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Selection of Longitudinal Modes in a Terahertz Quantum Cascade Laser via Narrow-band Injection Seeding

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Abstract: A terahertz quantum cascade laser is injection seeded with narrow-band seed pulses generated from a periodically poled lithium niobate crystal. The spectral emission of the quantum cascade laser is controlled by the seed spectra.

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

1. Introduction

Phase locking of terahertz (THz) quantum cascade lasers (QCLs) can be achieved through the use of injection seeding [1]. If the THz seed is generated by a femtosecond laser, the phase of the laser emission is also locked to the repetition rate of the femtosecond laser. This enables access to the time-resolved THz-field from the QCL via electro-optic sampling. Seeding of THz QCLs is typically realized with broad-band THz seeds generated from GaAs photoconductive emitters. The bandwidth of such seed pulses typically spans several THz which is much larger than the gain-bandwidth of the THz QCL. Consequently, all longitudinal modes in the spectral gain region are simultaneously excited. Thus the traditional goals of the injection seeding, namely frequency control and single mode emission cannot be achieved with broad-band THz seed pulses.

In this contribution a THz QCL is injection seeded with narrow-band seed pulses which have a full-width at half-maximum (FWHM) on the order of the longitudinal mode spacing [2]. The narrow-band THz seed pulses are generated in a periodically poled lithium niobate (PPLN) crystal from femtosecond laser pulses [3]. The narrow-band seed pulses enhance longitudinal modes that overlap the seed spectra and suppress modes that lie outside.

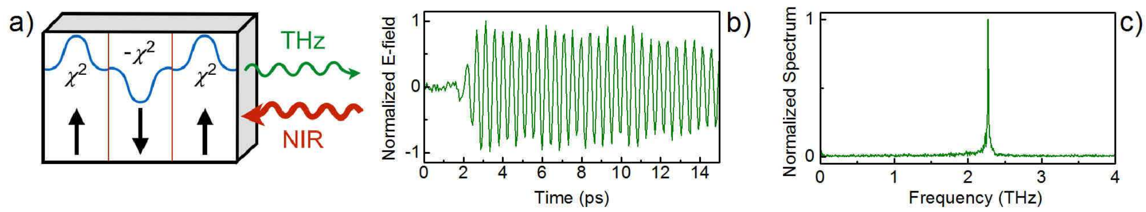

Figure 1 **a)** Schematic of a periodically pole lithium niobate crystal (PPLN). The reflection geometry is used to access the backward generated THz wave in order to minimize the THz bandwidth **b)** The electric field generated from the PPLN crystal measured using free space electro-optic sampling **c)** Spectral amplitude of the THz pulse in part **b)**.

2. Generation of narrow-band THz seed pulses

A PPLN crystal consists of a series of poled domains where the second order nonlinear susceptibility oscillates sign. This enables quasi-phase matching to occur between the femtosecond laser pulse and specific THz wavelengths that depend on the poling period. If absorption can be neglected, the bandwidth of the narrow-band THz emission is inversely proportional to the number of poling periods [3]. For a given femtosecond laser beam THz radiation is generated in both the forward and backward directions inside the PPLN crystal. For a given crystal length and THz frequency the backward THz wave requires more poling periods than the forward THz wave. Thus in order to minimize the FWHM of the THz seed pulses reflection geometry is chosen for THz generation. The length of each periodically poled region is 5 mm with a width of 0.5 mm, and a thickness of 0.5 mm. 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 electric field and spectral amplitude of a typically narrow-band probe pulse are shown in fig. 1b and fig. 1c. (The electric field oscillations extend for a much greater time than shown in fig. 1b.) In order to minimize THz absorption in lithium niobate which can be significant for frequencies greater than 2 THz

[4], the PPLN crystal is mounted in a cryostat and cooled to 10 K. The narrow-band THz seed pulses are coupled into the facet of the THz QCL with parabolic mirrors. Immediately after the arrival of the narrow-band seed in the QCL, a nanosecond bias is applied in order to injection seed the THz QCL. The emitted THz fields from the other QCL facet are measured using electro-optic sampling with a 1mm ZnTe crystal.

