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Continuously Tunable Coherent THz Synthesizer, 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. The THz synthesizer 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. A 2 THz quantum cascade laser with an output power of ~2 mW has been injection locked to the absolute frequency referenced, high spectral purity THz synthesizer 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

THz radiation has numerous potential applications such as molecular spectroscopy and high-resolution imaging suitable for medical, pharmaceutical, security, space science and astronomy. However, due to a 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, 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 [1] is promising due to its numerous advantages such as compactness, its ability to transport THz signals over longer distances via low loss, much lighter and more flexible optical fibres, availability of wide bandwidth optoelectronic components and frequency agility of optical 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 converter such as a wide bandwidth uni-travelling carrier (UTC) photodiode [2] or a photoconductor [3] to generate the heterodyne electrical signal at the THz frequency corresponding to the frequency difference between the two optical tones. Hence, the THz signal generated in this way can be broadly tuneable, with the 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 tones. Although the linewidth of lasers can be of the order of 10's of kHz to a 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 of MHz. In order to generate high spectral purity THz signals for applications such as molecular spectroscopy and high-resolution imaging, the relative frequency and 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) where the relative phase and frequency of the comb lines are exactly defined by a GPS disciplined microwave synthesizer. High spectral purity THz signals are generated by selecting a pair of suitably spaced comb lines using high-Q optical filters, and applying the selected two lines on to a high bandwidth photomixer as shown in Fig. 1.

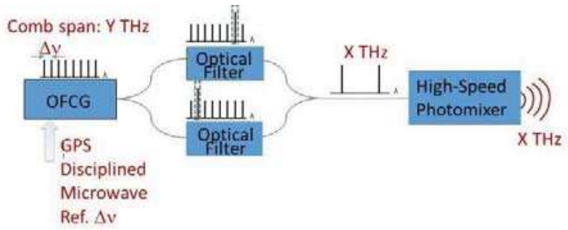

Fig. 1. Schematic of the photonic generation of microwave, mm-wave and THz signals.

Thus, 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 of Hz has been demonstrated. We also report detailed measurements of the composite (amplitude and phase) noise of the system up to 300 GHz. Although the spectral characteristics of the heterodyne signals are suitable for high-resolution applications, the signal power will be limited by the conversion efficiency of the opto-electronic converters. Hence, a high power 2 THz quantum cascade laser (QCL) has been direct-injection locked to this highly coherent THz synthesizer signal to realise a high power THz source with spectral characteristics referenced to a GPS disciplined microwave synthesizer.

II. Optical Frequency Comb

The infrared OFCG (IR-OFCG) developed in this work is based on an amplified re-circulating loop with a single phase modulator, described in detail in [4]. 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 at 1530 nm. In addition, to generate comb lines over a wider bandwidth, a 2 m length of dispersion compensating fibre with a dispersion coefficient of -120 ps/(nm.km) has been included to minimise the dispersion within the loop. The dispersion causes the higher order sidebands to suffer from accumulated phase mismatch, subsequently failing to satisfy the resonance condition. The total length of the loop was ~20 m, giving a free spectral range (FSR) of 10 MHz. In order to achieve high spectral purity comb lines, a RIO-Orion laser with a linewidth of 15 kHz, narrower than the FSR was used as the seed to the loop. In order to maintain the resonance condition with such a narrow linewidth seed laser, an active control of the loop length is required. A piezo-electric fibre stretcher with a control loop was implemented to compensate for any fluctuations in the seed laser frequency and temperature induced loop length variations.

The 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 was ~ 2.7 THz, and the linewidth of each of the comb lines was 10's of kHz, similar to the linewidth of the seed laser. The comb line spacing was exactly defined by a microwave synthesizer, referenced to a GPS disciplined 10 MHz oscillator (Quartzlock E8010) which acts as a self-calibrating frequency standard with frequency accuracy of 1 part in 10^{12}.

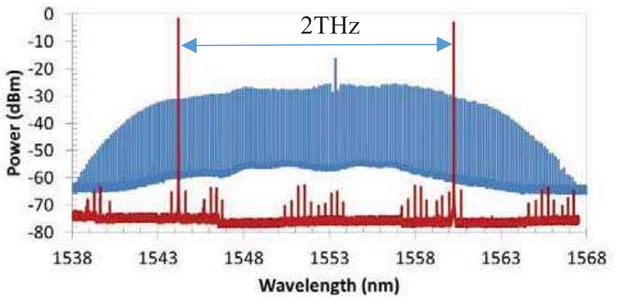

Fig. 2. Optical spectra of the OFCG and the injection locked DSDBR lasers; Comb line spacing referenced to primary frequency standards (resolution bandwidth : 0.04pm).

