The advent of optical frequency comb synthesizers (OFCSS), based on fs mode-locked lasers, has revolutionized the fields of frequency metrology and precision spectroscopy [1,2], providing direct absolute frequency references in the whole visible and near-infrared (IR) spectral regions. Several experiments have been implemented to extend the comb absolute frequency references to the mid-IR, by combining OFCSSs with sources based on nonlinear processes [3–5]. In a successful scheme, difference-frequency-generated (DFG) radiation obtained by mixing two visible/near-IR cw sources is linked to the primary frequency standard by locking pump and/or signal lasers to the comb [6,7]. Mid-IR radiation with outstanding frequency-noise properties was generated, achieving an intrinsic (or fast) linewidth as low as 10 Hz [7]. This scheme, however, has intrinsic limitations in terms of power scaling. In the mid/far-IR spectral regions, quantum cascade lasers (QCLs) are emerging as excellent sources for demanding applications [8,9], with wide tuning ranges and cw output powers up to several watts [10,11]. Significant steps have been made very recently towards frequency-noise analysis and linewidth measurements in QCLs [12–17] to explore the ultimate performance of these devices. In particular, these works shed light onto QCL high intrinsic spectral purity, which becomes practically accessible once an effective frequency stabilization is implemented.

In this work we show that, by using optical injection locking, the unique spectral features of a comb-referenced DFG source can be combined with the power scaling capabilities of mid-IR QCLs. Injection locking is a robust technique for synchronizing a free-running laser (slave) to another one (master) having a higher spectral purity and frequency control [18–20]; its application to QCLs has remained, so far, unexplored. This approach provides here a direct lock of the QCL (emitting at a 4.67 μm wavelength) to the optical frequency comb (covering the 500–1000 nm interval). The frequency-noise analysis carried out on both the master and slave radiations, described below, demonstrates that the stability properties of the DFG are transferred to the slave QCL, which is forced to oscillate at the master frequency, with an effective power amplification of a factor up to ~1000.

A schematic of the apparatus is shown in Fig. 1. The slave QCL is a cw Fabry–Perot type device grown by molecular beam epitaxy using strain-balanced InAs/AlAs/InP, with a slightly diagonal bound-to-continuum design for the active region [21]. In order to reduce waveguide losses, it was fabricated using a buried heterostructure process [22]. The laser facets are not antireflection-coated. The threshold current, in single-mode cw operation, is \( I_{th} = 580 \text{ mA} \) for a temperature of 255 K. The device was operated up to roughly 700 mA, with an optical power of ~20 mW per facet. Numerous mode hops were observed in all its tuning range.

The master radiation (maximum power ~100 μW) is produced by nonlinear DFG in a periodically poled LiNbO\(_3\) crystal using an Yb-fiber-amplified Nd:YAG laser (at 1.064 μm) and an external-cavity diode laser emitting at 867 nm. In order to control the phase/frequency of the generated IR radiation against our Ti:sapphire OFCS, we used an electronic scheme based on direct digital synthesis [7].

![Fig. 1. (Color online) Injection-locking setup. A DFG source referenced to an OFCS is used as master radiation for the optical injection locking of a room-temperature mid-IR QCL. In the figure, BS means beam-splitter and M is a removable mirror; all the wave plates necessary for optimal injection locking and beat-note analysis are not shown.](image-url)
this is an efficient way to cancel out both the comb carrier-frequency and repetition rate fluctuations, leading to a mid-IR radiation directly referenced to the clock (in our case a 10 MHz quartz oscillator disciplined by a Rb/GPS frequency standard, with a stability of $6 \cdot 10^{-13}$ at 1 s and a minimum accuracy of $10^{-12}$) and with the kHz-level spectral purity of the monolithic Nd:YAG laser. Therefore, the accuracy of the DFG absolute frequency is only limited by the reference oscillator of the OFCS [7].

An accurate spatial mode matching between master and slave, along with precise control of their polarization via quarter/half-wave plates, is necessary to achieve the injection-locking regime. The losses due to the coupling optics and the 50% beam-splitter reduce the DFG power effectively coupled to the QCL “rear” facet to about 1/4 of its starting value (~25 μW).

The injection-locking condition was checked and optimized by observing the slave radiation transmitted by a Fabry–Perot resonator (free-spectral-range 650 MHz, finesse ~20). The QCL remains injection-locked for several minutes without any active control. In this passive injection-locking regime, the frequency of the slave laser radiation can be continuously tuned within a locking range of ~1 GHz, wide enough for high-resolution spectroscopy on sub-Doppler or Doppler-broadened molecular transitions, by tuning the master laser. The wide gain curve of QCLs and recent theoretical studies [23] suggests that tuning ranges as high as tens to hundreds of GHz (depending on the slave/master power ratio) can be obtained by actively controlling the QCL.

