Frequency-domain modeling of semiconductor mode lock lasers

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Abstract: A frequency-domain description of semiconductor mode-locked lasers is presented. The approach provides self-consistent accounting of locking mechanism, gain saturation, mode competition and carrier-induced refractive index, in addition to directly connecting mode-locking performance to the bandstructure.

Keywords: *quantum-dot lasers, mode-locking, laser theory*

Recent advances in mode locking semiconductor quantum-dot (QD) lasers have potential applications ranging from ultrafast spectroscopy to RF metrology and wavelength division multiplexing for telecommunications. Mode locking in both single- and multi-section diode lasers are typically investigated with time-domain or traveling-wave approaches, because they have the advantage of giving a physical picture of pulse train formation. [1] This paper discusses a complimentary frequency-domain approach based on multimode semiclassical laser theory. [2] The motivation is the explicit connection of optical nonlinearities to electronic structure. The locking mechanism, gain saturation, mode competition and carrier-induced refractive index are treated on an equal footing via the quantum mechanical electron-hole polarization. This polarization arises from light-matter interactions within an inhomogeneously-broadened distribution of QDs providing gain to a large number of lasing modes influenced by group velocity dispersion. [3] Equally important and useful from using the frequency-based approach is that it allows a precise and physically intuitive description of the mode locking process from the Adler equation perspective. [4]

To illustrate the frequency-domain approach, we discuss insight gained from comparison of experiment and theory of a single-section InAs QD laser. In Fig. 1, the red curves are from measurements and the black curves are from theory. The calculated RF linewidth is 143 kHz, compared to the 100 kHz measured value (Fig. 1 (a)). There is also good agreement on the measured pulse shape (Fig. 1 (b)), where fitting with a sech pulse shape gives approximately 500 fs pulse duration. [5]

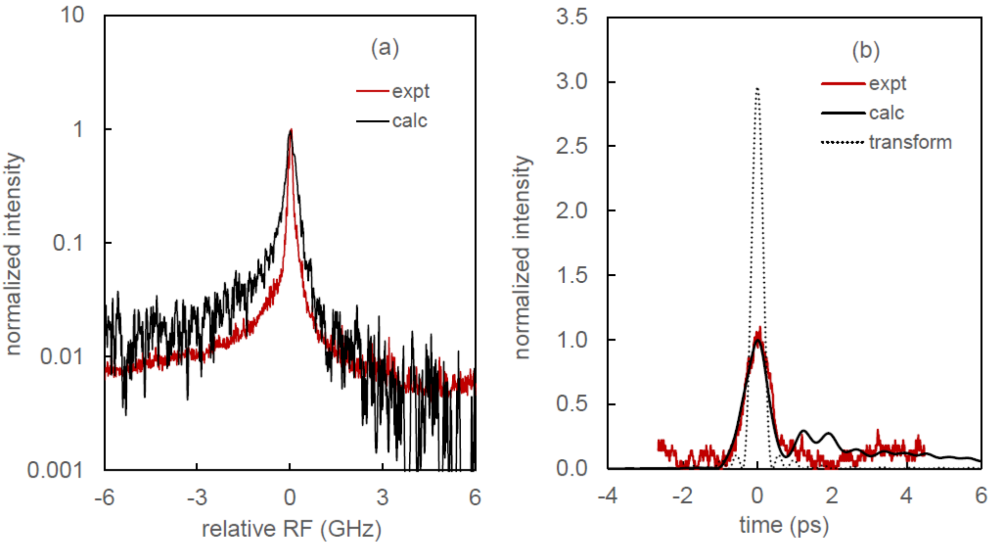

Figure 1. (a) RF spectrum and (b) mode-locked pulse from theory (solid black curves) and experiment (solid red curves). The frequency and time are referenced to the peak values. The dotted black curve in Fig 1 (b) shows the transform limit pulse based on the lasing bandwidth. Adapted from from Ref. 3.

The theory and experiment comparison helps identify the contributions limiting the experimental laser performance. In Fig. 2, the solid black curve from theory indicates only partial locking of the beatnotes in the experimental laser, with the flat portion of black curve covering only 30% of the lasing modes. Additionally, we found that the carrier-induced

978-1-7281-5891-4/20/$31.00 ©2020 IEEE

refractive index leads to an irregular dispersion across the lasing modes, which combines with the passive mode dispersion within the waveguide, to give appreciable variations in the beat frequencies between adjacent cavity modes (blue curve). This combined dispersion is the major reason for the considerable deviation from transform limit (dotted curve, Fig. 2 (b)). In a two-section laser, there is flexibility in increasing the saturable absorption to compensate for dispersion. With a single-section laser, the ability to increase the relative phase angle terms to increase mode-locking is constrained because they couple strongly to other gain medium nonlinearities, such as mode competition. This leaves reducing dispersion as the only avenue. In a separate study, we found that with QDs, the carrier-induced refractive index may be minimized with laser design. Experiments and calculations on linewidth enhancement factor show that QD lasers may be configured to operate with vanishingly small carrier-induced refractive index for combinations of inhomogeneous linewidth, p-dope density and threshold gain, that are reachable by present QD lasers. [6,7]

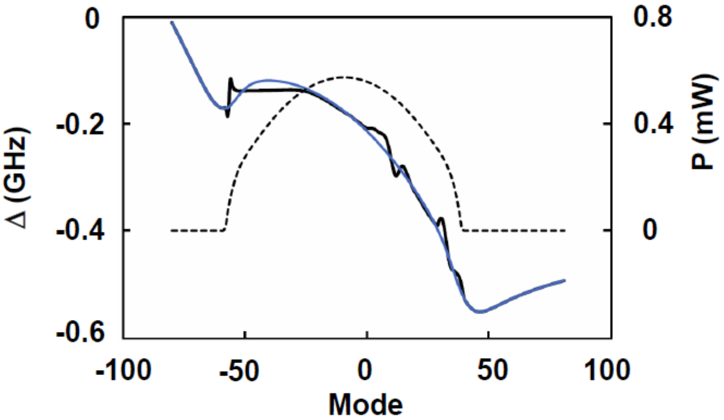

Figure 2. Difference in beatnote between adjacent lasing modes Δ versus mode number. The blue curve is the combined dispersion from the GaAs waveguide and InAs QDs and the solid black curve shows the effectiveness of the self mode locking. Also plotted is the mode intensity distribution (dotted curve). Reprinted from Ref. 3.

The research is supported in part by the Center for Integrated Nanotechnologies (CINT) through user proposals. The authors also acknowledge funding from Advanced Research Projects Agency, U.S. Department of Energy (DOE) under Contract No. DE-NA0003525, the Institut Mines-Télécom and the European Office of Aerospace Research and Development (FA9550-15-1-010).

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