Observation of Time-resolved Gain Dynamics in a Terahertz Quantum Cascade Laser

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***Abstract*—The dynamic response of a terahertz quantum cascade laser is probed as a function of time. The gain of the THz QCL is saturated by injection seeding the laser with an initial THz seed pulse. The time-resolved gain of the injection seeded laser is then probed with a second THz pulse.**

I. INTRODUCTION

The gain dynamics of quantum cascade lasers (QCLs) is of great interest for mode-locking and high-speed modulation. The intersubband lifetime in mid infrared QCLs are measured to be on the order of picoseconds which enables fast gain recovery time [1-2]. Compared to their mid-infrared counterparts there is a lack of investigation on the gain dynamics of terahertz (THz) QCLs [3-4]. The conventional way to resolve the gain dynamic is to perform THz pump-probe experiments. However, this requires extremely high pump electric fields. In addition only the spectral amplitude at the lasing frequency is involved in saturating the QCL gain. Thus essentially most of the power of a broad-band THz pulse is wasted. In order to generate such strong field pulses a free-electron laser (FEL) or an amplified femtosecond laser system must be used with an extremely low repetition rate. In this submission we saturate the gain with weak THz pulses by injection seeding the THz QCL. This allows us to measure simultaneously the gain and the laser field of the QCL in the time-domain [5].

II. RESULTS

In order to have access to the time-resolved QCL gain dynamics, two broad-band THz pulses are generated by illuminating a photo-conductive antenna (Fig. 1). Generated THz pulses are coupled into the facet of a 2.2 THz bound-to-continuum QCL and recorded with electro-optic sampling technique.

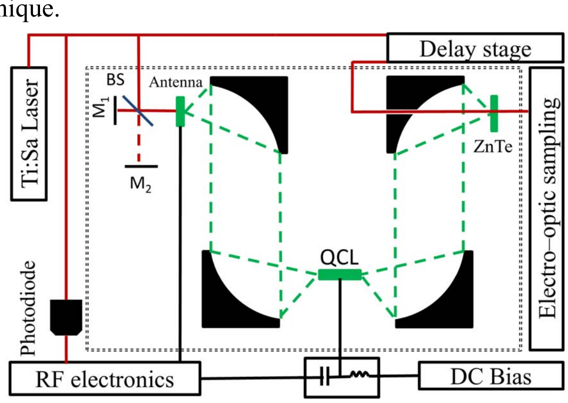

Fig. 1. Sketch of experimental setup. M1: Mirror, M2: mirror on a translation stage. BS: beam splitter.

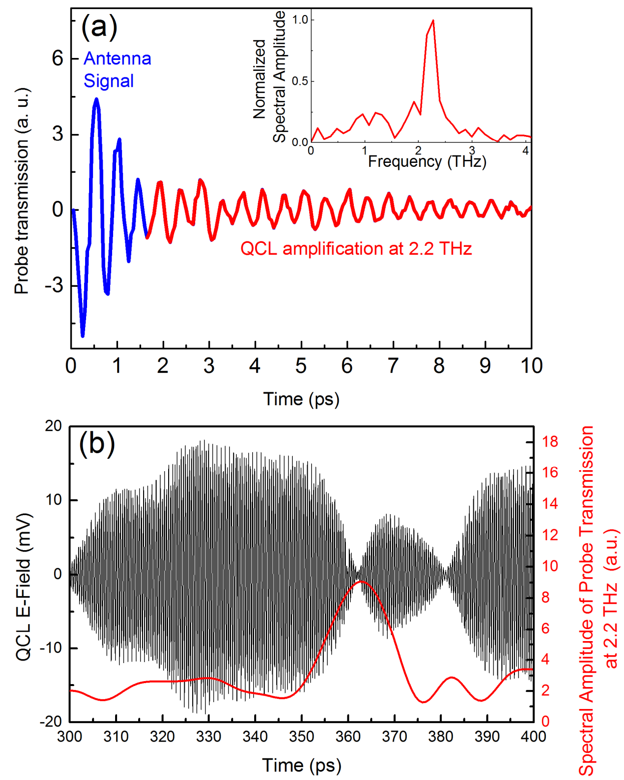

Fig. 2. a) Time resolved probe transmission. The blue/(red) oscillations correspond to the photoconductive antenna/(amplified probe transmission). The insert shows the amplified probe spectra. The maximum at 2.2 THz corresponds to the laser frequency. b) Black curve

After the first THz pulse enters the laser cavity, a bias pulse with a sub-nanosecond rise-time drives the gain of the QCL above the threshold value. This allows the first THz pulse to experience large amplification and saturate the gain of the QCL [6]. At a later time the second THz pulse probes the gain inside the QCL. The time resolved probe pulse is shown in fig. 2 (a). The probe pulse consists of what is essentially the unamplified THz probe frequencies (blue oscillations) and the amplified THz probe frequencies centered at 2.2 THz (red oscillations). In fig 2b the gain maximum (at 2.2 THz) of the spectral amplitude of the probe transmission (red curve) is superimposed with the injection seeded QCL emission (black curve). When the laser field goes to zero at approximately 360 ps the gain (probe transmission) rapidly recovers in 7.5 ps (from 20%-80%). Curiously, the gain then appears to be saturated in the presence of a weaker laser field at 370 ps and does not recover when the field goes to zero at 385ps.

