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Laser Feedback Interferometry with THz QCLs: a new technology for imaging and materials analysis

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Abstract: Considerable interest exists for sensing and imaging technologies in the terahertz (THz) spectral range, in particular for the interrogation of materials of an organic or biological nature. Development in THz quantum cascade lasers is seeing higher operating temperatures and peak output powers in pulsed mode, accentuating their place as the preferred source of coherent THz frequency radiation. Technological development of interferometric sensing schemes continues to take advantage of practical improvements in THz quantum cascade lasers. In this Summary, we give a brief overview of some recent developments in this regard.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (120.3180) Interferometry; (110.6795) Terahertz imaging.

1. Introduction

Laser feedback interferometry (LFI) with terahertz (THz) quantum cascade lasers (QCLs) is a coherent sensing technique [1, 2] proposed recently, well-suited to the development of compact sensing systems. The sensing technique relies on laser radiation being reflected back into the laser cavity from an external object, thus giving rise to measurable changes in the electronic and optical behavior of the laser. This physical phenomenon is frequently referred to as the “self-mixing” effect [3] and has been successfully applied to THz biomedical imaging, explosives detection, and THz radar imaging [4–8].

In all these implementations the THz QCL was operated in continuous-wave (cw) regime with low-frequency modulation current superimposed on the dc bias in order to sweep the laser frequency. For this mode of operation, the laser remained in a series of steady-states. From the practical point of view, pulsed operation yields superior performance over short timescales compared with cw operation, owing to the lower internal Joule heating within the THz QCL. An advantage of short-pulse high-repetition-rate operation, unrelated to the device itself, is the rapid acquisition of information regarding the external object including its optical properties and shape. Indeed, pulsed THz QCLs have been demonstrated with operating temperatures as high as 200 K [9] and peak THz output powers in excess of 1 W [10].

In most LFI applications, laser frequency is continuously tuned to obtain the interferometric signal containing information about the target. In pulsed operation, due to thermal transients, this continuous frequency tuning can be obtained even for a simple rectangular current pulse. Temperature change affects laser operation in a number of ways, including altering the refractive index and the physical dimensions of the internal laser cavity [3], which in turn alter the lasing emission frequency. The changes in temperature influence carrier dynamics and thus the laser state over a wide range of timescales, from picosecond-scale electro-optical dynamics to microsecond-scale thermal modulation. The thermal transients and accompanying effects brought about by self-heating are far more prominent in these devices than in other types of laser, to the extent that they may be used as a tool for tuning QCLs [11].

However, the thermal time-constant of the device imposes a constraint on the maximum duration of the frequency sweep when relying solely on thermal processes to frequency-tune the laser. For a typical THz QCL this time-frame will be in the tens of microseconds and the frequency change with time will be non-linear. One consequence of this on the interferometric waveform is that it will have continuously changing period. This creates a challenge in predicting and interpreting LFI signals in this mode of operation. As we discussed recently, a realistic model combining the electro-optical and thermal properties of the laser with optical feedback effect is required [11]. The model was designed for an exemplar bound-to-continuum THz QCL [12, 13] operating at 2.59 THz. It comprises two carrier rate equations, a photon equation and a phase equation for a single lasing mode, coupled to the thermal model. Feedback effects were included along the lines of the seminal model by Lang and Kobayashi [3]. Figure 1 shows the schematic explaining the geometry of the interferometer making explicit reference to thermal and feedback processes governing its pulsed operation.

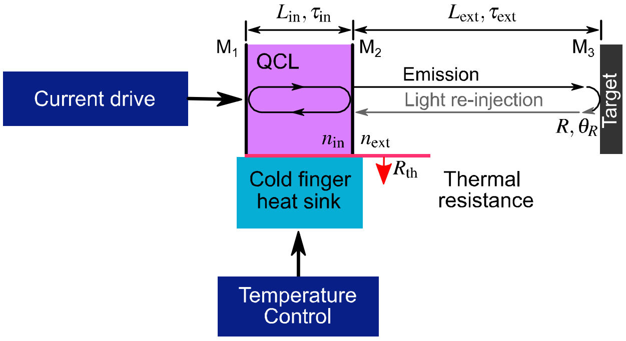

Figure 1. Three-mirror optical feedback model illustrating the role of thermal processes in pulsed operation of the laser feedback interferometer.

