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**Proceedings Paper:**

Talukder, MA orcid.org/0000-0002-2814-3658 (2017) Ultra-short pulses from quantum cascade lasers for terahertz time domain spectroscopy. In: Image Sensing Technologies: Materials, Devices, Systems, and Applications IV. SPIE Commercial + Scientific Sensing and Imaging, 09-13 Apr 2017, Anaheim, California, United States. Society of Photo-optical Instrumentation Engineers . ISBN 9781510609198

https://doi.org/10.1117/12.2267431

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# Ultra-short pulses from quantum cascade lasers for terahertz time domain spectroscopy

(Invited)

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## Abstract

Although the quantum cascade laser (QCL) is a promising compact semiconductor terahertz (THz) source, its success in creating ultra-short pulses is limited. THz short pulses have many applications, including in time domain spectroscopy. There have been demonstrations of short pulse (few picosecond duration) generation from THz QCLs based on active modelocking, although the stability of the pulses is limited. We show that THz QCLs can be modelocked passively using a two-section cavity, where the sections are independently controlled by bias voltages. While one of the sections produces gain, the other produces quantum coherent saturable absorption and helps to create ultra-short pulses.

## 1 Introduction

The realization of terahertz (THz) short pulses from compact semiconductor light sources, i.e., quantum cascade lasers (QCLs) has been a challenge for last one decade. Despite repeated attempts, there has only been limited success [1–5]. Recently, it has been shown that QCLs can be used to produce frequency combs using four-wave mixing or self frequency modulation [6–9]. However, there has been no experimental demonstration of passive modelocking to date, and although active modelocking has been experimentally demonstrated, pulses are not stable when the laser operates even marginally above the threshold, but undergo at least a slow evolution [3, 10].

Self-induced transparency (SIT) modelocking has been proposed to create short pulses from mid-infrared QCLs [11–13]. In this approach, either gain and active periods can be interleaved along the growth direction or the cavity can be segmented into gain and absorbing sections. In the first approach, if a pulse is seeded inside the laser, it is found that a stable short pulse evolves. The duration of the pulse depends on the number of gain and absorbing periods interleaved, input current, and the dipole moments of the gain and absorbing periods. By contrast, in the second approach, pulses can be formed from quantum noise and the pulse duration depends on the input current to the individual sections, length of the gain and absorbing sections, and the dipole moment of gain and absorbing sections.

In this work, we design a two-segment THz QCL structure for modelocking using SIT effect. One of the segments produces gain at ∼2.5 THz and the other produces resonant absorption at ∼2.5 THz. Finite difference time domain solutions of coupled Maxwell-Bloch equations show that ultra-short pulses on the order of ∼1 ps can be created from the designed THz QCL.

## 2 Designed THz QCL

The layer thicknesses of one period of the designed structure are (in Å) 42/108/24/95/38/198/20/120. The numbers in normal font are GaAs layers, while the numbers in bold font are AlGaAs layers. The numbers in bold fonts are $\mathrm{Al_{0.19}Ga_{0.81}As}$ layers, while the number in underlined bold font is an $\mathrm{Al_{0.4}Ga_{0.6}As}$ layer. If an electric field of ∼3.4 kV/cm is applied, the quantum heterostructure will absorb a resonant light of ∼2.5 THz. There are two levels in the active region as shown in Fig. 1. When an electric field of ∼3.4 kV/cm is applied, electrons are injected into the bottom level in the active region. The bottom level has a lifetime of >60 ps. The transition levels in the active region are coupled with a strong dipole moment of ∼4.5 nm and the transition frequency is ∼2.5 THz.

If an electric field of ∼6.3 kV/cm is applied, the quantum heterostructure will create gain at ∼2.5 THz. While working as a gain medium, the structure will work as a so-called resonant phonon structure. There are two levels in the active region as shown in Fig. 2. With an electric field of ∼6.3 kV/cm, electrons are injected into the upper level. The upper level has a lifetime of >65 ps. Therefore, population inversion is created between the two levels in the active region. The upper level is coupled with the bottom level by a strong dipole moment of ∼4.2 nm and the transition frequency between the two levels in the active region is ∼2.5 THz. After radiative transition from the upper level to the lower level, electrons are extracted by tunneling and then depopulated to lower energy levels by phonon excitation.

