Active phase-nulling of the self-mixing phase in a terahertz frequency quantum cascade laser

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Introduction

Self-mixing (SM) interferometry using quantum cascade lasers (QCLs) has recently emerged as a powerful sensing technique in the terahertz (THz) frequency range [1]. In this work, we develop an active phase-nulling scheme for THz QCLs under optical feedback (OF), through electronic feedback control of the emission frequency. We first apply this method to measurement of the frequency tuning of a laser as a function of drive current. Such characterization is essential for many applications, including gas spectroscopy, and frequency-modulated approaches to imaging and materials analysis using THz QCLs. In addition to offering real-time capability, our measurement approach provides a greatly reduced experimental complexity compared to previously reported schemes for characterizing frequency tuning in QCLs—these typically require detection of the high-frequency beat note generated by mixing the QCL field with that derived from a local oscillator source (e.g. either a second QCL or an optically pumped gas laser) [2]. In contrast to these approaches, which are restricted to the operating frequency range of the mixer, our technique can be applied across the full 1.2–5.2 THz spectral coverage range of THz QCLs. In addition, we demonstrate a simple SM scheme for determination of the absolute emission spectrum of the free-running laser.

We also demonstrate that our phase-nulling scheme can be applied to real-time displacement sensing of targets. This scheme achieves all of the advantages of previous SM-based displacement sensors whilst overcoming the resolution limits imposed by the quantization associated with fringe counting methods and simultaneously avoiding the need for parametric fitting to an OF model in post-processing.

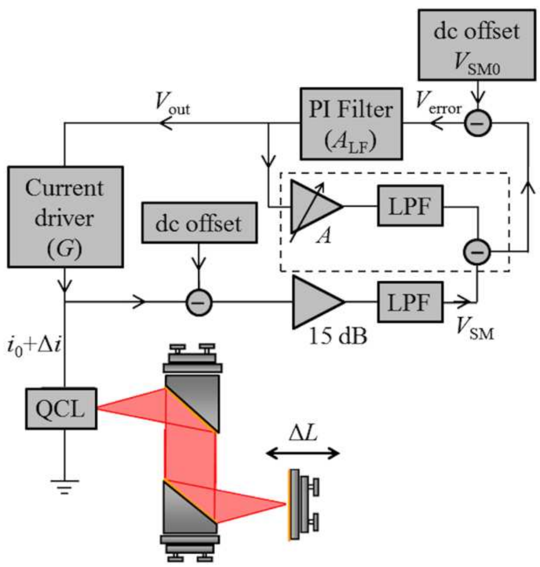

Fig. 1: Schematic diagram of the experimental system. The dashed box indicates the compensation loop used to cancel voltage modulation of the laser. LPF—low pass filter.

Measurement of frequency tuning and absolute emission frequency

The THz QCL consisted of a bound-to-continuum active region emitting at a frequency $\nu_0 \sim 2.6$ THz, which was processed into a semi-insulating surface-plasmon ridge waveguide. The phase change in the SM voltage signal arising from modulation of the external cavity length ΔL was compensated by an electronic feedback loop acting on the QCL emission frequency through dynamic control of the driving current. An adjustable inverting amplifier stage acting on the filter output V_{out} was used to subtract the unwanted direct modulation of the QCL terminal voltage from the input to the loop filter, as shown by the dashed box in Fig. 1. The filter output V_{out} was recorded in response to a $\Delta L \sim 25$ μm modulation of the external cavity length (approximately half a fringe). The resulting time-dependent frequency excursion of the laser $\Delta\nu$ can be deduced from the recorded mirror trajectory through the relation $\Delta\nu/\nu_0 = -\Delta L/L_0$. By correlating this with the measured control signal V_{out}, the frequency tuning can be mapped as a function of current perturbation Δi, enabling the tuning rate k to be determined. Figure 2 shows the relationship between Δi and $\Delta\nu$ obtained in this, which yields a value $k = -8.2$ MHz/mA.

We have also applied a simple SM scheme for determination of the absolute emission frequency of the free-running laser. In this case, the SM voltage signal was recorded as the cavity mirror was displaced through a distance 20 cm. By Fourier analysis of the interferometric data, the emission spectrum was acquired with a resolution of 750 MHz, as shown in the inset of Fig. 2.

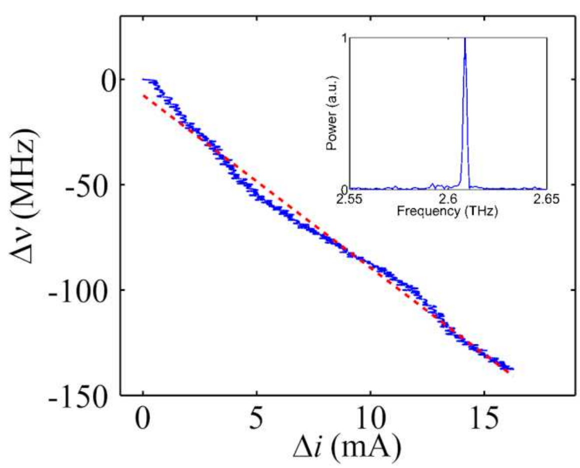

Fig. 2: Frequency tuning $\Delta\nu$ of the QCL arising from a current perturbation Δi, as determined from the feedback control signal V_{out} measured in response to a modulation of the external cavity length. The dashed line shows a linear fit to the data. Inset: Emission spectrum determined by SM interferometry.

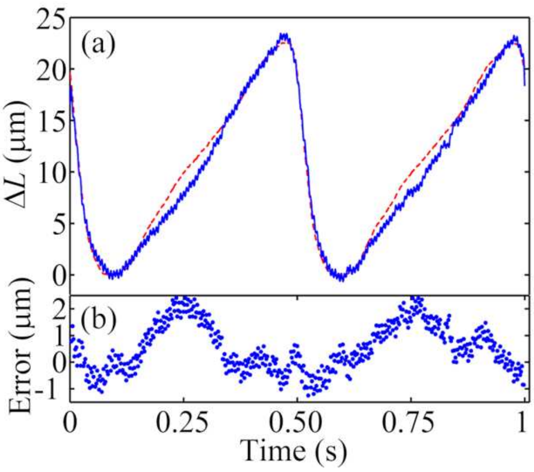

Fig. 3: (a) Displacement (solid line) determined from the feedback control signal V_{out}, in response to a vibrating target (actual displacement shown by the dashed line). (b) Error determined from the difference between the measured and actual displacements.

Real-time displacement sensing

As a second demonstration of our scheme, we have applied it to the real-time displacement sensing of targets. In this case, the filter output V_{out} generated in response to a moving target represents a replica of the target displacement, scaled by a responsivity factor. Figure 3 shows the displacement measured over two oscillation cycles of a mirror vibrating at 2 Hz with a peak-to-peak displacement, D=22.5 μm. From Fourier analysis of the filter output signal, the noise equivalent displacement was found to be ~0.2 μm for a 1-Hz measurement bandwidth centered around the oscillation frequency. Furthermore, the operating range of the electronic feedback loop in our system is expected to be ~3.6 cm, suggesting much greater displacement amplitudes could, in principle, be measured using our technique.

[1] P. Dean *et al.*, Opt. Lett. **36,** 2587-2589 (2011)

[2] A. Barkan, *et al.*, Opt. Lett. 29, 575 (2004).