Active mode locking of broadband Quantum Cascade lasers

Alex Soibel, Milton L. Peabody, A. Michael Sergent, Deborah L. Sivco and Alfred Y. Cho
Bell Laboratories, Lucent Technologies, 600 Mountain Ave, Murray Hill, NJ, 07974, USA.
hsasha@lucent.com

Federico Capasso
Division of Engineering and Applied Sciences, Harvard University, Cambridge, MA, 02138, USA.

Claire Gmachl
Department of Electrical Engineering, Princeton University, Princeton, NJ, 08544, USA.

Roberto Paiella
Department of Electrical and Computer Engineering, Boston University, 8 St. Mary's Street, Boston, MA, 02215, USA.

Harold Y. Hwang
Advanced Materials Science, University of Tokyo, Kashiwa, Chiba 277-8561, Japan.

H. C. Liu.
Institute of Microstructural Science, National Research Council, Ottawa, Ontario, K1A R6 Canada.

Christian Jirauschek and Franz X. Kärtner
Department of Electrical Engineering, MIT, Cambridge, MA, 02139, USA.

Abstract: Active mode-locking in broadband Quantum Cascade lasers with a repetition rate of about 14.3 GHz has been achieved through the modulation of the laser bias current.

Broadband lasers are of particular interest for ultrashort pulse generation based on active and passive mode-locking [1]. A mid-infrared broadband Quantum Cascade (QC) laser emitting in pulsed mode from 6 to 8 μm has recently been demonstrated [2], and subsequent optimization of the laser design resulted in broadband continuous wave emission at wavelengths spanning the range from 6.7 to 7.4 μm [3] There is significant interest in the demonstration of mode-locking in broadband QC lasers. In these devices laser action occurs in active regions designed for emission at different wavelength thus the gain spectrum is inhomogeneously broadened. The broad spectral gain of these lasers is expected to shorten the pulse duration below ps and leads to higher peak optical power both of which are essential for nonlinear spectroscopy. Furthermore, mode-locking in inhomogeneously broadened lasers, in particularly in intersubband lasers where all carrier relaxation times are very short, is not yet well understood.

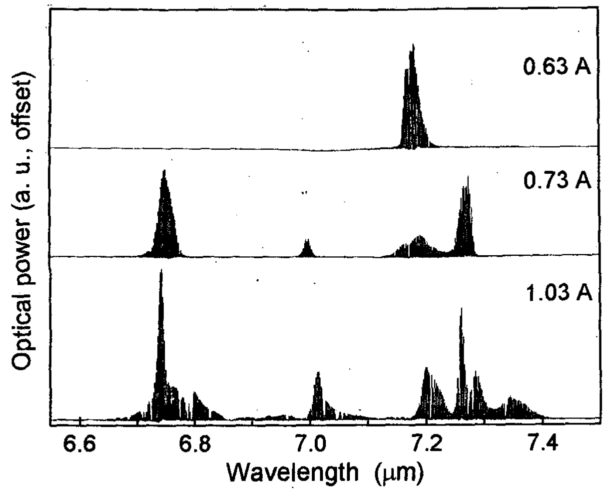

Fig. 1. Optical spectra of the actively mode-locked broadband QC laser at $T = 20$ K for various dc bias currents. The rf power is 30 dBm and the rf frequency is adjusted slightly ($f = 14.27 - 14.45$ GHz) with the laser bias current.

In this work we demonstrate active mode-locking of broadband QC lasers by modulation of the laser drive current at frequencies close to the cavity round trip frequency. Figure 1 show the optical spectra of the actively mode-locked broadband QC laser at various dc bias currents. The modulation frequency is varied with bias current to achieve the respective maximum spectral width. The laser spectral response depends strongly on the laser bias current and reflects the broad spectral gain of the laser and its wavelength dependence. At low drive currents $I = 0.63$ A, the rf modulation brings above threshold only Fabry-Perot modes near the wavelength of unmodulated laser, $\lambda \approx 7.16$ μm. At high dc currents, the active modulation results in the appearance of numerous Fabry-Perot modes across the entire gain spectrum from 6.7 to 7.4 μm. The corresponding photocurrent peaks are shown in Fig. 2. The sharp spike in the photocurrent spectrum arises from cross talk between the rf generator and detector. The broader peak results from the laser pulse emission at the cavity round trip frequency. The photocurrent peak broadens with increase of the laser bias current (or laser optical power). This broadening results from poor phase-locking of the modes across the broad spectrum associated with a variety of mechanisms such as cross gain and cross phase modulation.

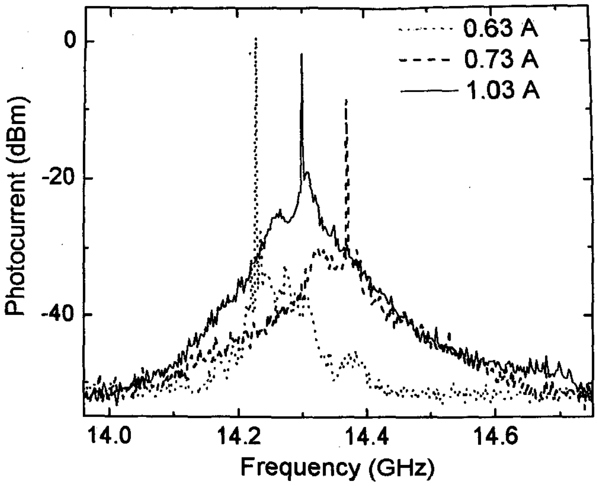

Fig. 2. The photocurrent spectra of the laser output the actively mode-locked broadband QC laser at $T = 20$ K for various dc bias currents measured with the QWIP. The rf power is 30 dBm and the rf frequency varies slightly with the laser bias current.

From the evolution of the emitted spectra with varying modulation frequency a value of the group refractive index dispersion is measured, $\Delta n_g \approx +9 \times 10^{-3}\ \mu\mathrm{m}^{-1}$, in good agreement with previous estimates [4]. The resulting negative group velocity dispersion (GVD) is consistent with the requirement for active and passive mode-locking in inhomogeneously broadened lasers. The spectral width of the optical emission in the actively mode-locked broadband QC lasers exceeds $\Delta\nu > 2$ THz, which is sufficient for the generation of the subpicosecond pulses.

This work is supported in part by DARPA/US Army Research Office under Contract No. DAAD 19-00-C-0096.

---

[1] C. Spielmann, P. F. Curley, T. Brabec, and F. Krausz, "Ultrabroadband femtosecond lasers," IEEE J. Quantum Electron. **30**, pp. 1100-1114, 1994.

[2] C. Gmachl, D. L. Sivco, R. Colombelli, F. Capasso, and A. Y. Cho, "Ultra-broadband semiconductor laser," Nature **415**, pp. 883-887, 2002.

[3] A. Soibel, F. Capasso C. Gmachl, D. L. Sivco, M. L. Peabody, A. M. Sergent, and A. Y. Cho, "Optimization of broadband Quantum Cascade lasers for continuous wave operation," Appl. Phys. Lett. **83**, pp. 24-26 (2003).

[4] C. Gmachl , A. Soibel , R. Colombelli, D. L. Sivco, F. Capasso, and A. Y. Cho, "Minimal group velocity dispersion and gain evolution in ultra-broadband quantum cascade lasers" IEEE Photonics Tech. Lett. **14**, pp. 1671-1673, 2002.