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Citation: Kuznetsova, L. et al. "Mode-locking via active gain modulation in quantum cascade lasers." Lasers and Electro-Optics, 2009 and 2009 Conference on Quantum electronics and Laser Science Conference. CLEO/QELS 2009. Conference on. 2009. 1-2. ©2009 Institute of Electrical and Electronics Engineers.

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: http://hdl.handle.net/1721.1/59483

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Mode-locking via active gain modulation in quantum cascade lasers

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Abstract: A mode-locking mechanism by active gain modulation is studied numerically and experimentally. The parameter window for the emission of stable pulse trains was found. Pulses as short as 3ps (~0.5pJ) were characterized by second-order autocorrelation.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.4050) Mode-locked lasers; (140.5965) Semiconductor lasers, quantum cascade

A stable train of ultrashort laser pulses with large peak power is a key element for many important applications such as nonlinear frequency conversion, time-resolved measurement, coherent control, and frequency combs. To date, the most common approach to generate short pulses in the mid-infrared region relies on the down-conversion of short-wavelength mode-locked lasers. These systems are very bulky, expensive and require complicated optical arrangement. Mid-infrared quantum cascade lasers (QCLs) [1], because of the flexibility in the design of the gain spectrum (peak wavelength, width and dispersion), are the best candidates for compact electrically-pumped ultrafast pulse source. However, the gain recovery time in QCLs (1-2 ps) is an order of magnitude smaller than the cavity roundtrip time. According to conventional mode-locking theory, this situation impedes the formation of ultrashort pulses through active mode-locking. If the gain recovery is much faster than the cavity roundtrip time, then gain will always follow the loss, and continuous-wave (CW) lasing cannot be fully suppressed, thus no pulse will be formed. There were several previous works reporting the observation of mode-locking in QCLs [2,3], based on broadband multimode behavior with a narrow microwave beat note in the power spectrum peaked at the cavity roundtrip frequency. This indicated that the phase relationships between the longitudinal modes were stable for about 10^5 roundtrips. The modes were therefore locked, however no autocorrelation study was reported to demonstrate that the circulating waveform was indeed a periodic sequence of isolated pulse, as in traditional mode locking [4].

Here we report the results of a systematic theoretical and experimental study of the mode-locking mechanism via active gain modulation for generation of mid-infrared picosecond pulses from QCLs. The stable train of short pulses was generated by actively modulating the current and hence the optical gain in a small section of an edge-emitting QCL. Pulses were characterized using a second-order interferometric autocorrelation (AC). The mode-locking dynamics in the QCLs, while not fitting into the standard active mode-locking picture of loss modulation [5], was modeled and simulated based on Maxwell-Bloch equations.

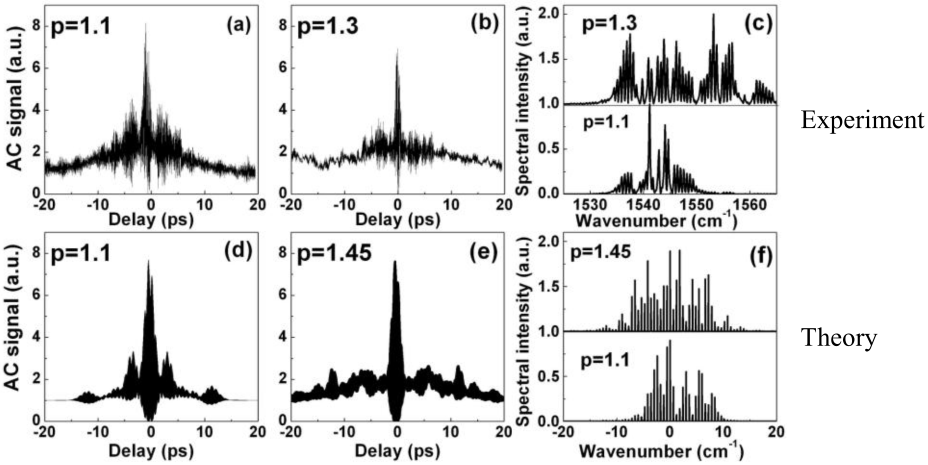

Fig. 1. Spectra and AC obtained from experiment (a-c) and numerical simulations (d-f). Parameters used in the simulations are: m=5, T_1=50 ps, T_g=10 ps, T_2=50 fs. The optical spectra of the device are measured with a Nicolet Fourier transform infrared spectrometer (FTIR). The RF modulation (35 dBm) is applied at the cavity resonance frequency of 17.41 GHz.

