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Investigation of Time-resolved Gain Dynamics in an Injection Seeded Terahertz Quantum Cascade Laser

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Abstract: The evolution of the gain of terahertz quantum cascade laser during injection seeding is probed as a function of time. Oscillations of the gain are commensurate with the variations of the field envelope.

OCIS codes: (320.7150) Ultrafast spectroscopy; (140.5965) Semiconductor lasers, quantum cascade

1. Introduction

The gain dynamics of quantum cascade lasers (QCLs) is of vital importance for mode-locking [1-2] and fast modulation of QCLs. The lifetime of the intersubband transitions mainly determines QCL gain dynamics which are expected to be on the order of picoseconds. Several previous studies have been performed on the gain dynamics of mid-infrared QCLs [3-4], and terahertz (THz) QCLs [5]. Typically these studies require a very strong initial pump pulse in order to saturate the gain. In this submission gain saturation is achieved by injection seeding the QCL with a relatively weak THz pulse from an 80 MHz oscillator. The THz pulse (i.e. seed pulse) is amplified by the THz QCL at the QCL frequency. This creates a strong-field pulse inside the laser that saturates the gain. The dynamics of the QCL gain is then probed with a second THz pulse. This offers a unique opportunity to explore the dynamics of evolution of the terahertz gain and field inside the QCL simultaneously.

2. Description of the experiment

A schematic of the experimental arrangement is shown in fig. 1a. Two consecutive THz pulses are generated by illuminating a low-temperature (LT) grown GaAs photoconductive emitter with femtosecond laser pulses. The time delay between the femtosecond laser pulses and hence the THz pulses is set by a delay stage in one arm of the Michelson interferometer shown in fig 1a. The LT-GaAs photoconductive emitter has a fast recombination time which allows the generation of nearly identical THz pulses when the LT-GaAs emitter is illuminated by consecutive femtosecond laser pulse as shown in figure 1b. A portion of the femtosecond laser pulse is used to trigger a fast-photodiode. This generates a nanosecond electrical bias pulse, shown in fig 1c, which is amplified and sent to the THz QCL. The first THz pulse from the LT-GaAs emitter (the seed pulse) arrives in the QCL at the same time as the rising edge of the nanosecond bias pulse.

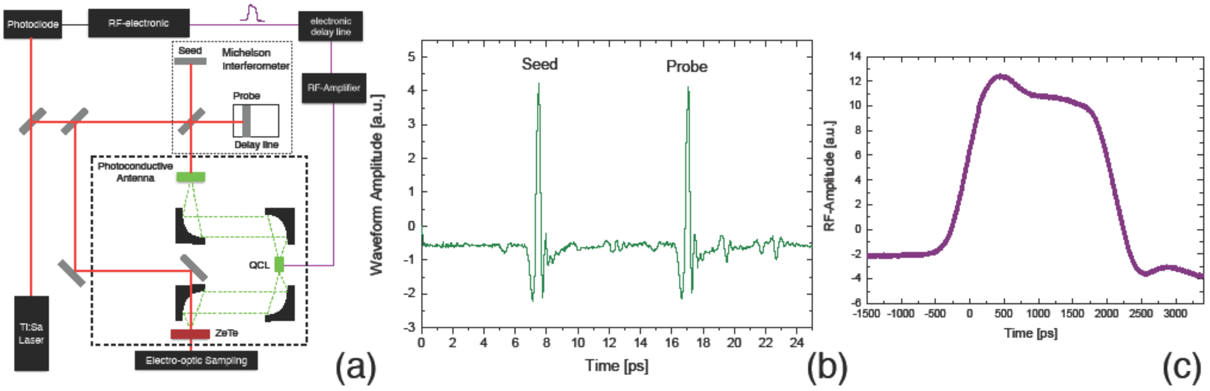

Figure 1 **a)** Experimental setup. The femtosecond laser beam (red lines) generates the terahertz radiation (green), triggers the nanosecond bias pulse (purple) and measures the emitted THz fields in a ZnTe crystal. **b)** Terahertz pulses emitted from low temperature grown GaAs photoconductive emitter. **c)** Electrical bias pulse applied to the QCL.