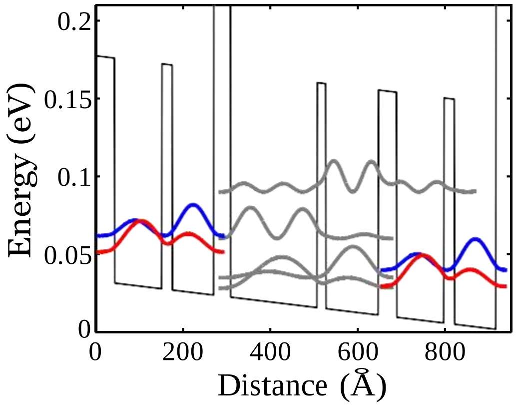

Figure 1: Cascaded structure with relevant moduli-squared wavefunctions at 3.4 kV/cm applied electric field.

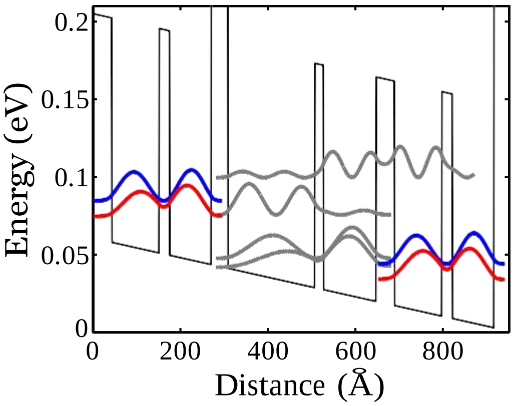

Figure 2: Cascaded structure with relevant moduli-squared wavefunctions at 6.3 kV/cm applied electric field.

## 3 THz QCL Cavity Dynamics

To find out the cavity dynamics of the designed THz QCL, we solve the coupled Maxwell-Bloch equations for the gain section given by [13]

$$\frac{n}{c}\frac{\partial E_\pm}{\partial t} = \mp\frac{\partial E_\pm}{\partial z} - i\frac{N_g\Gamma_g d_g k}{\varepsilon_0 n^2}\eta_{g\pm} - lE_\pm, \tag{1a}$$

$$\frac{\partial \eta_{g\pm}}{\partial t} = \frac{id_g}{2\hbar}(\Delta_{0g}E_\pm + \Delta_{2g}^{\mp}E_\mp) - \frac{\eta_{g\pm}}{T_{2g}}, \tag{1b}$$

$$\frac{\partial \Delta_{0g}}{\partial t} = \lambda_g + \frac{id_g}{\hbar}(E_+^*\eta_{g+} + E_-^*\eta_{g-} - \text{c.c.}) - \frac{\Delta_{0g}}{T_{1g}}, \tag{1c}$$

$$\frac{\partial \Delta_{2g}^{\pm}}{\partial t} = \frac{id_g}{\hbar}(E_\pm^*\eta_{g\mp} - E_\mp\eta_{g\pm}^*) - \left(\frac{1}{T_{1g}} + 4k^2D\right)\Delta_{2g}^{\pm}, \tag{1d}$$

and the coupled Maxwell-Bloch equations for the absorbing section given by [13]

$$\frac{n}{c}\frac{\partial E_\pm}{\partial t} = \mp\frac{\partial E_\pm}{\partial z} - i\frac{N_a\Gamma_a d_a k}{\varepsilon_0 n^2}\eta_{a\pm} - lE_\pm, \tag{2a}$$

$$\frac{\partial \eta_{a\pm}}{\partial t} = \frac{id_a}{2\hbar}(\Delta_{0a}E_\pm + \Delta_{2a}^{\mp}E_\mp) - \frac{\eta_{a\pm}}{T_{2a}}, \tag{2b}$$

$$\frac{\partial \Delta_{0a}}{\partial t} = \lambda_a + \frac{id_a}{\hbar}(E_+^*\eta_{a+} + E_-^*\eta_{a-} - \text{c.c.}) - \frac{\Delta_{0a}}{T_{1a}}, \tag{2c}$$

$$\frac{\partial \Delta_{2a}^{\pm}}{\partial t} = \frac{id_a}{\hbar}(E_\pm^*\eta_{a\mp} - E_\mp\eta_{a\pm}^*) - \left(\frac{1}{T_{1a}} + 4k^2D\right)\Delta_{2a}^{\pm}, \tag{2d}$$

