High-resolution frequency and phase control of a terahertz laser

Reshma A Mohandas[1], Lalitha Ponnampalam[2], Alwyn Seeds[2], Paul Dean[1], Edmund H Linfield[1], A Giles Davies[1] and Joshua R Freeman[1]

[1]School of Electronic and Electrical engineering, University of Leeds, Leeds, LS2 9JT, UK

[2]School of Electronic and Electrical engineering, University College London, London, WC1E 6BT, UK

***Abstract*—We report on the high-resolution frequency and phase control of a terahertz (THz) quantum cascade laser (QCL). The 2.0 THz QCL is locked to a stable microwave reference frequency via an all-fibre infrared frequency comb. The frequency of the QCL is controlled by optical injection and the phase is independently controlled by introducing a phase-lock loop that provides electronic feedback to the QCL, forming an optical injection phase locked loop (OIPLL). By implementing this, (1) the instrument limited linewidth of the locked QCL was <1Hz (2) for a fixed frequency, the phase of the THz QCL relative to the microwave reference frequency can be controlled within a range 0.3π.**

I. INTRODUCTION

A narrow linewidth, high-precision terahertz (THz) source is necessary for astronomical applications where it acts as a local oscillator for radiometry and spectroscopy, where many gas molecules have fundamental rotational and vibrational modes. THz QCLs are an ideal choice for these applications due to the intrinsically narrow linewidth (~kHz) and high power (>1W [1]) capabilities. However, an enhancement in the free-running THz QCL linewidth arises due to the electrical, thermal and mechanical noises in the system [2]. This can be avoided by phase locking the THz QCL to a stable source. There have been several works to lock the frequency and phase of the QCL, including locking to a femtosecond comb [3], gas absorption line [4], multiplied microwave source [5] etc. However, the relation between the locked frequency and phase is not well-defined in these methods. To address this issue, in this work, the QCL is optically injection locked (OIL). Injection locking occurs when a stable 'master' frequency is injected into an unstable 'slave' source. The locked slave frequency is exactly the same as that of the master. The frequency range over which the slave source is locked to the master is known as the locking range. According to Adler's theory [6], within the locking range, the frequency of the slave is the same as that of the master, whereas the phase undergoes a 'π' change relative to the master.

In this work, a 2.0 THz QCL is injection locked to an all-fibre infrared frequency comb [7], thus stabilizing the THz QCL frequency to a microwave reference. The phase of the optically injection locked THz QCL is controlled independently by introducing a phase lock loop, which provides an electronic feedback to the THz QCL forming an optical injection phase locked loop (OIPLL).

II. RESULTS

The all-fibre infrared frequency comb is generated by the successive phase modulation of a 'C-band' laser (1553.10 nm) in an amplifying, recirculating fibre loop. A series of comb lines are generated, separated at the microwave frequency, ν_{RF}, and spans a bandwidth of >2.7 THz [8]. In order to use the comb lines to injection lock the QCL with an emission frequency, ν_{QCL}, two comb lines spaced at the reference frequency, ν_{ref} (where $\nu_{ref} = N\times\nu_{RF}$, N is the integer number of comb lines) was used. The RF frequency was set to be, ν_{RF}=19.7734 GHz, corresponding to a ν_{ref} = 1997.1134 GHz. Two comb lines separated by N=101, is filtered out using an in-line filter and injected to two distributed Bragg reflector (DBR) lasers. The output from the DBR lasers are amplified using an EDFA and heterodyned in a fibre-coupled InGaAs THz photomixer transmitter (Tx) from TOPTICA Photonics (EK00724) generating THz radiation at the THz reference frequency. Although the linewidth of the individual comb lines is determined by the seed laser linewidth (<15kHz), the linewidth of the heterodyned signal between the two lines is $\Delta\nu_{ref} \approx 101\times\Delta\nu_{RF}$. Figure 1 shows the schematic of the experimental set-up used. The THz reference from the Tx is injected to the QCL using a pair of parabolic mirrors, injection locking the THz QCL. The THz radiation from the QCL is split into two using a beam splitter and detected on two identical coherent fibre coupled InGaAs photomixer receivers from TOPTICA Photonics (EK00725). The output from the receiver 1 (Rx1) was amplified using a transimpedance amplifier with 10^7gain and 0.22 MHz bandwidth and fed to a commercial PID controller. The PID controller gives an electrical feedback which then controls the low-noise QCL current source, forming the OIPLL. An optical delay line incorporated on the receiver 2 (Rx2) path was scanned to measure the THz QCL emission amplitude and phase.

The QCL used in this work is a bound-to-continuum active region design with an emission frequency of 2.0 THz. The devices were fabricated onto a single-plasmon waveguide active region. A 2.5 mm long device was indium soldered on a copper block and mounted onto the cold finger of a continuous flow liquid helium cryostat and kept at a constant temperature of 15 K.

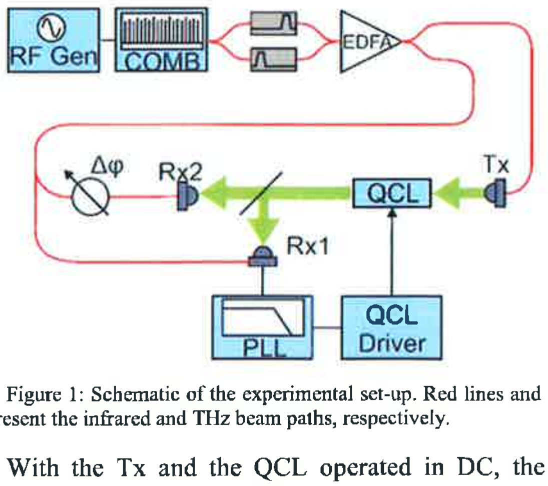

Figure 1: Schematic of the experimental set-up. Red lines and green lines represent the infrared and THz beam paths, respectively.

