Quantum cascade lasers linked to optical frequency comb synthesizers: a new IR metrological tool

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Summary

The work reports on the progresses towards the characterization and exploitation of the intrinsic properties of mid-IR quantum cascade lasers, in terms of linewidth and frequency stability. The results here discussed pave the way to a wide range of metrological applications of these innovative laser devices.

Introduction

Quantum cascade lasers (QCLs) are the most promising coherent sources in the infrared. The spectral coverage encompasses, at present, the entire range from a few hundred to a few microns wavelength, where the laser structures can be engineered to emit. This provides an extraordinary potential for molecular interrogation and detection, for a wide range of applications, including homeland security, environmental monitoring, biomedicine.

Although theoretical studies on QCLs have shown that extremely narrow linewidths can be potentially obtained, experimental exploitation of this peculiar feature has never been done. However, molecular transitions in the range covered by QCLs can have natural linewidths as narrow as a few hertz and the most demanding experiments should achieve such limits. In addition, high-sensitivity molecular detection requires high-finesse enhancement cavities, that may often require sub-kHz linewidth for efficient energy coupling.

In our group, we have undertaken a Project aiming to exploit the intrinsic QCLs features by making use of optical frequency comb synthesizers (OFCS) as frequency/phase references and Doppler and sub-Doppler molecular transitions as frequency-to-amplitude discriminators and benchmarks.

Discussion

Since the first demonstration of an optical link between a free-running mid-IR QCL and an OFCS for absolute frequency measurements of CO$_2$ ro-vibrational transitions [1], it has been clear that only an active stabilization of the QCL frequency would have provided a metrological-grade precision of the measurement. The use of a sub-Doppler saturation set-up and a weak frequency stabilization to molecular Lamb dips allowed to get a precision of a few parts in $10^{11}$ [2,3], with the possibility of a further improvement of almost two orders of magnitude by extending the locking-loop frequency bandwidth.

The efforts in providing the best suited signal for an effective frequency-locking loop led to the implementation, for the first time on mid-IR molecular transitions, of a differential-detection polarization-spectroscopy technique [4]. In this way, a sharp
sub-Doppler reference signal can be produced without any modulation of the laser frequency.

In parallel, a careful analysis of the frequency noise spectral density of the free-running QCL has been performed in order to identify the main contributions to the laser linewidth and frequency jitter. The latest measurements, in particular, confirm that, despite a free-running linewidth of a few MHz (over a 1-s timescale), these devices show a much narrower intrinsic linewidth (over shorter timescales).

Future developments

Next efforts will be oriented to the implementation of fast frequency and phase-locking loops, in order to achieve ultra-narrow, comb-referenced mid-IR laser sources.

References