Exact frequency and phase control of a terahertz laser: supplement

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Supplementary information

All-fibre frequency comb

The infrared (IR) comb used in this work is generated by the successive phase modulation of a narrow linewidth (<15 kHz) ‘C band’ seed laser (Redfern Integrated Optics, ORION) in an amplified recirculating fibre loop. A high-speed, LiNbO$_3$ travelling wave optical phase modulator (model T.PM1.5-22, V$_{\pi}$ < 7 V) is used for the phase modulation of the seed laser and is driven using a microwave synthesizer (Agilent technologies, E8257D).

Due to the successive phase modulation, the generated IR comb contains around 125 lines, separated by the microwave synthesizer frequency, $f_{RF}$, and centred on the seed laser wavelength (1553.10 nm) with a span of ~2.5 THz [1]. Because the closed-loop arrangement of the comb forms a resonator, the transmission is a periodic function with a free spectral range of 10MHz and $f_{RF}$ can be tuned in discrete steps of 10 MHz between 17.5 GHz to 20 GHz, to change the spacing between the comb lines. To enable continuous tuning of the line spacing across the frequency range a manual fibre delay line is included to control the length of the fibre loop. For changes in the microwave synthesizer frequency, $\Delta f_{RF} > 20$ kHz, the fibre delay line needs to be adjusted manually to match $f_{RF}$ with an integer multiple of the FSR. This limitation could be addressed by replacing the manual fibre delay line with an automated delay line.

To use the IR comb for injection locking the THz QCL with an emission frequency, $f_{QCL}$, two comb lines separated by the THz reference frequency, $f_{ref} = N \times f_{RF}$ are selected, where N is the number of comb line spacing between the selected lines. Although the linewidth of the individual comb line is determined by the seed laser linewidth, <15 kHz, due to the phase correlation of the comb lines with the microwave reference, the linewidth of the heterodyned signal is $N$ times the linewidth of the GPS disciplined microwave synthesizer reference signal $\Delta f_{RF}$, thus $\Delta f_{ref} \approx 10^1 \times \Delta f_{RF}$. Further details can be found in [1]. This results in an effective linewidth at the reference frequency (2 THz) of <101 Hz, with a frequency drift determined by a GPS locked Rubidium oscillator (Quartzlock E8010) with a quoted frequency drift of zero. We can compare this to femtosecond laser combs that have been used previously: Ref. [2] quotes an equivalent comb linewidth of 1 kHz at 2.7 THz. Ref. [3] uses an unstabilized comb with slow drifts of the order of hundreds of millihertz in 1 s, which, after multiplication of the 77.47 MHz repetition rate to 2.5 THz results in an equivalent frequency drift of ~10 kHz, measured over 1 s. For comparison with the state-of-the-art, a femtosecond comb stabilised to atomic frequency standards in ref. [4] has a measured stability of 3.4 mHz in 100 MHz over 15 mins, which would give an equivalent frequency drift of 68 Hz at 2 THz.

The output from the IR comb was split and filtered using two adjustable in-line fibre filters (TECOS, FC–1550B-1-0.6 and FC–1575B-1-0.6). The separation between the filtered comb lines, centred at 1543.19 nm and 1559.23 nm define the THz reference frequency, $f_{ref}$. A pair of ‘C band’ digital-supermode distributed Bragg reflector (DSDBR) lasers from Lumentum Technology [5] were each injection locked to one of the selected comb lines to achieve an improvement in optical signal to noise ratio (OSNR) by >30 dB, while preserving the phase coherence, without the need for multi-stage amplification.

Quantum Cascade Laser

The QCL used in this experiment has a bound-to-continuum active region with a design frequency of 2 THz [6]. The QCL wafer was processed into 200 µm wide ridges with single-plasmon waveguide using wet etching. A 2.5 mm long device was cleaved from the processed wafer and indium soldered to a copper block. The device was then mounted.
onto the cold finger of a continuous flow liquid Helium cryostat with the temperature maintained at 15 K. The IV and spectra of the device at 750 mA can be found in ref [7]. The device lases in a single mode with an emission frequency of 1.997 THz. A low noise QCL driver (Wavelength electronics QCL1000 OEM) with a modulation bandwidth of 10 MHz was used to power the THz QCL.

THz Injection

The output from the injection locked lasers were combined, amplified using an EDFA, then split using a 50:50 fibre splitter. One output of the splitter was connected to a fibre-coupled InGaAs CW THz photomixer emitter (EK-00724) from TOPTICA Photonics. The emitter (Tx) is a broadband photoconductive antenna which emits CW THz radiation at the THz reference frequency, $f_{\text{ref}}$ and can be operated in both pulsed and CW mode [8], but was operated in CW mode in this work. The THz power from the emitter was measured using a bolometer (calibrated using Thomas Keating absolute power meter) as 100 nW at 2 THz. The THz radiation from the emitter is linearly polarized and the polarization direction could be changed by rotating the emitter module. The THz signal from the emitter was collected and focussed to the QCL using two 2-inch off-axis parabolic mirrors. The second output of the splitter was split again using another 50:50 splitter and connected to two identical commercial fibre-coupled InGaAs CW THz photomixer receivers (EK-00725) from TOPTICA Photonics [9], labelled Rx1 and Rx2 in Figure S1. The signal from the receivers were amplified using transimpedance amplifiers (TIA) from Femto electronics (DHPA-100). These are low noise amplifiers with variable gain and bandwidths ranging between 0.22 MHz to 200 MHz.

