Self-heterodyne Characterization of a Fabry-Pérot Quantum Cascade Laser for Multi-heterodyne Spectroscopic Sensing

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Abstract: The optical properties of a Fabry-Pérot quantum cascade laser are characterized in a self-heterodyne interferometric measurement scheme. The narrow linewidths of the self-heterodyne beat notes indicate the ultimate resolution limits of multi-heterodyne spectrometers based on these laser sources.
OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (300.6310) Spectroscopy, heterodyne; (120.2230) Fabry-Perot; (300.6380) Spectroscopy, modulation.

Quantum cascade lasers (QCLs) are frequently used in contemporary laser-based spectroscopic systems for trace gas detection of species that have strong rotational-vibrational transitions in the mid-infrared region. Traditionally, the field has been dominated by single mode DFB-QCLs due to their ease-of-operation and inherent selectivity. However, in recent years more and more attention has been devoted to the study of the frequency comb nature of QCLs [1], with the intent to investigate their applicability for broadband multi-heterodyne spectroscopy in the dual comb configuration [2]. Such mode of operation would enable compact and purely electronically controlled mid-infrared systems with a large spectral coverage suitable for detection of broadband molecular species in gas phase.

The correlation of the phases of the modes generated by a Fabry-Pérot (FP) QCL determines whether the laser is acting as a conventional multi-mode laser or if it exhibits the typically large coherence similar to that of frequency combs. By using the coherence properties, we have previously shown that FP-QCLs are capable of performing high resolution multi-heterodyne spectroscopy [3].

Several techniques have been explored to assess the degree of coherence of the QCLs modes for different operating regimes [1,4,5]. These typically focus on evaluating the behavior of the beat note produced by the QCL at the round-trip frequency by using a sufficiently fast photodetector. While these methods have proved to yield important coherence information, they require access to extremely fast photodetectors that need cryogenic cooling [1]. In this work, to evaluate the self-coherence of a multimode FP-QCL, we used a self-heterodyne method with an acousto-optical modulator (AOM) followed by measuring the beat note characteristics in a conventional interferometric configuration (see Fig. 1). This relieves the requirements on the bandwidth of the photodetector and enables beat note spectrogram measurements without cryogenically cooled equipment. Moreover, this measurement scheme provides critical information about the self-coherence of the source that is required to implement more advanced spectroscopic measurement schemes, such as wavelength modulation spectroscopy (WMS) [6], Faraday rotation spectroscopy (FRS) or chirped laser dispersion spectroscopy (CLaDS) [7].

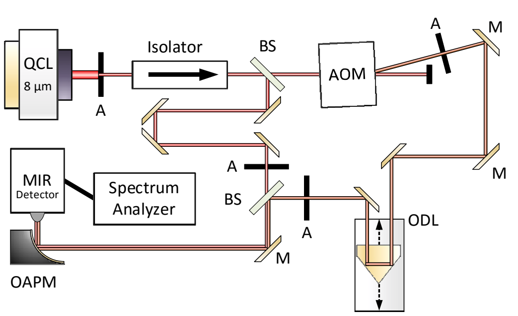

Fig. 1. Schematic overview of the experimental setup. Interferometric self-heterodyne beat note measurements of unshifted and frequency shifted modes originating from one single quantum cascade laser source is obtained by the use of an optical delay line together with an AOM. QCL – Quantum cascade laser, BS – Beam splitter, AOM – Acousto-optical modulator, M – Mirror, ODL – Optical delay line, OAPM – Off-axis parabolic mirror, A – Aperture, MIR – mid-infrared

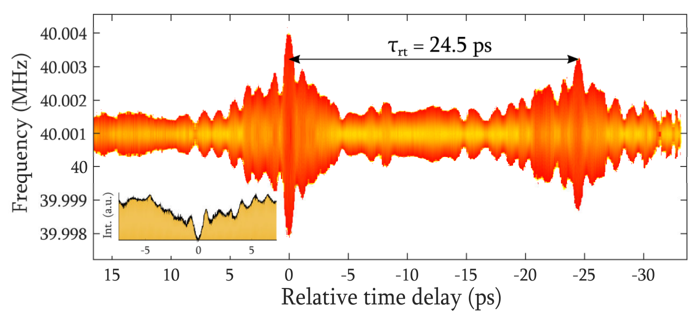

Fig. 2. Beat note spectrogram measured at the AOM frequency. The inset shows the beat note interferogram measured at 40 MHz with a bandwidth of 100 kHz showing a minimum at zero optical path difference, which indicates a well-define phase relation between the modes [1].