where $E_x$ denotes the envelope of the electric field, $\eta_x$ denotes the dielectric polarization, $\Delta_{0x}$ denotes the population inversion, and $\Delta_{2x}$ denotes the inversion grating. The quantities with a +(–) subscript or superscript represent fields that are propagating in the positive (negative) z-direction, and the subscripts g and a represent gain and absorption, respectively. The parameters $E_x$, $\eta_x$, $\Delta_{0x}$, and $\Delta_{2x}$ are assumed to vary slowly with respect to space z and time t. The parameter n denotes the index of refraction, c denotes the speed of light, $\varepsilon_0$ denotes the vacuum permittivity, ħ denotes the Planck's constant, $N_x$ denotes the electron density in the active region, $\Gamma_x$ denotes the overlap factor between the laser mode and the active region, $T_{1x}$ denotes the gain recovery time, $T_{2x}$ denotes the coherence time, l denotes the linear cavity loss per unit length not including mirror losses, $\lambda_x$ denotes the pump parameter, D denotes the diffusion coefficient, $d_x$ denotes the dipole matrix element of the laser transition, and k denotes the wave number associated with the optical resonance frequency. We may write $k = \omega n/c$, where $\omega$ denotes the angular frequency of the electric field.

The simulation results are shown in Figs. 3 and 4. In Fig. 3, we show the pulse evolution from quantum noise. The pulses are formed and become stable after few round-trips. In Fig. 4, we show a zoomed-in time window of Fig. 3. We note that the pulses are stable and individual pulses are replica of one another. The pulse duration of stable pulses is ~2.6 ps.

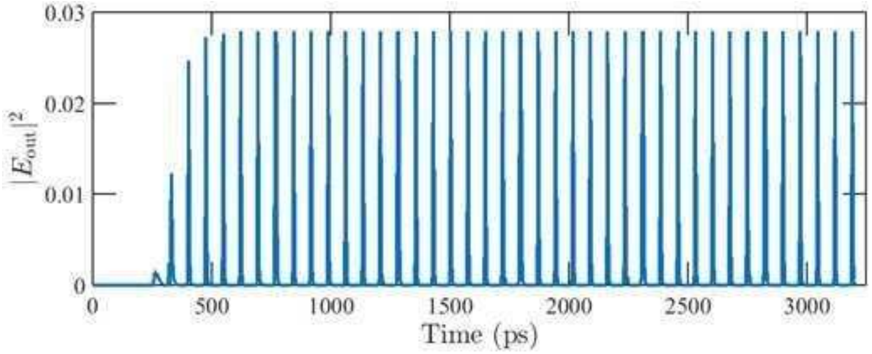

Figure 3: Collected intensity at the output of the facet of the SIT structure up to 100 round-trip time. The intensity is captured at the output with an interval of 2 roundtrip time. In this simulation, the cavity length $L_c$ = 3 mm and the gain section length $L_g$ =2.6 mm.

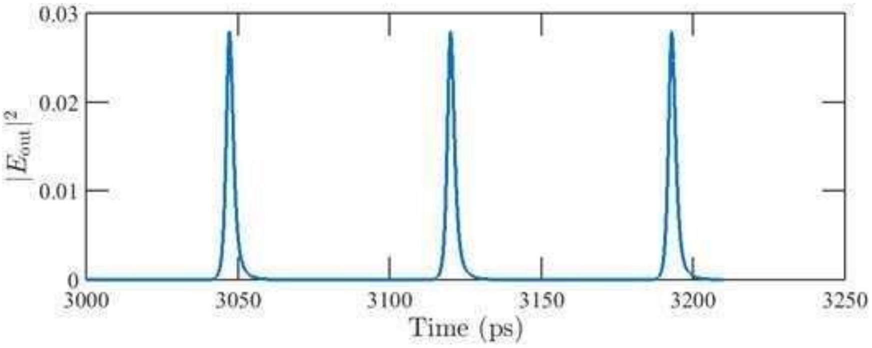

Figure 4: Collected intensity at the output of the facet of the SIT structure for six round-trip time. The intensity is captured at the output with an interval of 2 roundtrip time. In this simulation, the cavity length $L_c$ = 3 mm and the gain section length $L_g$ =2.6 mm.

## 4 Conclusions

In conclusion, we design and theoretically show that THz ultra-short pulses can be created from a two-segment SIT modelocking structure. By solving coupled Maxwell-Bloch equations, we find that stable pulses of ~2.6 ps pulses are formed when the gain section has a length of 2.6 mm and the absorbing section has a length of 0.4 ps. The pulse repetition rate and the duration will depend on the length of the cavity and the lengths of the gain and absorbing sections.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 703912

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