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Quasi-optical injection locking of a terahertz quantum cascade laser to a fibre-based frequency comb

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Introduction

High-resolution spectroscopy in the terahertz region can not only identify atoms and molecules, but can also provide detailed information on their chemical and physical environment, and relative motion. The most promising solid-state source for these applications is the THz frequency quantum cascade laser (QCL), however, the linewidth of this compact semiconductor laser is typically too broad for many applications and its frequency is not directly referenced to primary frequency standards.

Results

In this work we injection lock a QCL operating at 2 THz using a quasi-optical system to a compact fibre-based telecommunications wavelength frequency comb, figure 1. Our near-IR comb source uses a narrow linewidth C-band laser to seed an amplified fibre loop incorporating a high speed phase modulator, driven by a microwave frequency synthesiser which determines the comb line spacing [1]. The fibre loop operates as a resonant cavity and multiplies the number of comb lines produced by the phase modulator. The resulting all-fibre frequency comb generates over 125 lines and spans >2.7 THz, centred around 1552.5 nm. The comb line spacing is exactly equal to the microwave modulation frequency. This results in the QCL frequency locking to an integer harmonic of the microwave reference, and the QCL linewidth reducing to the multiplied linewidth of the microwave reference, < 100 Hz.

We make use of photoconductive mixers, optimised for continuous-wave terahertz operation, to generate the terahertz signal to be injected, and to coherently detect the locked QCL. The measured heterodyne beat frequency between the QCL and the THz reference frequency is shown in Figure 3a as a function of QCL drive current and hence frequency. The heterodyne signal with the THz transmitter turned off is shown in black; the QCL current is tuned to adjust the beat frequency. The same axes also shows the equivalent spectra when the transmitter is switched on (red). Upon switching the THz transmitter on, a significant amount of frequency pulling is observed. As the heterodyne frequency between the QCL and THz reference frequency is reduced by tuning the QCL current, this frequency pulling effect increases, until, when the frequency difference is less than ~5 MHz, the heterodyne beat is no longer visible when the transmitter is switched on (Fig. 3(a) panels (iv)–(vi)). At this point all of the signal appears at zero frequency (DC), and the QCL is injection locked to the reference frequency [2]. The vertical axis of Figure 3a shows relative power, in dB, to the peak signal at zero frequency when the QCL is locked.

We have also performed phase-resolved detection of the locked QCL, measuring the electric field and characterise the phase noise of the locked system to be –75 dBc/Hz at 10 kHz offset from the 2 THz carrier. This is the first time a QCL has been directly injection locked using a quasi-optical system. This results in reduced complexity, removes the need for a fast detector and can compensate for phase fluctuations across a wider bandwidth, when compared with laser locking using feedback loops.

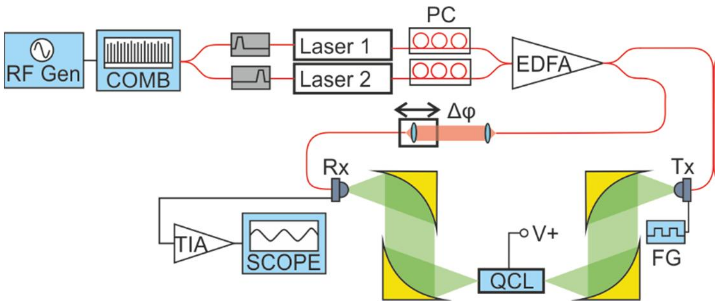

Figure 1. Experimental arrangement used for injection locking the THz QCL; electronic connections are shown in black, fibre connections and near-IR are in red, and free-space THz radiation is in green. Also shown, from the top left are: the RF signal generator (RF Gen); the wideband comb source (COMB); tunable bandpass filters; tunable DBR lasers, laser 1 and laser 2; polarisation controllers (PC); an erbium-doped fibre amplifier (EDFA); the continuous-wave THz transmitter (Tx); a function generator (FG); the quantum cascade laser (QCL); a free-space optical delay line for phase adjustment (Δψ); the continuous-wave THz receiver (Rx); a transimpedence amplifier (TIA); and an oscilloscope (SCOPE) for data acquisition.

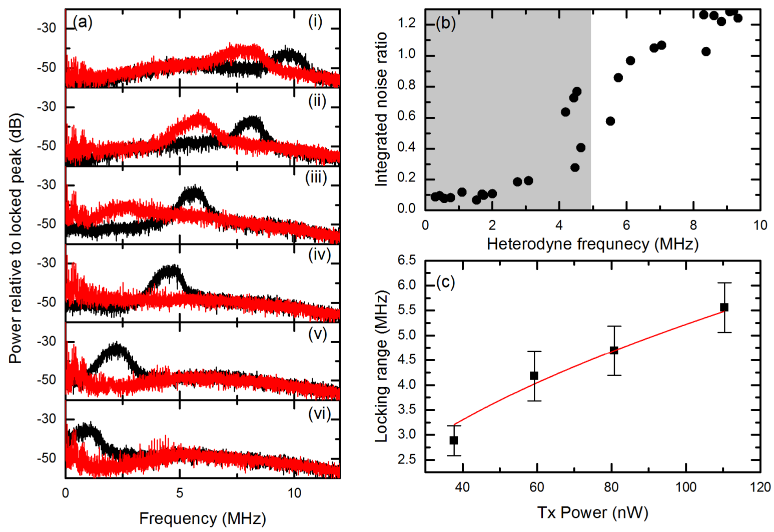

Figure 2. (a) The beat signal between the reference signal derived from the comb source and the QCL for the THz transmitter is off (black) and on (red). The QCL current is adjusted to tune the QCL frequency. The QCL current is adjusted over a range of 1.5 mA to tune the QCL emission frequency over the 9 MHz range shown in the figure. (b) The integrated noise (0-10 MHz) as a function of the heterodyne beat signal position. The shaded region indicates the heterodyne frequencies for where the QCL becomes locked. (c) The observed locking range as a function of Tx power, showing a least-squares fitting to Adler's equation.

References

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