An overview of the self-heterodyne optical setup is given in Fig. 1. After the collimating lens, the output beam of the FP-QCL is sent through a Faraday isolator to reduce the unwanted optical feedback that would otherwise perturb the operation of the laser. A beam splitter is inserted to divide the beam into two arms. One undergoes a frequency shift (40 MHz) induced by the AOM, followed by propagation through a motor-controlled high precision delay line to introduce a highly controlled optical path difference with respect to the other arm, whose frequency remains unchanged. The two beams are overlapped on a combining beam splitter and detected by a Peltier-cooled MCT detector from VIGO.

The resulting beat note at the AOM frequency is measured by a spectrum analyzer (Tektronix RSA6106A) with a resolution bandwidth of 10 Hz and a bandwidth of 100 kHz around the AOM frequency. A spectrogram is obtained by recording the beat note spectrum for different optical path differences through movement of the motorized translation stage (T-LSR450B, Zaber Technologies).

Fig. 2. shows the beat note spectrogram at 40 MHz, where the physical delay line position has been recalculated into the corresponding time delay in picoseconds. The pattern clearly reveals a periodicity at the round-trip frequency of 24.5 ps (~ 40.8 GHz), which corresponds well to the mode spacing of 1.36 cm^{-1} obtained through FTIR measurements (Nicolet, 8700). A clear minimum in the interferogram intensity pattern (shown in the inset) is repeated every roundtrip time and indicates a large coherence of the FP modes [1].

We have previously implemented multi-heterodyne direct absorption spectroscopy (DAS) and WMS with dual-FP-QCL sources. These approaches yielded very promising high-resolution, broadband spectroscopy results, but were limited by the requirements of complex control and stabilization of the optical frequencies of both laser sources (as shown in Fig. 3), as well as ~MHz linewidths of the measured beatnotes caused by uncorrelated phase noise of the two FP-QCLs.

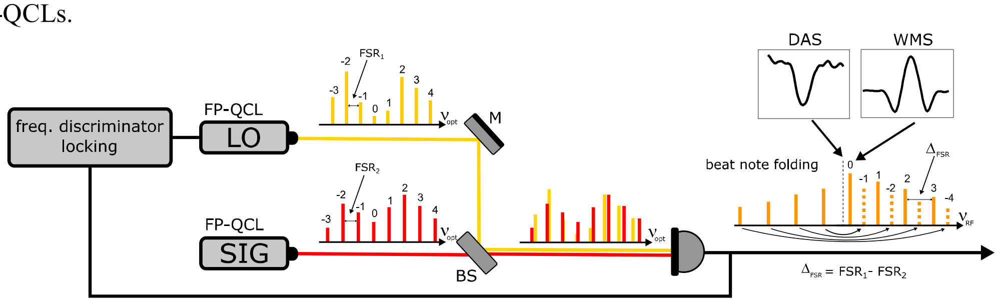

Fig. 3. The multi-heterodyne spectroscopy setup used for direct absorption and wavelength modulation spectroscopy. The lowest frequency beat note is filtered out to create an error signal supplied to an analog PID-controller for active control of the local oscillator current [6].

The high coherence of a single FP-QCL source indicated in the results from Fig. 2 promises significant improvement of the ultimate resolution of multi-heterodyne spectrometers down to the ~10 kHz regime. This opens up a possibility for ultra-high resolution, broadband multi-heterodyne spectrometers, which will be discussed in detail.

Acknowledgements: The authors gratefully acknowledge funding by the U.S. EPA (RD-83513701-0), by the NSF ERC MIRTHE (EEC-0540832), and by the DARPA SCOUT program.

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