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Narrow Bandwidth Injection Seeding of a THz Quantum Cascade Laser

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***Abstract*—Narrowband THz pulses generated from a periodically poled lithium niobate crystal are used to injection seed a terahertz quantum cascade laser. The phase locked spectral emission from the quantum cascade laser is significantly influenced by the spectrum of the seed pulse.**

I. INTRODUCTION

PHASE locking of terahertz (THz) quantum cascade lasers (QCLs) was recently investigated in the context of injection seeding [1]. In this technique a THz seed pulse generated by a femtosecond laser sets the phase of the laser emission from a QCL. This enables the detection of the emitted QCL laser field by using the same electro-optic sampling techniques employed in THz time-domain spectroscopy. Injection seeding is implemented by turning on the QCL gain with an electrical bias pulse immediately after the external THz seed enters the QCL laser cavity. Since the broadband (FWHM > 1 THz) seed pulse excites several longitudinal laser modes simultaneously, this time-resolved technique has been used to investigate mode-locking in THz QCLs [2]. However, the traditional goal of the injection seeding, namely single mode emission and control of the emission frequency from the seed [3], cannot be achieved with broadband seed pulses that span several longitudinal modes.

In this contribution a THz QCL is injection seeded with narrow-band seed pulses whose FWHM is on the order of the longitudinal mode spacing of the QCL. The narrowband THz seed pulses are generated in a periodically poled lithium niobate (PPLN) crystal with femtosecond laser pulses [4]. In the PPLN crystal quasi-phase matching occurs between the femtosecond laser pulse and specific THz wavelengths that depend on the poling period. If absorption can be neglected, the bandwidth of the narrowband THz emission is inversely proportional to the number of poling periods [4]. A reflection geometry for THz generation was used in order to access the backward propagating wave, which has smaller bandwidth for a given crystal length. The length of each periodically poled region is 5 mm with a width of 0.5 mm, and a thickness of 0.5 mm. The PPLN crystal has several poled regions with periodicities ranging from 18.50 to 20.90 μm in increments of 0.30 μm. By moving the PPLN crystal with respect to the focused femtosecond laser beam different periodically poled regions (and hence different THz seed frequencies) can be selected. The corresponding THz frequencies range from 2.270 THz to 2.023 THz in steps of 0.03 THz. In order to minimize THz absorption in lithium niobate [6], the PPLN crystal was mounted in a helium-cooled continuous-flow cryostat and cooled to 10 K. The THz QCL was a 3.25-mm-long and 0.15-mm-wide bound-to-continuum GaAs/AlGaAs laser processed as a surface plasmon waveguide [7]. It had a threshold current of 100 A/cm^2 (at a two-terminal voltage of 3.3 V), and a maximum operating temperature of 70 K.

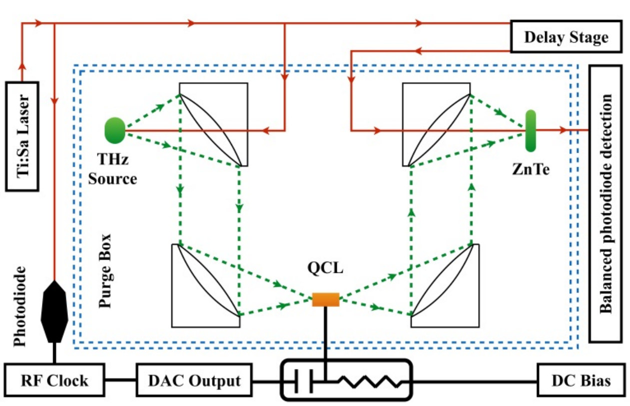

Fig. 1 Red lines - 800 nm laser beam. Green dash lines - THz beam. Blue dash lines - purge box. The seed pulses are coupled into and out of the QCL with off-axis parabolic mirrors. The fields are measured by free space electro-optic sampling with a 2mm thick ZnTe crystal.

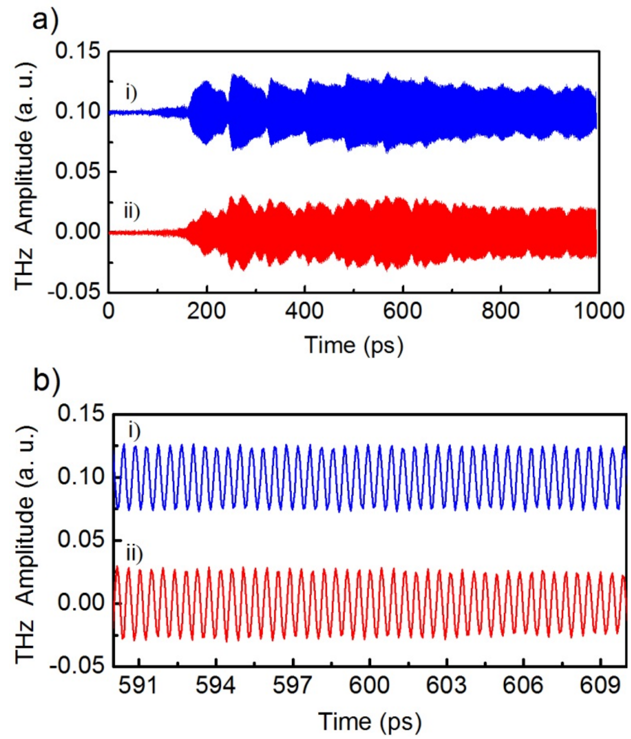

Fig. 2 a) THz field amplitudes emitted by the QCL for narrow-band seed pulses from the PPLN crystal with central frequencies of 2.174 THz (i-blue), and 2.240 THz (ii - red). **b)** Close up of part a) showing the oscillations of the electric field.

