Double-pulse Injection Seeding of a Terahertz Quantum Cascade Laser

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***Abstract*—Double-pulse injection seeding is used to modify the spectral emission of a terahertz quantum cascade laser (THz QCL). Two broad-band THz pulses delayed in time imprint a modulation on the single THz pulse spectrum. The resulting seed enables modification of the QCL emission spectrum, even though, the spectral bandwidth of each THz pulse is much broader than the QCL gain bandwidth. For a proper time delay between the pulses, the seeded THz QCL emission can even be switched from a multimode to a single mode regime.**

I. INTRODUCTION

Quantum cascade lasers (QCLs) are promising sources of terahertz radiation. Typically the emission spectrum of a THz QCL consists of several free-running longitudinal modes. The control of the THz QCL mode emission can be useful for spectroscopy. One method to achieve selectivity of the mode of a laser is to use injection seeding technique. In this case, a weak tunable seed pulse whose spectrum is narrower than the mode spacing is amplified by the laser. The spectral emission of the laser is thus controlled by the seed spectrum. Recently, a THz QCL was injection seeded with narrow-band THz seeds, which enabled the QCL emission to be switched between longitudinal modes by selecting the appropriate narrow-band seed frequency [1]. Although THz pulses can be easily generated with a photo-conductive antenna and a femtosecond laser in order to injection seed a THz QCL [2], their spectrum is typically an order of magnitude wider than the spectral emission. Thus previous reports of injection seeding with broad-band THz seed pulses have exhibited multi-mode emission [2], and even an enhancement in the number of emitted longitudinal modes [3].

II. RESULTS

In this contribution we demonstrate that two broad-band THz pulses can be used to modify and control the spectral emission of a THz QCL. Specifically, two THz pulses with a variable time delay are used to seed the QCL. This induces a delay dependent modulation of the frequency components within the single THz pulse spectrum, whose period is the reciprocal of the delay time. Thus by choosing an appropriate delay time, the seed spectrum can be modified to either favor or inhibit lasing on particular modes.

A schematic of the experimental setup is shown in Fig.1. At the output of the femtosecond Ti:Sa laser, the near infrared (NIR) beam is divided into three parts. The first part of the beam is focused on a fast photodiode to generate RF pulses for biasing the QCL. The second part of the beam is used for electro-optic sampling of the THz signal from the QCL with a 2 mm ZnTe crystal. This allows the THz electric field to be measured in the time domain. The third part of the beam, which contains the majority of the laser power, is sent to an optical Michelson interferometer with 50:50 beam splitter that generates two NIR pulses. A time delay between the two NIR pulses is introduced by moving the mirror M2 (see in Fig.1). The two THz pulses are generated from photo-excitation of a biased photo-conductive antenna. It is processed on low temperature (LT) grown GaAs. The LT-GaAs prevents screening of the bias field from the first NIR laser pulse and enables the generation of a second THz pulse at shorter time.

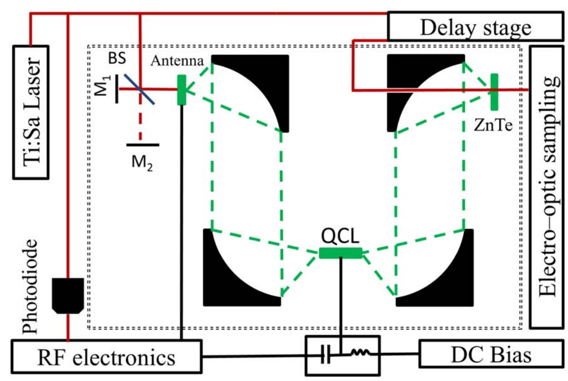

Fig.1 Schematic of the experimental setup. 80 fs laser pulses (average power 1.7 W repetition rate 80 MHz) are generated by a Ti:Sa laser. The laser beam is sent to the Michelson interferometer where it is split into two branches and focused on the photo-conductive antenna. By introducing a delay between mirrors M1 and M2, two THz pulses are generated that are coupled into the QCL. The QCL is gain-switched with an RF-pulse (which is synchronized with the Ti:Sa laser) just before the first THz pulse arrives at the facet of the QCL. Time-resolved measurements of the injection seeded QCL emission are obtained by electro-optic sampling with a ZnTe crystal.

