Continuously Tunable Coherent THz Synthesiser, Referenced to Primary Frequency Standards

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***Abstract*—We present a highly coherent tunable THz source based on an optical frequency comb generator with frequencies referenced to primary frequency standards to injection lock a high power 2 THz quantum cascade laser for spectroscopy applications. The THz synthesiser is continuously tunable from 122.5 GHz to greater than 2.7 THz, with a spectral resolution of 10's of Hz and a frequency accuracy of 1 part in 10^{12}. The composite noise has been measured up to a record frequency of 300 GHz, and is -75 dBc/Hz at an offset frequency of 10 kHz, limited by the scaled phase noise of the reference synthesizer. The THz synthesizer has been used to injection lock a 2 THz quantum cascade laser to realize a high power, narrow linewidth source suitable for high-resolution spectroscopy.**

Keywords—optical frequency comb, photonic THz generation, coherent, tunable, optical heterodyning, quantum cascade laser, phase noise, injection locking

I. Introduction

Although the THz radiation has numerous potential applications such as molecular spectroscopy [] and high-resolution imaging [] suitable for medical, pharmaceutical, security, space science and astronomy, due to lack of high power, tuneable, coherent sources, full exploitation of this part of the electromagnetic spectrum is yet to be realised. In particular, as a large number of molecular structures exhibit closely spaced Hz-linewidth transitions in the THz region, this part of the spectrum represent the region for molecular fingerprinting and hence, high power highly coherent tuneable THz sources, referenced to primary frequency standards are key for the development of high-resolution molecular spectroscopy.

Development of THz sources based on photonics technology [] is promising due to its compactness, ability to transport THz signal over long distances via low loss, much lighter and more flexible optical fibres, availability of wide bandwidth optoelectronic components and frequency agility of optical components, characteristics that cannot be easily accomplished through conventional microwave components. In order to generate mm-wave or THz signals by optical means, two optical tones separated by the desired frequency are applied to an opto-electronic converters such as a wide bandwidth UTC photodetector [] or a photoconductor [] to generate the heterodyne electrical signal at the frequency corresponding to the frequency difference between the two optical tones. Hence, the THz signal generated in this way can be broadly tuneable, tuning range largely limited by the bandwidth of the opto-electronic converter; however, its spectral purity will be determined by the linewidth and frequency stability of each of the optical tone. Although the linewidth of lasers can be of the order of 10's of kHz to few MHz, their frequency stability is affected by thermal, mechanical and electrical noise which can broaden the linewidth of the heterodyne signal to 100's MHz. In order to generate high spectral purity THz signal for applications such as molecular spectroscopy and high-resolution imaging, the relative frequency and the phase between the two optical tones have to be preserved. In this work, this is achieved by developing a multi-THz span optical frequency comb generator (OFCG). Here, the relative phase and frequency of the comb lines are exactly defined by a GPS disciplined microwave synthesiser, and high spectral purity THz signals are generated by selecting two of the comb lines using a high-Q optical filter, and applying the selected two lines on to a wide bandwidth opto-electronic converter as shown in Fig. 1.

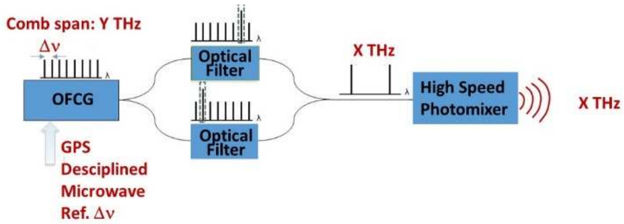

Fig. 1. Schematic of the photonic generation of microwave, mm-wave and THz signals.

Thus absolute frequency referenced, continuously tuneable THz signal over a frequency range from 122.5 GHz to >2.7 THz, with additional gapped bands down to 17.5 GHz, with a linewidth of 10's Hz has been demonstrated. We also report detailed measurements of the composite (amplitude and phase) noise of the system up to 300 GHz, which will be critical for many applications. We also present the first results of the injection locking of 2 THz quantum cascade laser (QCL) using the THz synthesiser developed here.