2. Frequency Tuning and Self-Mixing Signal Response

Figure 2 shows the simulation output when the laser was driven by a simple square pulse for three different pulse durations: 2, 20, and 200 µs, all for the drive current of 485 mA. We present the temporal evolution of the laser lattice temperature and the resulting change in the emission frequency of about 400 MHz [Fig. 2, (g)]. In the presence of optical feedback this frequency change results in variations in optical power [Fig. 2, (h)], the high frequency component of which we style the “self-mixing signal” [Fig. 2, (i)]. The results suggest that the practical constraint on pulse duration is of the order of several tens of microseconds. Practically the signal can be acquired not for the power variations, but the accompanying changes in the laser compliance voltage.

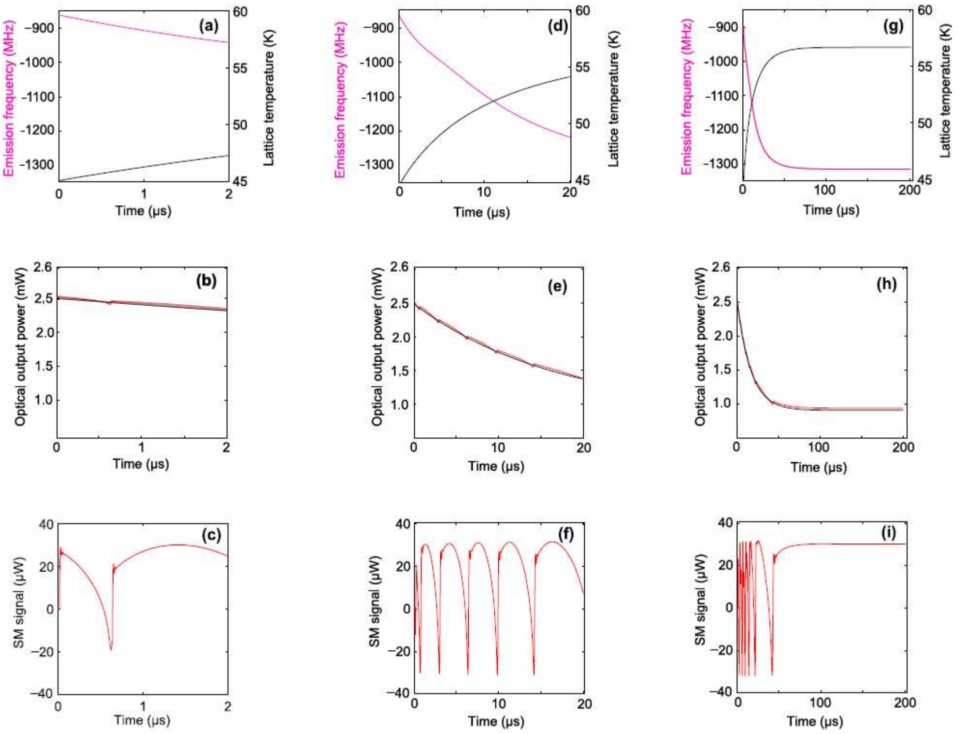

Figure 2. Self-mixing response to thermal modulation.

3. Extending the Frequency Tuning Range

In order to facilitate the identification of a material under test, probing of its optical properties at frequencies near unique spectral features can require a wider spectral range than is possible relying only on frequency-tuning as a result of thermal processes. One way to achieve this extended frequency tuning range is with a coupled-cavity (CC) THz QCL, where localized electrical heating in an optically coupled passive cavity permits selection from and stepping through several discrete lasing modes [14]. As a tunable THz emission source, CC THz QCLs can provide single-mode operation with electrically-controlled frequency tuning. A CC THz QCL is composed of two cavities separated by an air gap. Traditionally the active cavity is driven above the lasing threshold while the passive cavity is operated below threshold to control the dominant mode. However, by using the thermal heating effect induced by the driving pulses applied on the active cavity, both continuous frequency tuning and discrete mode hopping could be obtained to effectively probe the external target at a series of THz frequency bands. In order to identify a particular material, the geometry of the CC THz QCL structure can in principle be accurately designed and fabricated to permit lasing modes which target specific spectral features. An LFI system operating in pulsed mode and built around such a CC THz QCL will permit ultra-high-speed sensing for material identification, and if augmented by a fast-scanning mirror, effectively real-time THz image formation in a compact system.

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