The experiment is performed under purged conditions. The optical NIR power focused onto the antenna, for each THz pulses, is approximately 220 mW. The 2.1 THz QCL used in this experiment is a bound-to-continuum GaAs/AlGaAs laser processed as a surface plasmon waveguide. The QCL ridge is 2 mm long and 0.15 mm wide. It is mounted on a gold coated copper sub-mount for effective heat sinking in the cryostat, which is maintained at 20 K. The RF bias pulse generated by the fast photodiode are sent through an electronic comparator and high power electronic amplifier. The amplified RF pulses turn the gain of the QCL on with assistance of a DC bias. When the QCL gain crosses threshold, a broad-band THz seed is injected into the laser cavity. This enables the THz seed pulse to experience large gain that is not saturated by a pre-existing laser field. In the scheme of an injection seeding experiment, the QCL acts as an amplifier of the seed frequency components within the QCL gain bandwidth. In order to ensure the QCL operates in the injection seeding regime, the seed amplitude is set so that it lies well beyond the transition region between the linear and injection seeded regimes as shown in Fig. 3. Under these conditions it has been shown that the majority of the QCL emission is locked to the THz seed pulse [3]. Finally, a second and identical THz pulse is also injected into the QCL cavity in order to induce mode selection.

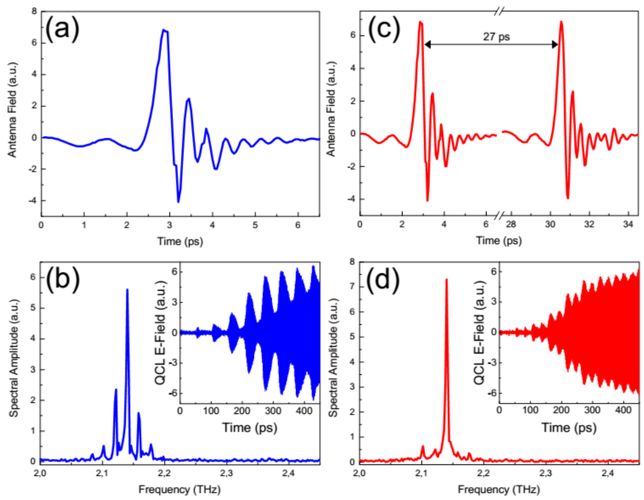

Fig.2 **a)** Single broad-band THz seed pulse **b)** Spectrum of the injection seeded QCL with the single seed pulse shown in part **a)**. Insert: Electric field of the single pulse seeded QCL emission **c)** Two broad-band THz seed pulses separated by 27 ps time delay. **d)** Spectrum of the injection seeded QCL with two seed pulses shown in part **c)** Insert: Electric field of the double pulse seeded QCL emission.

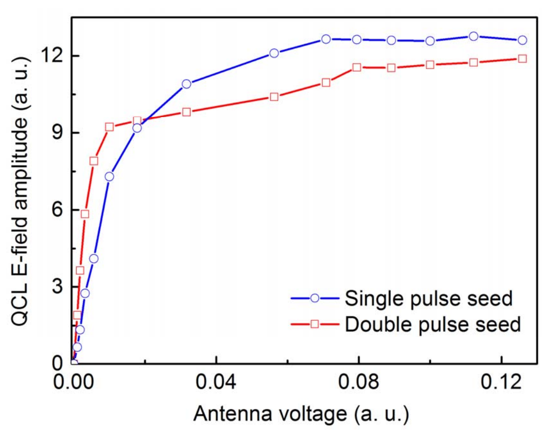

Fig.3 Saturation curves of the seeded QCL emission as function of the antenna bias for the spectra describe in Fig.2.

Injection seeding with a single broad band THz pulse (Fig 2a) with the second THz pulse blocked is illustrated in Fig. 2 b. Three main longitudinal modes are present in the QCL seeded spectrum. In Fig.2 c, we unblock the second THz pulse which is generated 26 ps after the first one. In this case, the QCL seeded emission is switched from multi-mode to single mode emission as shown in Fig. 2d.

III. Summary

Double pulse phase seeding with broad-band THz pulses can modify the spectral emission of a QCL laser, even though, the spectra of the individual THz pulses is much broader than the QCL emission spectra. By generating a second THz pulse at a proper time delay, the multi-mode emission from a QCL can be made predominantly single mode.

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