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# Short pulse generation from active mode-locked THz quantum cascade lasers

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## 1. Introduction

The generation of ultrashort and intense pulses of radiation from QCLs has proved to be challenging. It has been suggested that the ultrafast electron dynamics of these devices leads to inherent multimode instabilities that prevent mode-locking and pulse formation. Nonetheless, active mode-locking has been recently demonstrated [1] [2] in THz QCLs by electronically modulating the device at a microwave frequency corresponding to the cavity round-trip. This has been attributed to the longer gain recovery time of THz QCLs than those operating in the mid-infrared. Here we demonstrate that this is not the case: the dominant factor necessary for active pulse generation is in fact the electronic microwave modulation and its synchronization with the THz pulse in the QCL. By using phase resolved detection [3] of the electric field in QCLs embedded in MM waveguides, we demonstrate that active mode locking requires the phase velocity of the microwave round trip modulation to equal the group velocity of the generated THz pulse. This allows the THz pulse to propagate in phase with the microwave modulation along the gain medium, permitting pulse generation [4]. We also demonstrate how the limitations of the microwave modulation to the pulse width can be overcome using new waveguides to engineer the index dispersion.

## 2. Results

This work was performed on MM waveguide QCLs employing phonon depopulation active regions (designed for 2.6 THz emission). Compared to all previous demonstrations (based on single plasmon and bound-to-continuum designs) these type of designs permit high temperature operation (> 77K) and large gain bandwidths (> 500 GHz).

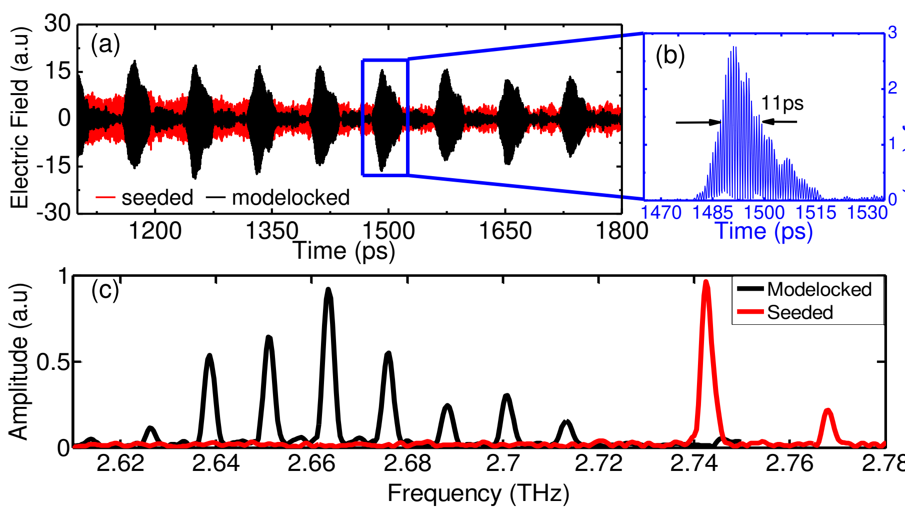


Fig. 1. Active modelocking of the metal-metal QCL at 77K. (a) Output electric field for the seeded (red) and the mode-locked (black) QCL. (b) Expanded view of the THz pulse intensity between 1470 ps and 1530 ps. (c) FFT of figure (a) for seeded (red) and mode-locked (black) QCL.

Figure 1a shows the time resolved electric field of the QCL at 77 K that shows clearly the generation of a train of THz pulses when actively mode-locked with a microwave modulation of 12.4 GHz (The red curve shows the output field when the QCL is driven freely). Figure 1b is an expanded view of the THz pulse intensity showing the generation of 11ps pulses. The spectra (FFT of figure 1a) is shown in figure 1c) demonstrating more modes being brought above threshold when mode-locked. The spacing between the modes corresponds to a group refractive index of 3.87, compared to 3.67 when not mode-locked. The former is equal to the microwave index and this thus suggests that pulse generation is observed if the THz group index is equal to the effective modal index of the microwave modulation. Combined with pulse generation only observed close to threshold and an increase in the gain bandwidth does not translate into much shorter pulses, this implies that pulse generation from QCLs arises from a direct microwave modulation above and below laser threshold, and that the pulse width is limited by the sinusoidal microwave modulation. The QCL ultrafast gain recovery time is not a limiting factor and can be used rather as an advantage to generate more intense and shorter pulses if short intense electrical pulses can be used to switch on the QCL gain.

To conclude, we have shown that mode-locked pulses are generated from QCLs when phase matching between the microwave phase velocity and the envelope of the THz emission is obtained. This works brings a significantly enhanced understanding of mode-locking of QCLs and will permit new concepts to be explored to generate shorter and more intense pulses in the terahertz and mid-infrared ranges using a compact and practical semiconductor source. Indeed, by employing a coupled cavity as a passive dispersion compensation scheme, combined with the active modulation, we also show the possibility of shortening the pulses down to ~4ps, considerably shorter than the current state-of-the-art (~10ps).

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