II. Optical Frequency Comb

The OFCG developed in this work is based on an amplified re-circulating loop with a single phase modulator, described in detail in []. In order to obtain a flattened gain profile, a highly doped fibre amplifier was used with a length carefully selected to suppress the usual gain peak seen at 1530 nm. A 2m dispersion compensating fibre with a dispersion coefficient of -120 ps/(nm.km) has been included to maximise the comb span. The total length of the loop was ~20m, giving a free spectral range (FSR) of 10 MHz. In order to achieve high spectral purity comb lines, a RIO-Orion seed laser with a linewidth of 15 kHz, narrower than the FSR was used. In order to maintain the resonance condition with such a narrow linewidth seed laser requires an active control of the loop length. A piezo-electric fibre stretcher with a control loop was implemented to compensate for any fluctuations in the seed laser frequency and any variation in the loop length caused by temperature.

OFCG described here generated phase correlated comb lines over a record span of 3.8 THz for a loop with a single phase modulator as shown in Fig.2. The -6 dB bandwidth is ~ 2.7 THz, and the linewidth of each of the comb lines is 10's kHz, similar to the linewidth of the seed laser.

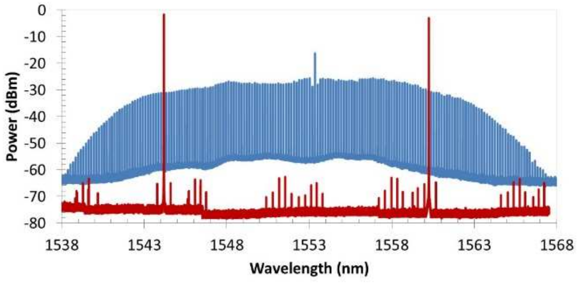

Fig. 2. Optical spectra of the OFCG and the injection locked DSDBR lasers; Comb line spacing referenced to primary frequency standards (resolution bandwidth : 0.04pm).

III. Comb Line Filtering

A tuneable optical filter with high Q-factor will be required to select the required comb line from the OFCG while suppressing the other. The passive optical filters that are currently available in the market have many drawbacks: (1) can have up to 10's of dB insertion loss (2) 3 dB bandwidth of 10's of GHz, allowing several comb lines to pass through (3) can have periodic transmission spectra. By phase locking a laser to the required comb line by means of optical injection locking [] or optical phase lock loop [], the spectral characteristics of the comb line are transferred to the laser, making it an attractive alternative to the passive filters. Laser locking techniques can offer optical gain with high-Q filtering, and in this work, a high power widely tuneable Digital Supermode Distributed Bragg Reflector (DS-DBR) laser injection locked to the required comb line operates as an active, high-Q optical filter with optical gain greater than 30 dB, preventing the need for multiple amplification stages.

Fig.3 shows the schematic of the injection locked THz synthesiser. To minimize the instability of the DBR laser, the amplified output from the OFCG was passed through an optical band pass filter (OBPF) to limit the number of comb lines injected into the DBR laser. The DSDBR lasers were tuned to lock to two of the required comb lines. Optimum locking was achieved by adjusting the polarisation of the comb lines with respect to the DBR lasers on each arm.

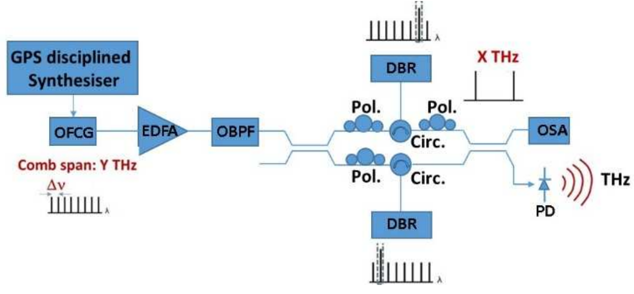

Fig. 3. Schematic of the optical injection locked THz synthesiser (EDFA : Erbium doped fibre amplifier; Pol. : polarisation controller; Circ : circulator; PD : photodetector; OSA : optical spectrum analyser).

