An Instability Study in Terahertz Quantum Cascade Lasers

M. Moradinasab*, M. Pourfath†*, and H. Kosina*
*Institute for Microelectronics, TU Wien, Gußhausstraße 27–29/E360, 1040 Wien, Austria
†Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran
e-mail: moradinasab@iue.tuwien.ac.at

Terahertz ($1-10\ \mathrm{THz},\ 30-300\ \mu\mathrm{m}$) frequencies are among the least developed electromagnetic spectra even though they have wide ranging applications in spectroscopy, imaging, and remote sensing [1]. Since the report of quantum-cascade-lasers (QCLs) operating in the terahertz spectral region by Köhler *et al.* [2] there has been significant progress concerning the available frequencies, the temperature performance, and the understanding of the dynamics of a QCL. [3]. QCLs have a relatively long gain recovery time compared to the cavity round-trip time. Therefore, saturable absorber (SA) dominated self-mode locking seems impossible in typical QCLs. However, the elusive Risken-Nummedal-Graham-Haken (RNGH)-like instability is observed in QCLs [4]. Instability mechanisms in QCLs can be evaluated by linear stability analysis in which the criteria for RNGH instability is expressed in terms of the parametric gain $g(\Omega)$ as a function of the resonance frequency Ω:

$$g(\Omega) = -\frac{c}{2n}\mathrm{Re}\left[l_0\frac{(\Omega T_1+i)\Omega T_2-2(p-1)}{(\Omega T_1+i)(\Omega T_2+i)-(p-1)}+\frac{\gamma\hbar^2(p-1)}{\mu^2 T_1 T_2}\frac{(\Omega T_1+i)(3\Omega T_2+2i)-4(p-1)}{(\Omega T_1+i)(\Omega T_2+i)-(p-1)}\right], \quad (1)$$

where T_1 is the gain recovery time , T_2 is the dephasing time, l_0 is the linear cavity loss, μ is the matrix element of the lasing transition, γ is the SA coefficient, and p is the pumping above lasing threshold for $\gamma = 0$. Based on this analysis each mode, which is identified by the resonance frequency Ω, is stable if the parametric gain is positive, otherwise it is unstable.

In this paper we investigate the SA and pumping factor effects on instability characteristics of terahertz and mid infrared QCLs. A Pauli master equation-based description of electronic transport in QCLs along with a multi-objective optimization algorithm is employed to design QCLs operating under a desirable instability condition and at optimum performance. The required parameters for instability analysis (μ, T_1, and T_2) are extracted from these simulations.

Figure 1 (a) indicates that the instability threshold decreases faster with SA coefficient for mid infrared QCL sample while the terahertz QCL sample still operates below the instability threshold. SA can bring $g(\Omega)$ above zero, thereby triggering an instability which is more effective for mid infrared QCL. The parametric gain of the optimized structure at various pumping strengths is shown in Fig. 1 (b). A larger pumping strength broadens the instability characteristics and decreases the instability threshold which is significant for mid infrared QCL. The results indicate more stability for QCLs operating in terahertz spectral region.

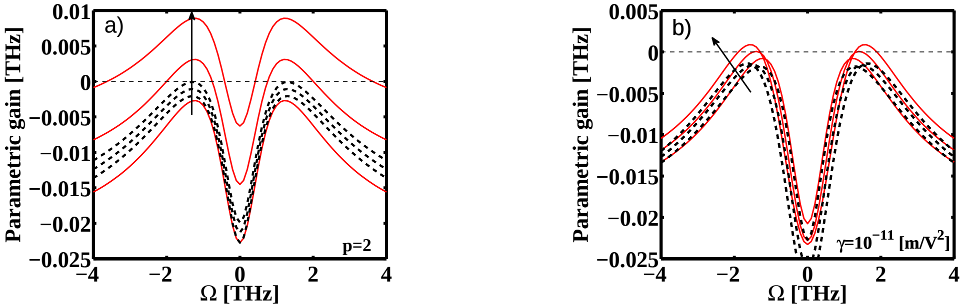

Fig. 1. The parametric gain $g(\Omega)$ as a function of the resonance frequency Ω at various (a) SA coefficients ($\gamma = 0, 3,$ and 6 m/V^2) and (b) pumping strengths $(2, 2.4, 2.8)$ for a mid infrared QCL (solid red line) and a terahertz QCL (dashed black line).

[1] S. Kumar *et. al.*, Appl. Phys. Lett., **84**, 2494 (2004).
[2] R. Köhler *et. al.*, Nature, **417**, 156 (2002).
[3] A. Benz *et. al.*, Appl. Phys. Lett., **90**, 101107 (2007).
[4] C. Y. Wang *et. al.*, Phys. Rev. A, **75**, 031802 (2007).