The effectiveness of injection locking was directly studied by analyzing the beat-note spectrum between master and slave radiations. For this measurement, we shifted the slave radiation frequency by 90 MHz with an acousto-optic modulator. The master and slave beams were superimposed and finally detected onto a fast HgCdTe detector (nominal bandwidth 200 MHz). The beat note was measured by a real-time fast Fourier transform (FFT) spectrum analyzer. Figure 2 shows the recorded beat notes, with the QCL in unlocked (gray trace) and locked (black trace) conditions. The slave is operated at 618 mA, with an output power of ~6 mW, corresponding to a slave/master power amplification $P_S/P_M \approx 250$. The first trace maps the broad power spectrum of the unlocked QCL, while the second trace shows a narrow peak, whose width is limited by the resolution bandwidth of the spectrum analyzer, rising about 40 dB above a residual plateau. A zoomed view (50 kHz span) of the central peak is shown in the inset. From a numerical integration of the peak and the baseline spectrum (in the full 70 MHz range), we estimate that more than 94% of the slave power is channelled into the master mode. In this condition, we expect that the QCL absolute frequency is determined with the same accuracy as the DFG.

For a deeper understanding of the frequency-noise characteristics of the injection-locked radiation, we carried out a measurement of the frequency-noise power spectral density (FNPSD) for both laser sources (Fig. 3). Both the master and slave radiations were alternatively coupled to the Fabry–Perot cavity, and the slope of a transmission mode was used as a frequency discriminator to convert frequency noise into amplitude fluctuations. The same fast HgCdTe detector as the beat-note analysis is used. Similarly to what was previously observed [16], the free-running QCL (trace c) exhibits a FNPSD dominated by the current driver above ~1 kHz. Trace b is the FNPSD of the injection-locked slave laser, trace a that of the master radiation. Above ~10 MHz, the traces overlap due to the detector noise floor. It emerges that, in the injection-locking regime, the QCL reproduces well the noise features of the master source throughout the investigated interval. Compared to the free-running case, phase fluctuations are reduced by 3 to 4 orders of magnitude in most of the frequency interval. Optical injection also strongly reduces the noise contribution from the laser current driver, allowing it to overcome one of the main limiting factors to the QCL linewidth and thus loosening the requirements on QCL power supply.

![Fig. 2. Master/slave beat notes in unlocked (gray trace) and locked (black trace) conditions with resolution bandwidth of 18.75 kHz. Inset: horizontal zoom of the beat note in locked condition (resolution bandwidth: 234 Hz).](image)

![Fig. 3. (Color online) FNPSD of master (trace a) and slave radiations in both free-running and injection-locking regimes (traces c and b, respectively). Lasers are operated in the same conditions as the previous beat-note analysis. Inset: power spectral profiles (in a linear vertical scale) of the free-running (curve c) and injection-locked (curve b) QCLs, over a 50 ns timescale. For a better readability, the amplitude of curve b has been reduced by a factor of 100.](image)
A numerical integration on the acquired noise spectra following the approach proposed in [24] allows us to reconstruct the laser spectral profile and to measure its linewidth over any desired timescale. We took into account the whole spectral range of Fig. 3 (20 Hz to 20 MHz), obtaining the spectral profiles and linewidths over a 50 ms timescale (inset of Fig. 3). By switching from the free-running to the injection-locking regime, the QCL linewidth is reduced by more than 2 orders of magnitude, from 2.75 MHz to 23 kHz (HWHM).

We repeated the FNPSD measurements for different slave/master power ratios by attenuating the DFG radiation. The frequency noise of the injection-locked QCL remains substantially unaltered until \( P_S/P_M \lesssim 600 \). By further reducing the master power, the slave noise progressively increases: when \( P_M \) approaches about 1/5 of its maximum value (\( P_S/P_M \sim 1000 \)), the injected-slave linewidth (about 200 kHz) still remains a factor of 10 below the free-running case.

In conclusion, we demonstrate that single-frequency, narrow linewidth, widely tunable, absolutely linked, powerful mid-IR coherent radiation can be generated by injection locking QCLs. The QCL linewidth is narrowed by a factor of \( >100 \) with respect to the free-running condition, scaling from a few MHz (HWHM) down to about 20 kHz over a 50 ms timescale. The observed strong frequency-noise reduction (3 to 4 orders of magnitude) shows that the injection-locked slave stability is basically limited by that of the master source. We believe that present results enable further exploitation of the unique features of QCLs for a broad range of demanding applications.

This work was financially supported by Ente Cassa di Risparmio di Firenze, Regione Toscana through the projects CTOTUS and SIMPAS in the framework of POR-CReO FESR 2007-2013, and the Swiss National Foundation under the NCCR project Quantum Photonics.

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