Fig.4 shows the electrical spectrum of the heterodyne signal between the two adjacent line, with a FWHM linewidth of < 10 Hz, limited by the resolution bandwidth of the spectrum analyser. The linewidth of the heterodyne signal beteen the comb lines separated by N comb line spacing will be N time the linewidth og the referene synthesiser. The optical spectrum of the two comb lines, selected by this laser locking technique, separated by 2 THz is shown in Fig. 5. The locked lasers provide an optical gain of >30 dB, compared to the comb line power in Fig. 2, and the optical signal to noise ratio (OSNR) improved to > 60 dB, compared to the OSNR of the comb lines itself. The two selected phase coherent optical tones were applied to a fast photodetector to generate a high spectral purity signal at the required frequency.

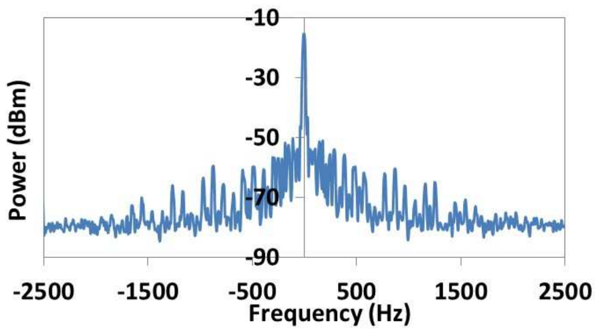

Fig. 4. Electrical spectrum of the heterodyne signal between adjacent two lines (RBW : 10 Hz).

The locking range for this system was measured to be ± 1 GHz for an injection level of -30 dB. This can be improved further by incorporating an optical injection phase lock loop (OIPLL) [], in which a low bandwidth OPLL will be sufficient to track the long term frequency/phase fluctuations while the fast fluctuations can be compensated for by the optical injection locking. Implementation of OIPLL will enable wider locking range with lasers with wider linewidths (few MHz), without the stringent restriction on loop delay.

IV. Tuneability

Continuous tuning of mm-wave and THz signals are desirable for many applications. In this work, a tuneable optical delay line has been included within the fibre re-circulating loop to continuously tune the comb line spacing, which is otherwise restricted to the FSR of the loop. The comb line spacing has been continuously tuned over 105 MHz (Fig. 5) when the loop was operating on a particular mode, however, to achieve continuous tuning of the mm-wave/THz signal, tuning of only over a FSR of the loop (~10 MHz) is necessary. This requires a change in loop length of only ~15 mm in a 20m loop. Thus, the comb line spacing has been continuously tuned from 17.5 GHz to 20 GHz, limited by the bandwidth of the electronic components., This translates to a continuous frequency coverage from 122.5 GHz to >2.7 THz, with additional gapped bands down to 17.5 GHz [].

V. System Noise

The composite (amplitude and phase) noise of the heterodyne signal between the comb lines up to a frequency of 300 GHz (N = 15) has been studied in detail. For frequencies less than 40GHz (bandwidth of the electrical spectrum analyser, ESA), the composite noise was measured directly using a UTC photodetector and a Rhode and Schwarz FSQ spectrum analyser. Fig. 7 shows the composite noise for N=1, compared to the phase noise of the reference synthesiser and the ESA, and it is less than -90 dBc/Hz at an offset frequency of 10 kHz, but it is higher than that of the reference synthesiser due to the noise contribution from the OFCG itself, which will be dominant at lower frequencies as will be shown later.