The signal from Rx1 is amplified by a TIA with a bandwidth of 220 kHz, $10^7$ V/A gain then connected to a high speed servo controller (Newport LB1005) that provides negative electrical feedback to the QCL DC source, forming a phase locked loop (PLL). It incorporates an input filter section to remove any offset and an output amplifier section with variable proportional gain. The corner frequency of the filter can be selected as 0 Hz (a true integrator, with no frequency cut-off), 10 Hz or 10 MHz (3dB cut-off frequency). With the PLL in the active state, the QCL DC current is controlled by the PLL feedback voltage.

THz-IPLL and THz-IL– Amplitude and Phase measurements

The frequency and phase stabilized CW signal from the QCL at the Rx2 was measured using a lock-in amplifier. An optical chopper was introduced on the Rx2 infrared beam path with the variable delay line to extract the amplitude and phase information of the locked THz QCL. The chopper was operated at 2.4 kHz and was used as a reference for the lock-in amplifier. This allowed detection of the locked QCL signal only. The TIA connected to the Rx2 had $10^7$ (V/A) gain and 0.22 MHz bandwidth.

Linewidth measurement

The experimental arrangement used for the linewidth measurement is shown in Figure S1. The outputs from laser 1 (L1) and laser 2 (L2) were both split using 50:50 fibre splitters. One of the outputs from both L1 and L2 was combined using a 50:50 fibre combiner (2×2) and amplified using an EDFA before exciting the Tx and Rx1, ensuring coherent detection for the THz-IL and THz-IPLL system. A polarization-maintaining fibre-coupled acousto-optic modulator (T-M080-0.4C2J-3-F2P, Gooch and Housego) was incorporated on the other output of the L2 (Figure S1). The acousto-optic modulator (AOM), when driven using a low noise RF synthesiser (Agilent E8257D) produces a
The frequency-shifted L2 line was combined with the second output of L1 using a 50:50 fibre combiner (2×2) and amplified using an EDFA, then connected to Rx2. The EDFA used in the experimental system are identical and due to the long coherence length of the locked lasers (L1 and L2), the coherent detection of the measurement at Rx2 is unaffected. The signal from the Rx2 is amplified using TIA with a gain and bandwidth of $10^4$ (V/A) and 80 MHz, respectively and measured on an electrical spectrum analyser (Agilent, CXA 9000A). The microwave reference synthesizer, RF synthesizer for the AOM and the electrical spectrum analyser were referenced to a GPS locked Rubidium oscillator (Quartzlock E8010), which provides a frequency stability of $<1x10^{-12}$ over 100s.

Fig. S1. Schematic of the experimental system used for the linewidth measurement. EDFA, erbium doped fibre amplifier; Tx, photomixer emitter; Rx1 and Rx2, photomixer receivers; PLL, phase lock loop; $\Delta \phi$, variable delay line; ESA, electrical spectrum analyser. Electrical connections are shown in black, optical fibre and IR connections in red and THz connections in green.

**Phase-locked power**

The phase-locked power, $\theta_{n1}^2$ is calculated using the equation [10],

$$\theta_{n1}^2 = 1 - \frac{P_s + P_{bg}}{P_p}$$

where $P_s$, $P_{bg}$, $P_p$ represents the integrated power on the sideband, background and peak, respectively. We have integrated the AOM data for a 1kHz span and 1Hz RBW. Since the peak and background power is similar for the THz-IL and THz-PLL, we can...
infer that the difference in phase-locked power is due to the contribution from sideband peaks.
Fig. S2. (a) Measured THz amplitude from the Rx2 plotted as a function of time. The amplitude oscillations for the THz-IPLL state (dashed red box) was found to be much lower compared to the THz-IL state (dashed blue box). (b) FFT of the THz-IL (blue) and THz-IPLL (red) data with the same time window length. The spectral noise of the THz-IL state was higher to the THz-IPLL state for frequencies < 1 kHz.
Low frequency noise

Figure S2(a) shows the THz signal measured on Rx2 over 5 s, first with the THz-IPLL switched on, then after around 2 s the electronic PLL is turned off to demonstrate the effect of the PLL. For this measurement, the TIA of the Rx2 was set to be 10^7 gain with a bandwidth of 0.22 MHz and was recorded using a fast data acquisition oscilloscope (DS0S404A) with a sampling rate of 2.5 MHz. The delay line for Rx2 is set so that the electric field is at a node and the response to phase variations produce a linear change in voltage (red curve in Figure 2). The action of the PLL reduces the underlying frequency variations of the QCL, and hence the phase variations between the QCL and the reference frequency. The amplitude fluctuations in the THz-IPLL is approximately ±4 nA, which corresponds to a phase variation of ~0.08 radians. When the feedback voltage is turned off so the QCL is in the THz-IL state the amplitude fluctuations increase to around ±10 nA corresponding to a phase variation of ~0.2 radians. The observed dip in the THz-IL signal at ~3 s is due to the QCL slipping out of the lock.