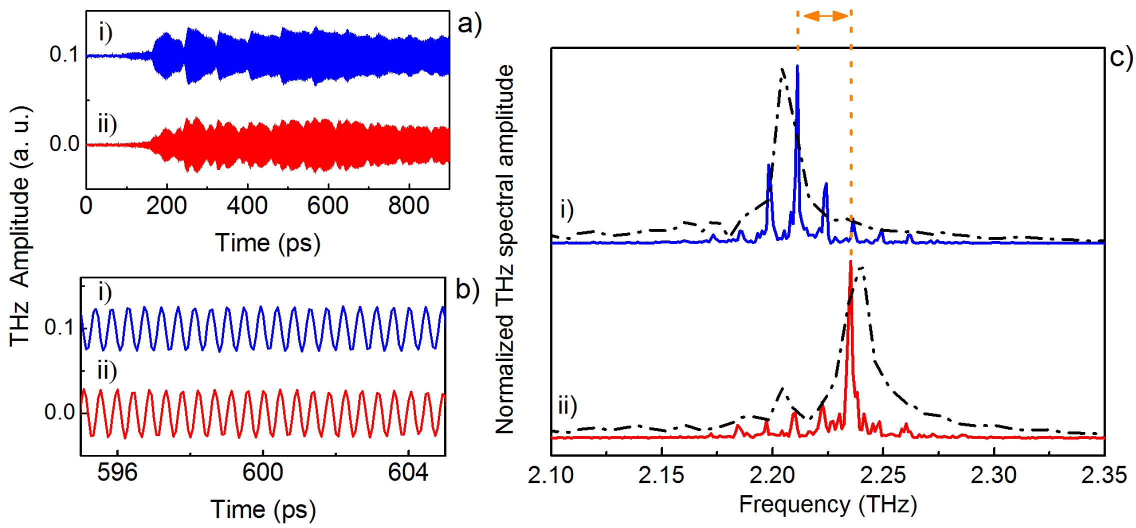

Figure 2 **a)** Emission of the injection seeded QCL versus time with seed frequencies of 2.174 THz (i-blue) and 2.240 THz (ii-red). **b)** A zoomed in portion of the electric field in part **a)** which shows the electric field oscillations. **c)** Normalized spectral amplitude of the fields in part **a)**. The normalized spectra of the corresponding seed pulses are superimposed on the data as dotted black lines.

3. Results and Discussion

The emitted fields from the QCL, when injection seeded with two narrow-band seed frequencies (2.174 THz and 2.240 THz) are shown in fig. 2a. The first pass of the narrow-band seed through the QCL occurs at time zero in fig. 2a. The amplitude of the first pass is too small to be seen in the figure. After the arrival of the narrow-band seed in the QCL cavity, the QCL is driven above threshold by a nanosecond bias pulse, this results in significant amplification of the narrow-band seed pulse after two round-trip times (~150 ps). At later times (>200ps) the gain is saturated by the THz field and no further amplification occurs. Fig. 2b shows that the phase of the electric field oscillations can be resolved in time. The spectra of the QCL can thus be obtained by taking the Fourier transform of the electric field. As shown in figure 2c, when the QCL is seeded with two different frequencies the spectral emission of the QCL is shifted by two longitudinal modes.

The normalized spectra of the PPLN seed pulses (dash lines) are superimposed on the corresponding QCL spectra in fig. 2c. The maximum spectral amplitude of the seed pulses roughly corresponds to the maximum of the QCL emission. Although, the FWHM of the seed pulses is of the order of the longitudinal mode spacing (0.012 THz), the wings of the seed spectra extend across several longitudinal modes. This results in satellite peaks around the predominant longitudinal mode. In conclusion we demonstrate the spectral emission from an injection seeded THz QCL can be controlled by the spectrum of a narrow-band THz seed pulse.

4. References

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