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Terahertz Frequency Quantum Cascade Lasers: Optical Feedback Effects and Applications

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Remarkable progress in terahertz (THz) technology over the past decade has been driven by the potential applications of THz waves in areas such as biomedical imaging, long-range screening, and organic materials identification [1]. This growth is in no small measure related to the success of the quantum cascade laser (QCL) which has established itself as one of the most promising radiation sources at terahertz frequencies [2]. The appeal of these novel semiconductor lasers stems from their compact size, broad spectral coverage ($\sim$ 1–5 THz), and high output powers [3]. The ability of THz QCLs to generate coherent emission with quantum noise-limited linewidths, make them particularly suited to the development of interferometric THz sensing and imaging systems.

In this paper, we will discuss the dynamics of THz QCLs based on the reduced rate-equation model and explore the mutual interplay between the electro-optical and thermal processes and the mode transition dynamics in these devices. We will then focus on the effect of optical feedback on THz QCLs, propose a number of interferometric schemes based on feedback effect in cw driven and pulsed QCLs and finally outline several practical applications of these interferometers.

Laser feedback interferometry (LFI) with THz QCLs is a recently-developed technique, ideally-suited to the development of compact THz sensing systems, in which radiation is reflected back into the internal laser cavity from an external target of interest. The optical feedback gives rise to measurable changes in the electronic and optical behaviour of the laser, in a phenomenon frequently referred to as self-mixing [4].

All LFI systems operate according to the same basic principle: light emitted from a laser is transmitted to an external target from which it is partially reflected back to the laser. A portion of it re-enters the laser cavity, and there the re-injected wave interacts (mixes) with the resonant modes of the laser [4], [1]. Due to the self-coherent nature of laser feedback interferometers, they are inherently highly sensitive, suppressing most radiation entering the laser cavity that is not their own. Furthermore, the maximum speed of response to optical feedback is determined by the frequency of relaxation oscillations in the laser itself [5]. By mixing in the laser cavity, the re-injected light perturbs the intra-cavity electric field, transferring this information from outside the laser cavity (phase and amplitude in the transmission path and upon reflection from the target) which then becomes measurable through the resulting perturbations to the operating parameters of the laser, such as a change in gain leading to variations in optical power, lasing frequency, and laser terminal voltage. These variations in the laser terminal voltage are frequently monitored directly [6], [7].

Most THz LFI systems to date have employed THz QCL sources in cw operation [8]. Nevertheless, pulsed THz QCL operation yields superior performance over short timescales compared with cw operation, owing to the lower internal Joule heating within the THz QCL, and hence higher optical gain, lower net electrical power consumption and higher wall-plug efficiency. Indeed, pulsed THz QCLs have been demonstrated with operating temperatures as high as 200 K and peak THz output powers in excess of 1 W [3]. Single-mode THz emission with broad frequency tuning is highly desired for a wide range of spectroscopic sensing and imaging applications.

A challenge remains, though, in the interpretation of LFI signals when a pulsed source is used, since the lasing dynamics are significantly more complex than in cw operation. This is caused by the interplay between the electro-optic response to the retroinjected THz field and the thermal transients occurring in a pulsed THz QCL. In this paper we present the comprehensive model of these coupled effects (See Fig. 1), thereby providing an accurate platform for predicting and analysing the behaviour of a pulsed THz QCL under optical feedback. We also discuss the role of frequency tuning for interferometric applications and the means by which we achieve it. We use the coupled-cavity (CC) THz QCL as an exemplar structure with the extended frequency tuning range achieved by localized electrical heating in an optically coupled passive cavity. Figure 2 shows the steady-state spectral power density (SPD) distribution as a function of the tuning current for a CC-QCL simulated using our multi-mode reduced rate equations model.

In the final part of the paper we will discuss the cw frequency-modulated LFI systems based on THz QCLs and applications, the potential for pulsed THz LFI techniques and applications in THz imaging and materials identification.

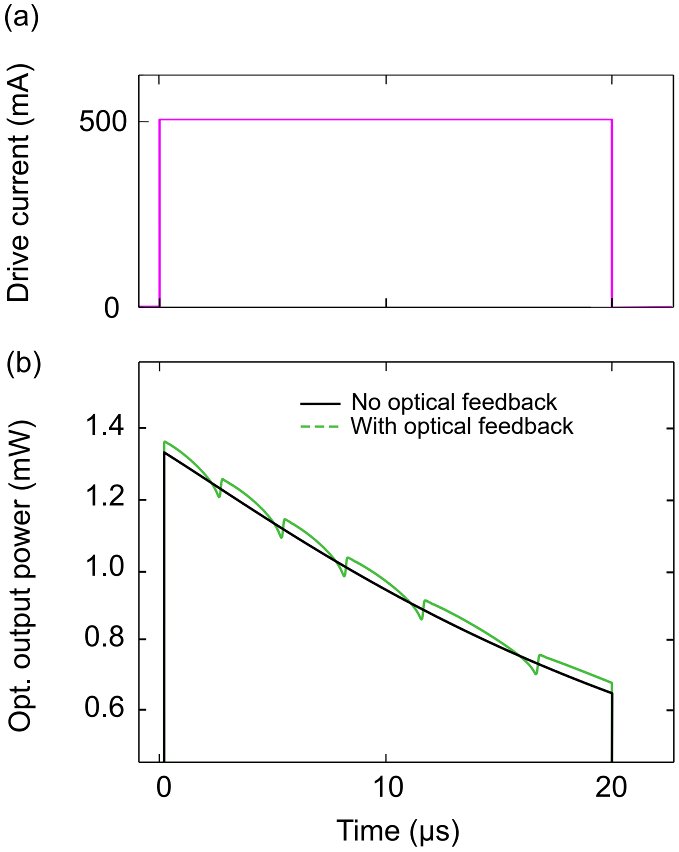

Fig. 1. Self-mixing response to thermal modulation. Part (a) shows drive current to the laser and part (b) the optical output power with and without optical feedback present. Cold finger temperature was 47 K, target reflectivity 0.2, and external cavity length 2.272 m, giving an Acket's characteristic parameter of 2.06.

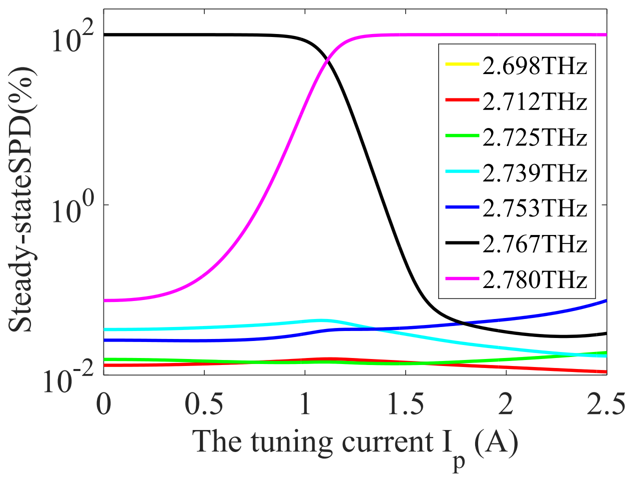

Fig. 2. The steady-state spectral power density distribution as a function of the tuning current I_p for a CC-QCL simulated with the lasing cavity length L_a = 3.0 mm, the air gap length L_g = 16 µm and the passive cavity length L_p = 1.6 mm. The mode transition from Mode 6 (2.767 THz) to Mode 7 (2.780 THz) was observed when the amplitude of the tuning current was increased from 0 A to 2.5 A.

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