The experimental apparatus is shown in fig. 1. A fast photodiode was used to generate the clock for the RF electronics, and ensured that the repetition rate of the 1.5 ns bias pulses was synchronized to the 80 MHz repetition rate of the femtosecond laser and the THz seed pulses. In order to rapidly turn on the QCL gain, a 2 W RF bias pulse (with a rise time of 400 ps and duration of 1.5 ns) was applied to the QCL. To achieve injection seeding the THz seed pulse was sent into QCL cavity during the rise time of the RF pulse. A quasi-DC bias (two-terminal voltage: 1.5 V, current density: 45 A/cm^2) was also applied to the QCL along with the RF pulse. The quasi-DC bias reduces the amount of RF power that is required to drive the QCL above threshold. Since initially there is no laser field inside the QCL cavity, the seed pulse experiences large amplification until the field inside the cavity is sufficient to saturate the gain.

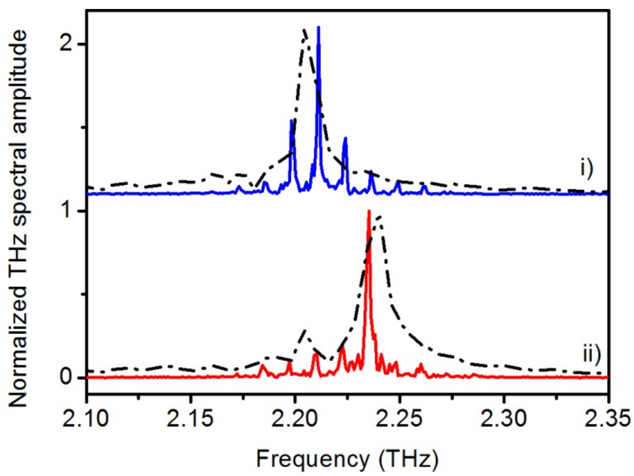

Fig. 3 Normalized spectral amplitude when the QCL is seeded by the narrowband seed pulses with center frequencies - 2.174 THz (i-blue) and 2.240 THz (ii-red). The corresponding normalized PPLN seed spectra are superimposed on the QCL spectra as black dashed lines.

II. Results

The emitted fields from the QCL, when injection seeded with two narrowband seed frequencies (2.174 THz and 2.240 THz) are shown in fig. 2. The first pass of the narrow-band seed through the QCL occurs at time zero. Its amplitude is too small to be seen in fig. 2. Since no laser field is present in the cavity at time zero, the gain of the laser is not saturated. Consequently, the seed pulse gain is greater than the total losses. The THz emission is significantly amplified after two round-trip times (154 ps) in the laser cavity. The maximum amplitude value of the THz field pulse is reached after three round-trip times (starting at 231 ps). After this time the gain is more or less saturated by the field in the cavity and no further amplification occurs. For both seed frequencies the output of the QCL was found to saturate with the amplitude of the seed pulse, which implies the majority of the QCL emission is phase locked to the seed [5]. Fig. 2b) shows that the phase of the electric field oscillations can be resolved in time. The spectra from the QCL can be obtained by taking the Fourier transform of the data in fig. 2.

When the QCL is seeded with different frequencies the spectral emission of the QCL shifts. In fig. 3, the frequency of the maximum spectral emission is shifted by two longitudinal modes. Only the ratio of the intensity between the modes is influenced by the seed spectra. The frequencies of the longitudinal modes are determined by the round-trip time of cavity. The normalized spectra of the PPLN seed pulses (dash lines) are superimposed on the corresponding QCL spectra in fig. 3 for comparison. The maximum spectral amplitude of the narrow-band seed pulses roughly correspond to the maximum of the QCL emission. The FWHM of the seed pulses is of the order of the longitudinal mode spacing (.012 THz). However, the wings of the narrow band seed spectra extend across several longitudinal modes that are present as satellite peaks in QCL spectra.

III. Summary

We succeeded in shifting the spectral emission of a QCL by injection seeding it with narrow band THz seed pulses. The narrowband THz seed pulses were generated with a PPLN crystal and a femtosecond laser. The narrowband THz seed pulse was injected into the QCL cavity just before the application of a nanosecond bias pulse. The bias pulse turned on the QCL and consequently amplified the narrowband seed. The spectra of the seeded QCL overlapped the spectrum of the narrowband seed pulse.

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