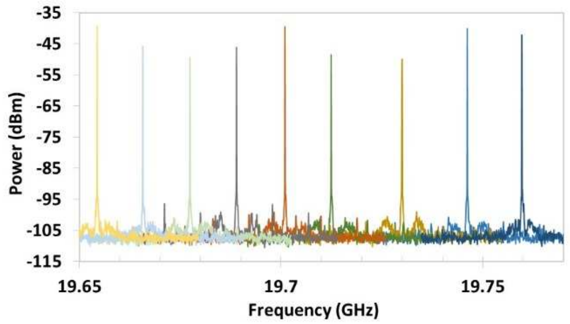

Fig. 5. Tuning of the comb line spacing with optical delay line (RBW : 1kHz)

As shown [], the overall composite noise of the system below 40 GHz can be calculated from,

$$CN = 10 * log(10^{\frac{[S1+20\log(N)]}{10}} + 10^{\frac{y}{10}} + 10^{\frac{F}{10}}) \quad dBc/Hz \quad (1)$$

where the contributions of the phase noise from the reference synthesiser (S_1 dBc/Hz), composite noise from the OFCG (y dBc/Hz) and the phase noise from the ESA (F dBc/Hz) have been combined. However, for frequencies greater than 40 GHz, the signal was down converted using a double harmonic mixer (Virginia Diodes, WR3.4MixAMC) with a X6 frequency multiplier, and hence the noise contribution from the local oscillator, [S2 + 20log(12)] dBc/Hz will need to be added to (1). From Fig. 7, the measured composite noise at the fundamental frequency is -97 dBc/Hz at 100 kHz offset, the noise contribution from the OFCG, y dBc/Hz is derived from (1) as -97dBc/Hz.

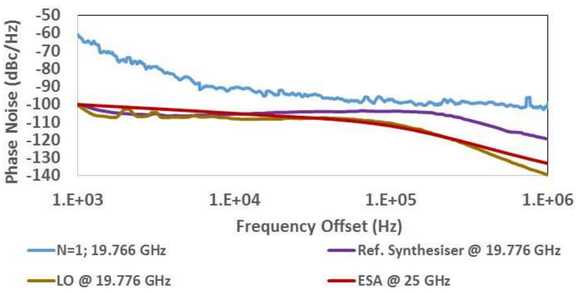

Fig. 6. Composite noise of the heterodyne signal between two adjacent comb lines compared to the phase noise of the reference, LO and the ESA.

The calculated and the measured composite noise of the heterodyne signal for frequencies up to N = 15 (296.5 GHz) at a 100 kHz offset is compared with the scaled phase noise of the reference synthesiser, [S_1 + 20log(N)] dBc/Hz (Fig. 8). It is evident that the noise converges with the scaled phase noise of the reference synthesiser at higher multiplication factors, however at lower frequencies (N $\leq$3), the contribution from the OFCG, y dBc/Hz is dominant. In order to syntehsiser at high frequencies such as at 2 THz, it is imperative to have a low noise reference source to drive the modulator within the OFCG loop.

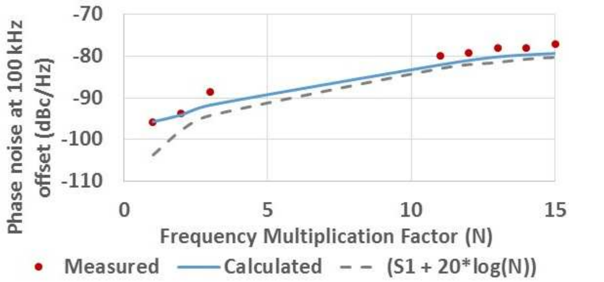

Fig. 7. Measured and calculated noise at 100 kHz offset frequency compared to the scaled phase noise of the synthesiser.