A tuneable optical filter with high Q-factor is needed to select the required pair of comb lines from the OFCG while suppressing the other lines. The passive optical filters that are currently available in the market have many drawbacks: they can have (1) insertion loss up to 10's of dB, (2) -3-dB bandwidth of 10's of GHz, allowing several comb lines to pass through, and (3) periodic transmission spectra. By phase locking a laser to the required comb line by means of optical injection locking [5] or optical phase lock loop [6], the spectral characteristics of the comb line can be transferred to the laser, making it an attractive alternative to the passive filters, offering optical gain with high-Q filtering. In this work, a pair of high power widely tuneable Digital Supermode Distributed Bragg Reflector (DS-DBR) lasers [7], each of which was injection locked to the required comb lines, operate as active, high-Q filters with an optical gain greater than 30 dB (Fig. 2), preventing the need for multiple amplification stages. In addition, this filtering technique also improved the optical signal to noise ratio (OSNR) to > 50 dB.

Fig. 3 shows the electrical spectrum of the heterodyne signal between the two adjacent lines, with a FWHM linewidth of < 10 Hz, limited by the resolution bandwidth of the spectrum analyser. The linewidth of the heterodyne signal between the comb lines separated by N comb-line spacings will be N times the linewidth of the reference synthesizer. 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) [10], in which a low bandwidth OPLL tracks 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.

III. TUNEABILITY

In order to continuously tune the frequency of the heterodyne signal, a tuneable optical delay line has been included within the fibre re-circulating loop to continuously tune the comb line spacing (Fig. 4), which was otherwise restricted to the FSR of the loop. Nonetheless, to achieve continuous tuning of the mm-wave/THz signal, tuning only over an 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 2.5 GHz of tuning of line spacing translates to a continuous frequency coverage from 122.5 GHz to >2.7 THz, with additional gapped bands down to 17.5 GHz [4].

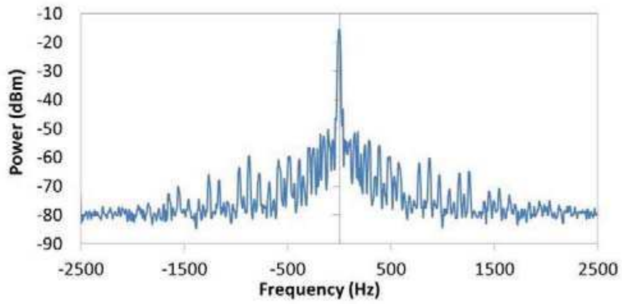

Fig. 3. Electrical spectrum of the heterodyne signal between adjacent two lines (RBW : 10 Hz).

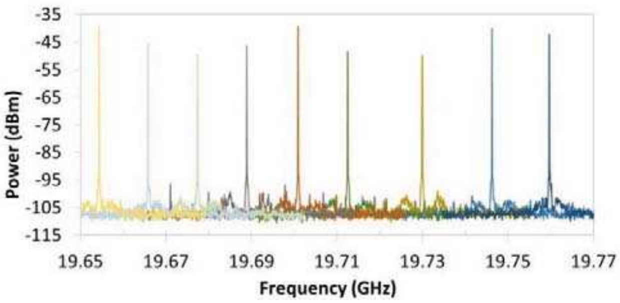

Fig. 4. Tuning of the line spacing with optical delay line (RBW : 1kHz).

IV. 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 40 GHz (bandwidth of the electrical spectrum analyser, ESA), the composite noise was measured directly using a UTC photodiode and a Rhode and Schwarz FSQ spectrum analyser, while 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. Hence, the overall composite noise of the system can be calculated from,

$$CN = 10 * log(10^{\frac{[S1+20\log(N)]}{10}} + 10^{\frac{y}{10}} + 10^{\frac{[S2+20\log(12)]}{10}} + 10^{\frac{F}{10}}) \quad dBc/Hz \qquad (1)$$

where the contributions of the scaled phase noise from the reference synthesizer ([S_1 + 20log(N)] dBc/Hz), composite noise from the OFCG (y dBc/Hz), scaled phase noise from the local oscillator, [S2 + 20log(12)] dBc/Hz and the phase noise from the ESA (F dBc/Hz) have been combined. Fig. 5 shows the composite noise for N=1, compared to the phase noise of the reference synthesizer and the ESA, and it is less than -90 dBc/Hz at an offset frequency of 10 kHz. This is higher than the phase noise of the reference synthesizer due to the noise contribution from the OFCG itself. There is also a noise penalty for offset frequencies <10 kHz, which may be due to imperfect stabilization of the loop length. The measured composite noise beyond 1 MHz offset frequency was limited by the measurement noise floor. The noise floor was calculated as -104 dBc/Hz, from the difference between the internal noise power of the ESA (-144 dBc/Hz) and the signal power (-40 dBm).

