the passage of the pump pulse. In the time-domain, this is indicated by the reduction in oscillation time and amplitude, while the spectra (Figure 2(b)) reveal a reduced peak at 2 THz. Figure 2(c) shows the peak spectral power at 2 THz as a function of PPD, plotted for four separate bias conditions.

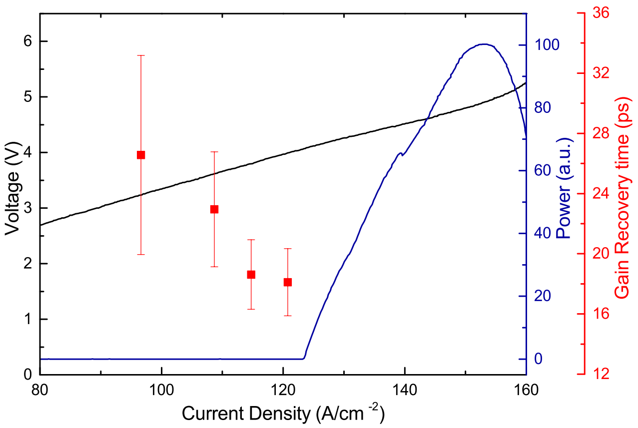

Figure 3: Measured gain recovery time at different current densities (red squares), with error bars determined by the exponential fit. The blue line is the THz power. The black curve is the IV response of the QCL.

Exponential fits have been used to determine the recovery time for these values of current density, and these are plotted together with the light-current-voltage characteristics for this device in Figure 3. The data reveals a significant decrease in the GRT from 27 ps to 18 ps as the laser approaches threshold. We expect the recovery time to be dominated by carrier transport from the injector into the upper-lasing state through the 'injection barrier' of the active region, and we attribute the decreased recovery time to increased coupling efficiency between these wave-functions.

As the QCL current is increased above threshold the mechanisms involved in gain recovery become more complex. The rise in the cavity photon density adds an additional mechanism for depopulation of the upper lasing level through stimulated emission. This mechanism is influenced by mirror losses, spectral hole burning, and the precise photon distribution in the cavity. For the purposes of rate equation calculations and modelocking considerations, only the "bare cavity," purely electronic, recovery time is relevant. To obtain reliable measurements of the gain recovery time when the laser is biased for peak gain, antireflective coatings could be used to suppress lasing and move the threshold to higher current density. We also note that the rate of gain recovery is expected to differ for different active region designs, in particular, THz QCLs based on LO-phonon extraction (rather than the miniband extraction design measured here) are expected to exhibit faster dynamics and further measurements are required to investigate this.

IV. SUMMARY

We have shown that the GRT of a bound-to- continuum THz QCL is reduced as the laser is brought towards threshold, attaining a value of 18 ps just before laser action commences. This value is significantly higher than has been measured for QCLs operating in the mid-IR range (2–3 ps) where the active region transport is based on rapid phonon-depopulation designs. We note that the values of GRT agree well with the estimate of 15 ps obtained by Maxwell-Bloch simulations of pulsed seeding of a bound-to-continuum THz QCL[7]. The fast gain recovery measured in this work explains why conventional methods for modelocking THz QCLs are problematic.

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