VI. Injection Locking of 2THz QCL To The IR-OFCG

In this section, the first results of a QCL injection locked to the above infrared OFCG are presented. The QCL which was a bound-to-continuum design with a single plasmon waveguide operating at 1.97 THz was mounted on a cold finger in a helium cryostat, maintained at a temperature of 14 K. High spectral purity sources such as frequency multipliers, photoconductors and uni-travelling photodectors (UTC-PD) operate over frequencies up to 1.5 THz, and their output power levels drop significantly for frequencies beyond 1.5 THz. The most promising source for frequency in the 1.5 – 5 THz region are the quantum cascade lasers (QCLs) which are electrically pumped semiconductor lasers capable of delivering hundreds of milliwatts of continuous wave coherent radiation. Although the QCL has intrinsically narrow linewidth (~100 Hz), due to thermal, electrical and mechanical fluctuations, its linewidth can be as broad as 1 – 10 MHz, requiring phase/frequency stabilisation for many high-resolution applications. 1.7mW

Previously, phase locking of QCLs to gas line, frequency multipliers, femtosecond lasers and frequency combs have been demonstrated using a negative feedback loop. Here, a simpler approach of direct injection locking of 2THz QCL is demonstrated to an infrared fibre comb, design of which can be translated to a monolithic integration platform that could lead to a compact system suitable for many applications. Here, the amplified pair of comb lines, whose heterodyne frequency is close to the QCL frequency was split by a 50:50 power splitter, and one part was incident on the Toptica THz transmitter (Tx), which was operated at a pulsed frequency of 1.15 kHz with a 50% duty cycle. The other part was incident on the Toptica THz receiver (Rx) to generate the reference signal. The generated THz signal by the transmitter close to the QCL frequency is coupled into the QCL to injection lock as shown in Fig. 9 [], and the maximum transmitter power was ~80 nW. An optical delay line is introduced in the receiver path to control the phase difference between the THz signal from the QCL and the THz reference signal. The current generated at the receiver was amplified by a transimpedance amplifier and was displayed on an oscilloscope. The transimpedance amplifier provided a variable gain of 10^5, 10^6 or 10^7 Ω with a detection bandwidth of 14 MHz, 1.8 MHz and 50 kHz respectively.

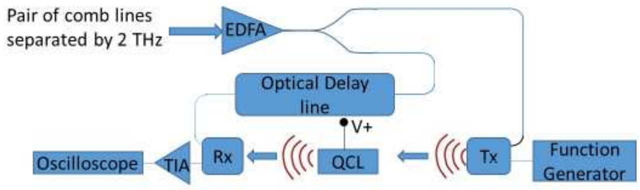

Fig. 8. Experimental arrangement used for injection locking the THz QCL; electronic connections are shown in black, fibre connections and near-IR are in red, and free-space THz radiation is in green. Also shown, from the top left are: the RF signal generator (RF Gen); the wideband comb source (COMB); 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.

The measure heterodyne signal between the signal from the QCL and the THz reference signal is shown in Fig. 10, as a function of QCL drive current. The QCL had a tuning efficiency of 6.5 MHz/mA. The 3-dB linewidth of the beat signal was measured to be 1 MHz, of which the linewidth of the reference signal was less than 100 Hz. Hence, the measured linewidth accounts for the broad linewidth of the free running QCL due to the electrical, thermal and mechanical noise inherent in such systems. As the QCL frequency was tuned such that the heterodyne frequency was tuned from 10 MHz to 4 MHz, the frequency of the QCL was pulled towards the THz reference frequency by as much as 1MHz []. When the QCL frequency was brought within 4 MHz to the THz reference frequency, the beat signal becomes no longer visible, indicating that the QCL is injection locked to the THz reference signal. The narrower locking range of ±4 MHz compared to the estimated locking range of ±14 MHz at this injection level may be due to non-optimised coupling of the THz signal into the QCL cavity [].