With the Tx and the QCL operated in DC, the QCL is optically injection locked (OIL) when ν_{ref} is close to the QCL frequency, ν_{QCL}. Once the QCL is OIL, it is brought into the OIPLL state by switching on the PLL. OIL can compensate for the fast frequency fluctuations and PLL can compensate for larger amplitude fluctuations arising due to thermal and mechanical drift, which are usually slow in nature. The PLL is operated in an integrator mode, producing a feedback voltage proportional to the input voltage integrated over time.

Figure 2a shows the THz amplitude and phase measured at the Rx2 as a function of time for the OIL system i.e. without any feedback to the QCL current source (hollow squares) and the OIPLL system (solid squares). The Rx2 delay line was scanned to measure the amplitude and phase of the QCL emission. We can see that over 10 minutes, the THz amplitude and phase of the OIPLL system was ~325 mV±10 mV and -0.06 π respectively, and it remained stable throughout the measurement period. However, for the OIL system, the amplitude (~225mV±100mV) and phase (~0.1 π) drifted significantly after the 5th minute. The amplitude drifts by more than 50%, whereas the phase underwent ~0.4 π shift. This drift could be due to the thermal, electrical or mechanical noises in the system. Adding the PLL enhanced the amplitude and phase stability of the OIPLL system.

When in the OIPLL state, the locked QCL frequency is determined by the injected THz reference frequency and the phase of the locked QCL (relative to the reference phase) can now be controlled independently by adjusting the offset of the PLL. Inset in Figure 2a shows the measured THz amplitude and phase values as a function of the offset voltage. With the THz amplitude remaining constant, the QCL phase undergoes a 0.3 π phase shift when the offset voltage is changed between -0.3 V to 0.3 V. Beyond the 0.3 V, the PLL filter amplifier saturated.

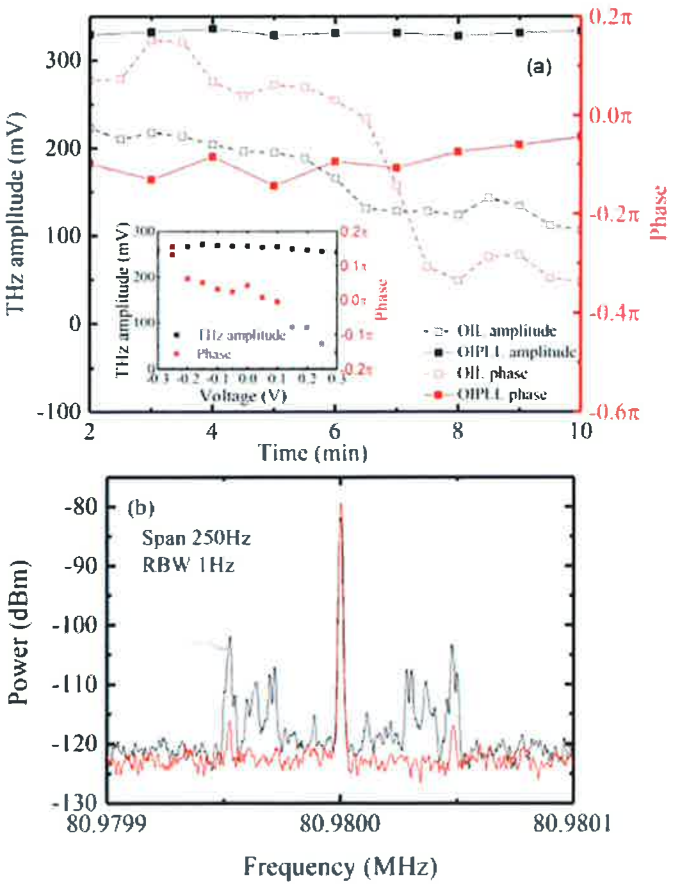

Figure 2: (a) The THz amplitude and phase at Rx2 measured as a function of time for the OIL (hollow squares) and OIPLL (solid squares) system. Inset shows the THz signal amplitude (black symbols and line) and phase (red symbols and line) plotted as a function of the DC voltage offset. (b) Measured linewidth spectra for the OIL (black) and OIPLL (red) states.

The linewidth of the locked QCL was measured for the OIL and OIPLL states by heterodyning the locked QCL frequency and frequency-shifted version of the THz reference frequency in the Rx2. A fibre-coupled acousto-optic modulator was used to frequency shift one of the DSDBR lasers by 80.98 MHz on the Rx2 beam path. The transimpedance amplifier gain and bandwidth was adjusted to be 10^4 and 80 MHz, respectively. Figure 2b shows the measured linewidth spectrum for the OIL and OIPLL states at a 250 Hz span and a RBW of 1 Hz. The 3 dB linewidth is <1 Hz for both states suggesting that the spectrum analyser limits the measured linewidth of the locked QCL. The presence of sideband peaks on the OIL spectrum at 80.98 MHz± 50Hz is due to the electrical and mechanical disturbances, which are compensated by the use of PLL resulting a cleaner spectrum for the OIPLL.

III. SUMMARY

We report the absolute frequency and phase control of a THz QCL locked to a microwave optical synthesizer by an OIPLL. The THz amplitude and phase was stabilized using the OIPLL system. The stabilized phase of the locked QCL was controlled using a PLL. The instrument-limited linewidth of the locked QCL was measured to be <1Hz. All the components used in the work, IR comb, QCL, PLL and photomixers could be monolithically-integrated onto a single photonic chip making a compact and portable high-precision THz system.

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