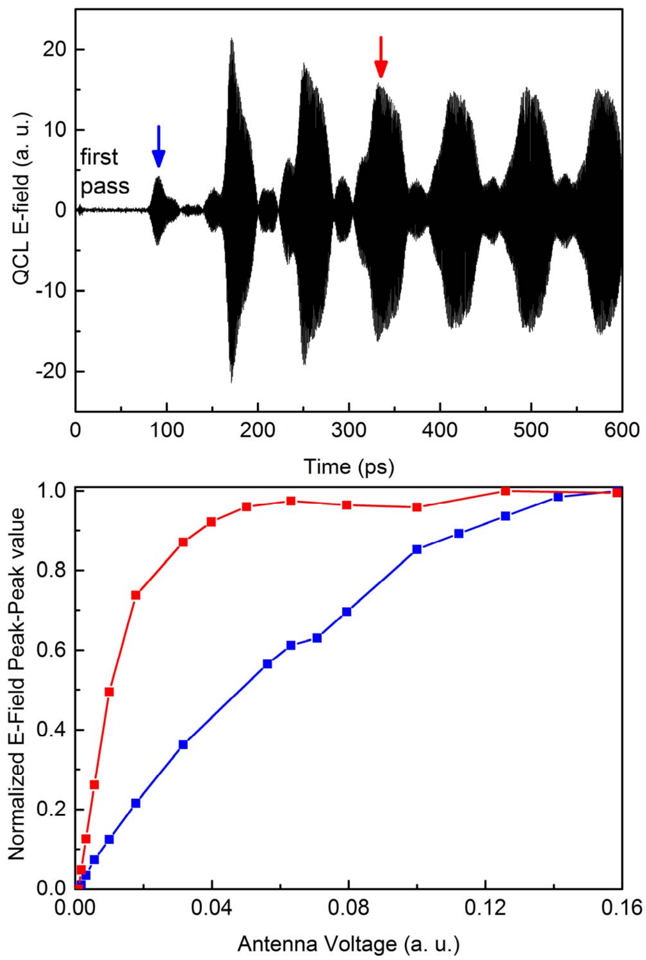

Fig. 3 Fig. 3 a) Injection seeded waveform with a single THz pulse. b) Blue and a red arrows in Fig. 2 a) indicate the THz pulse on which the RF pulse was optimized (adjust/shifted in time) and the respectively color coded saturation curves were measured.

However, in contrast to a conventional pump-probe experiment the present measurements take place in a cavity with a round-trip time of 80 ps and the THz probe can also be saturated by reflections propagating in the opposite direction. One of the crucial details of this experiment is the free running laser. To be able to record the recovery (fig. 2 (b)) of the probe transmission it is necessary to avoid the spontaneous emission. The detected QCL emission with electro-optic sampling technique enables to detect only the phase locked emission to the femtosecond laser.

The influence of spontaneous emission can be seen in fig. 3. By biasing the QCL with the RF bias and driving the QCL above the threshold it is important to adjust the RF pulse in time accordingly to the THz seed. Fig. 3 shows the effect on the saturation curves (Fig. 3 (b)) and hence on the QCL emission if the RF pulse is optimized on different pulses of the injection seeded QCL that are indicated with the blue and the red arrows in Fig 3(a). For these two cases (blue and red arrows in fig. 3(a)) saturation curves are taken (fig. 3 (b)). The saturation curves show the peak to peak value of the recorded electric field versus the applied antenna bias (seed amplitude).

In case of the blue saturation curve, the QCL emission is not saturated this leads to a significant amount of amplified spontaneous emission in the laser cavity [7]. For this the gain recovery was not observed. In the case of the red saturation curve it is much easier to saturate the QCL emission and it does not require strong THz seed. For this saturation curve the gain recovery measurements are shown in fig. 2 (b).

III. Summary

In The gain dynamics of an injection seeded THz QCL was explored in the time domain. The probe transmission experiences a fast recovery time of 7.5 ps which corresponds to the gain recovery in the THz QCL. In comparison to pump-probe experiments this introduced technique enables to record the trace of the probe recovery and hence offers the possibility to study the dynamics on each THz pulse of the injection seeded QCL.

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