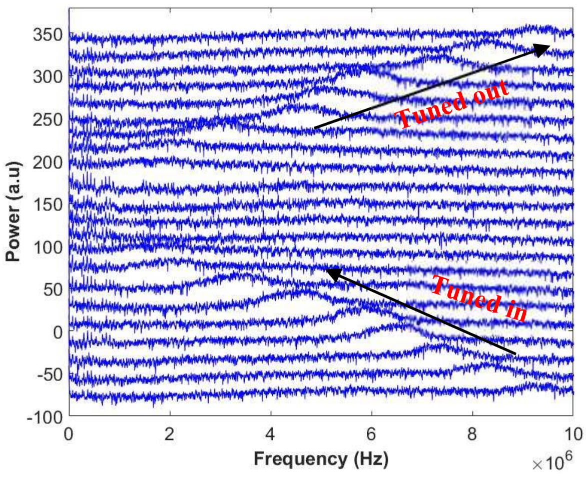

Fig. 9. The beat signal between the reference signal derived from the comb source and the QCL for the THz transmitter is off (black) and on (red). The QCL current is adjusted to tune the QCL frequency. The QCL current is adjusted over a range of 1.5 mA to tune the QCL emission frequency over the 9 MHz range shown in the figure.

As shown in Fig. 9, the relative phase of the reference signal with respect to the QCL signal can be varied using the free-space optical delay line. Thus, the amplitude and phase of the locked QCL signal was measured using a lock-in amplifier while the QCL drive current was varied (Fig. 11). For these measurements, the gain of the transimpedance amplifier was set at 10^6 with a bandwidth of 1.8 MHz to ensure that only the QCL signal that is locked are measured. Fig. 11 shows the amplitude and phase of the QCL when it is well locked (green) and partially locked (black). The amplitude of the QCL increased when the QCL frequency approaches the edge of the locking range and remains the same within the locking range. However, the phase of the signal changed from $-\pi/2$ to $+\pi/2$ as the frequency of the QCL was tuned in and away from the frequency of the THz reference signal as expected []. The reduced locking range in Fig. 11 may be due to imperfect alignment of the Transmitter and the QCL. Fig. 12 shows the spectrum of the heterodyne signal between the locked QCL signal and the THz reference signal at the modulation frequency of the transmitter, measuring a FWHM linewidth of 80 Hz.

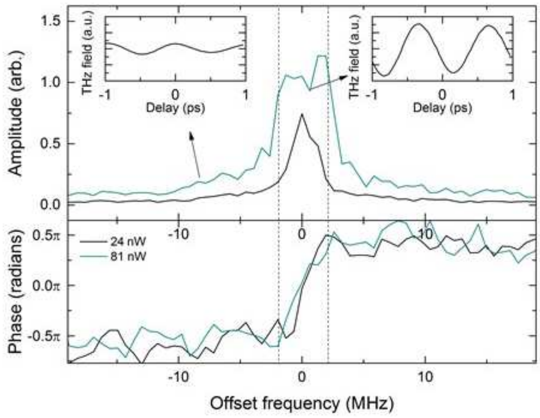

Fig. 10. The amplitude and phase of the locked signal measured using a lock-in amplifier. The frequency of the QCL is adjusted via its drive current and converted to frequency using the measured dependence of –6.5 MHz/mA. For each current (frequency) value, the detection phase is scanned and the sinusoidal waveform from the receiver recorded on the lock-in amplifier (shown in the insets). The amplitude and phase of this signal is shown for two injection powers. Because the detection is coherent, only QCL signals phase-locked to the comb will lead to a measurable signal.

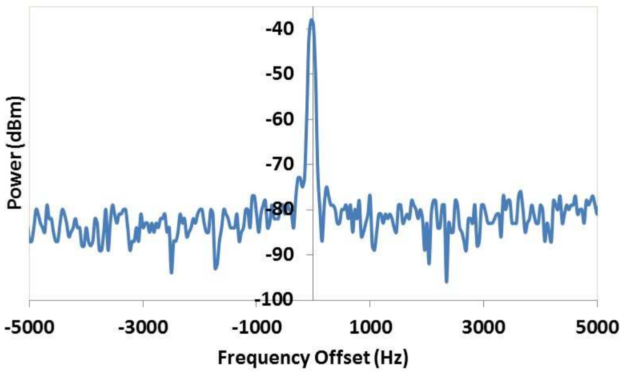

Fig. 11. RF spectrum of the locked QCL signal at the modulation frequency of the transmitter (RBW : 50 Hz).

VII. CONCLUSION

ACKNOWLEDGMENT *(Heading 5)*

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