To achieve stable mode-locking, the QCL structure was engineered with longer gain recovery time than in the case of conventional design. The lasers were based on a “diagonal transition” in real space [6]. The devices were processed into ridge waveguides with multiple electrically independent sections. The laser was biased at a constant DC voltage, and an additional radio-frequency (RF) signal was injected into a short (~150µm) section at one end of the 2.6mm-long laser ridge via a bias tee to modulate the small section pumping current.

To understand different mode-locking regimes, two key parameters were varied: RF modulation power and DC pumping current. The pumping for the long laser section is $\lambda = p\lambda_{th}$, where λ_{th} is the pumping at threshold, and for the small modulated section: $\lambda = p\lambda_{th} + m\lambda_{th}\sin(2\pi f_R t)$ is assumed, where m is the RF current modulation amplitude, and f_R is the cavity roundtrip frequency. By modulating the injection current in the QCL short section, the gain is modulated. The pulse is formed at the gain modulation peak. The amplitude of the current modulation has to be high enough compared to the DC current in order to form a periodic stable train of pulses.

Pulses were characterized using a second-order interferometric autocorrelation technique based on a nonlinear quantum well infrared photodetector (QWIP) [7]. First, when the DC current amplitude was kept close to the laser threshold (Fig.1 (a)) the observed peak-to-background ratio was close to 8:1, indicating stable mode-locking. The FWHM pulse width was 3ps and the estimated energy per pulse was close to 0.5 pJ. When the DC pumping was increased to p=1.3 (Fig.1(b)), the peak-to-background ratio was decreased significantly. This indicates that the laser output now consists of pulses superimposed onto a background as the RF gain modulation amplitude is not sufficient to fully suppress CW lasing. Increasing the DC current leads to broadening of the optical spectra (Fig.1 (c)) but the majority of the longitudinal modes is not locked in phase. Numerical simulations (Fig.1 (d-f)), based on one-dimensional Maxwell-Bloch equations in a Fabry-Perot cavity for an “open” two-level system [4], are qualitatively in agreement with the experiment. The introduction of spatial hole-burning in the model explains both the general features observed experimentally in the AC (Fig.1 (d,e)) and the broadening of the spectrum (Fig.1 (f)).

While operation in the near threshold regime for DC pumping current is essential to achieve stable mode-locking, a sufficiently large RF modulation amplitude is also necessary. Fig.2 (a-c) show the experimental autocorrelation traces for various RF modulation amplitude values when the DC current was near threshold (p=1.1). Both numerical simulations and experimental autocorrelation traces (Fig.2) show that pulse quality degrades dramatically as the RF power decreases from 28 dBm (m~5.0) to 12 dBm (m~0.6).

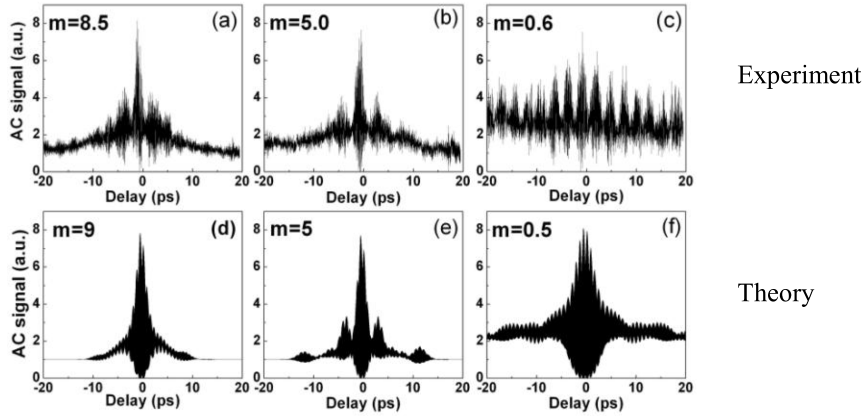

Fig. 2. (a-c) Autocorrelation trace measured in the experiment with different RF modulation powers 35 dBm (m=8.5), 28 dBm (m=5.0), 12 dBm (m=0.6). The RF modulation amplitude (*m*) for each RF power value was calculated numerically by the Runge-Kutta method using an equivalent electrical circuit model for the device. (d-f) Calculated AC from the numerical simulations (parameters used: p=1.1, T_1=50 ps, T_g=10ps, T_2=50fs).

In conclusion, the study of the mechanism of mode-locking in QCLs via active gain modulation shows that a window of stable mode-locking is determined both by the RF modulation power and DC current. As revealed by second-order autocorrelation measurement, periodic pulses as short as 3 ps can be generated if both the DC pumping current is close to the laser threshold and the RF modulation is sufficiently large. These results represent a significant step towards a compact, electrically-pumped source of ultrashort mid-infrared pulses.

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