The measurement here is equivalent to the quadrature method of phase noise measurement [11], as such we are able to calculate the low-frequency phase noise of each case from the Fourier transform of the time-domain data shown in figure S2(a). This is shown in figure S2(b), where we have used the phase/amplitude conversion factor of 0.48 V/radians. The noise spectrum of the THz-IPLL had a phase noise of ~70 dBc/Hz for an offset of 100 Hz which is ~20 dB lower compared to the THz-IL. The THz-IL phase noise shows a broad peak in the 10 – 100 Hz range which we believe originate from electrical and mechanical fluctuations. This data is in agreement with the data acquired by using a frequency offset provided by an AOM (Figure 3), where the low-frequency noise in the 10-100 Hz region is clearly visible.

This measurement also allows us to calculate the fraction of the power locked to the reference frequency. From the data shown in figure S2, we calculate that 94% and 99% of the power is locked in the THz-IL and THz-IPLL case, respectively. The higher values of locked power calculated here are from the higher SNR in this measurement. The reduced bandwidth means that a higher transimpedance gain can be used.

References

1. L. Ponnampalam, M. Fice, H. Shams, C. Renaud, and A. Seeds, "Optical comb for generation of a continuously tunable coherent THz signal from 122.5 GHz to 27 THz," Opt. Lett. 43, 2507 (2018).
2. S. Barbieri, P. Gellie, G. Santarelli, L. Ding, W. Maineult, C. Sirtori, R. Colombelli, H. Beere, and D. Ritchie, "Phase-locking of a 2.7-THz quantum cascade laser to a mode-locked erbium-doped fibre laser," Nat. Photon. 4, 636–640 (2010).
3. L. Consolino, A. Taschin, P. Bartolini, S. Bartalini, P. Cancio, A. Tredicucci, H. E. Beere, D. A. Ritchie, R. Torre, M. S. Vitello, and P. De Natale, "Phase-locking to a free-space terahertz comb for metrological-grade terahertz lasers," Nat. Commun. 3, 1040–1045 (2012).
4. D. Fehrenbacher, P. Sulzer, A. Liehl, T. Kälberer, C. Riek, D. V. Seletskiy, and A. Leitenstorfer, "Free-running performance and full control of a passively phase-stable Er:fiber frequency comb," Optica 2, 917 (2015).
5. A. J. Ward, D. J. Robbins, G. Busico, E. Barton, L. Ponnampalam, J. P. Duck, N. D. Whitbread, P. J. Williams, D. C. J. Reid, A. C. Carter, and M. J. Wale, "Widely tunable DS-DBR laser with monolithically integrated SOA: Design and performance," IEEE J. Sel. Top. Quantum Electron. 11, 149–156 (2005).
6. J. R. Freeman, O. Marshall, H. E. Beere, and D. A. Ritchie, "Improved wall plug efficiency of a 1.9 THz quantum cascade laser by an automated design approach," Appl. Phys. Lett. 93, 9–12 (2008).
7. J. R. Freeman, L. Ponnampalam, H. Shams, R. A. Mohandas, C. C. Renaud, P. Dean, L. Li, A. Giles Davies, A. J. Seeds, and E. H. Linfield, "Injection locking of a terahertz quantum cascade laser to a telecommunications wavelength frequency comb," Optica 4, 1059 (2017).

8. D. Stanze, A. Deninger, A. Roggenbuck, S. Schindler, M. Schlak, and B. Sartorius, "Compact cw terahertz spectrometer pumped at 1.5 \( \mu \)m wavelength," J. Infrared, Millimeter, Terahertz Waves 32, 225–232 (2011).

9. T. Göbel, D. Stanze, B. Globisch, R. J. B. Dietz, H. Roehle, and M. Schell, "Telecom technology based continuous wave terahertz photomixing system with 105 decibel signal-to-noise ratio and 35 terahertz bandwidth," Opt. Lett. 38, 4197 (2013).

10. R. E. Best, Phase-Locked Loops (McGraw-Hill, 2003).

11. A. L. Lance, W. D. Seal, and F. Labaar, "Phase Noise and AM Noise Measurements in the Frequency Domain," Infrared Millim. Waves 11, 239–289 (1984).