The nanosecond bias pulse drives the QCL above threshold and the first THz pulse (the seed pulse) experiences large amplification until it saturates the gain of the QCL. The second THz pulse, which has a variable time delay, is then used to probe the gain dynamics. The emitted THz field from the QCL is detected using free space electro-optic sampling with a ZnTe crystal. In order to detect THz fields originating from the seed pulse the probe arm of the interferometer is blocked and both the QCL and antenna are modulated for lock-in detection. In order to detect the transmittance of the second THz pulse, an optical chopper is placed in the probe arm and the chopper frequency is used as the reference for lock-in detection.

3. Results and Discussion

Figure 2a shows both the seed pulse emission from the QCL (black curve) which saturates the QCL gain and the transmission of the probe pulse at the laser frequency (red curve). The rapid oscillations of the electric field (black curve) are shown in fig. 2b. In order to increase the signal to noise ratio of the probe transmission the first echo of the probe pulse is recorded. This increased the probe pulse duration to approximately 20 ps. Since the time in fig. 2 corresponds to the start of the probe pulse and the Fourier transforms are taken over 20 ps the probe transmission curve is shifted with respect to the seeded emission of the QCL. Initially for times between 50-125 ps, the probe transmission (i.e. gain) is nearly constant with the time. The amplitudes of the 2nd and 3rd seeded pulses in figure 2a are not strong enough to saturate the gain. However at later times the amplitude of the seeded pulses increases and the probe transmission is clearly seen to saturate for the 4th seeded pulse. The probe transmission then partially recovers before being saturated by 5th seeded pulse. For longer times secondary seed pulses that arise from reflections in the dielectric substrate of the LT-GaAs emitters are amplified and become visible. These secondary seed pulses connect the primary seed pulses and significantly reduce the modulation of the seeded field in the QCL. Consequently the modulation of the probe transmission decrease with time especially after the 6th seeded pulse. In addition for long times (>350 ps) the average probe transmission between pulses is nearly constant and consecutive pulses are nearly identical indicating that the laser is entering the steady-state regime.

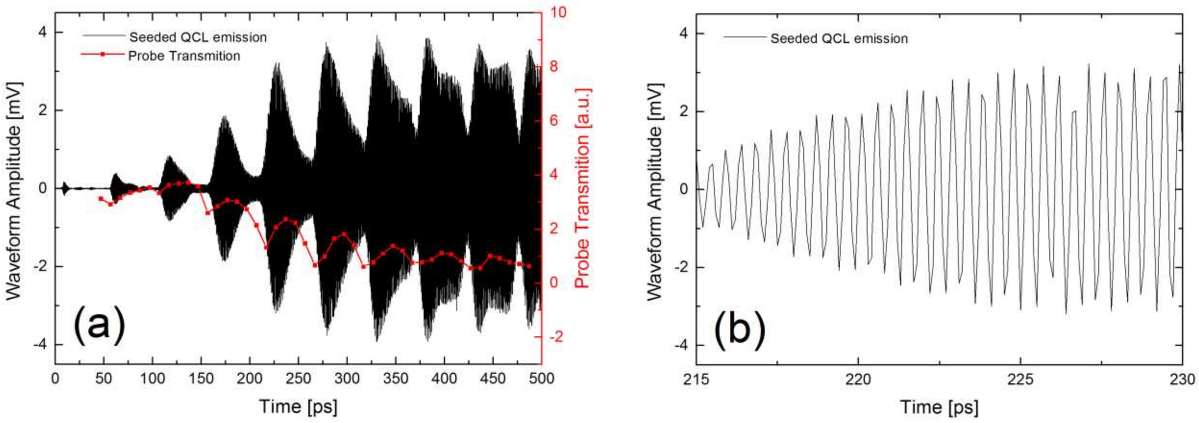

Figure 2 **a)** Black lines - the seeded emission from the QCL that originates from the first THz pulse injected into the QCL. Red lines – the transmission of spectral amplitude of the probe pulse at the QCL transition frequency. Note that the duration of the probe pulse shifts the transmission with respect to the seeded QCL emission to earlier times. **b)** Zoomed-in view (215 ps to 230 ps) to show the oscillations of the electric field in part **a)**.

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