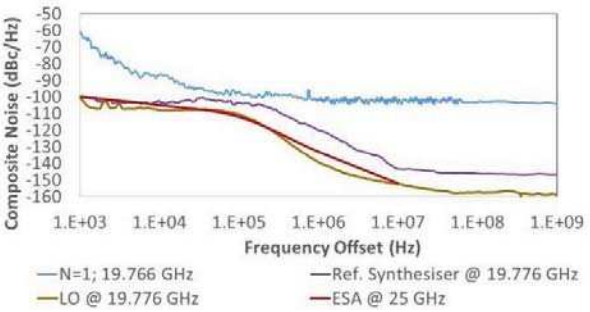

Fig. 5. Composite noise of the heterodyne signal between two adjacent comb lines compared to the phase noise of the reference, LO and the ESA.

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 synthesizer, [S_1 + 20log(N)] dBc/Hz (Fig. 6). It is evident that the noise converges with the scaled phase noise of the reference synthesizer at higher multiplication factors, however at lower frequencies (N ≤3), the contribution from the OFCG, y dBc/Hz is dominant. Hence, for signal generation at higher frequencies such as at 2 THz, it is essential to have a low noise microwave reference synthesizer.

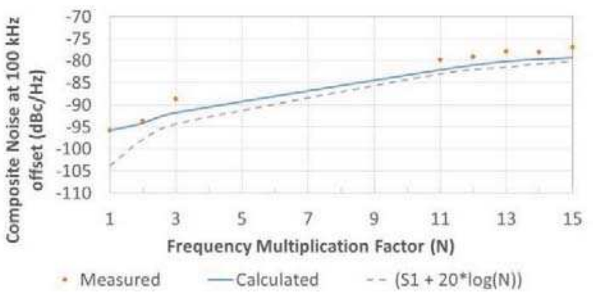

Fig. 6. Measured and calculated noise at 100 kHz offset frequency compared to the scaled phase noise of the synthesizer.

V. INJECTION LOCKING OF 2THZ QCL TO THE IR-OFCG

High spectral purity sources such as frequency multipliers, photoconductors and 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 sources for frequencies 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.

In the past, phase locking of QCLs to gas lines, frequency multipliers, femtosecond lasers and frequency combs have been demonstrated using a negative feedback loop. Here, a simpler approach of direct injection locking of the 2 THz QCL to the above IR-OFCG is demonstrated (Fig. 7) [9], design of which can be translated to a photonic integration platform that could lead to a compact system suitable for many applications.

The QCL used in this experiment was mounted on a cold finger in a liquid helium cryostat, and its temperature was maintained at 14 K. It was of a bound-to-continuum design with a single plasmon waveguide, and had an output power of ~2 mW, at an operating frequency of 1.997 THz with a drive current and tuning efficiency of 775 mA and 6.5 MHz/mA respectively. The amplified pair of comb lines, whose heterodyne frequency (f_{REF}) was close to the QCL frequency (f_{QCL}) 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 THz reference signal. The power of the generated signal by the transmitter at f_{REF} (~2 THz) was ~80 nW and was coupled into the QCL to injection lock as shown in Fig. 7.

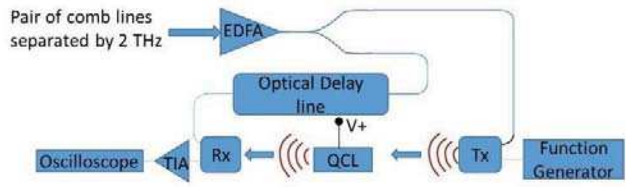

Fig. 7. Experimental arrangement of the injection locking of THz QCL (EDFA : erbium-doped fibre amplifier; Tx : THz transmitter; QCL : quantum cascade laser; Rx : THz receiver; TIA : transimpedence amplifier).

An optical delay line was introduced in the receiver path to control the relative phase of 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 acquired by a 36 GHz Lecroy Real-time 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. The homodyne locking of the QCL is shown in Fig. 8, where the drive current to the QCL was changed such that f_{QCL} was tuned into and away from the f_{REF}. When the QCL was unlocked, the SNR was ~20 dB, and the measurement noise floor was -70 dBm. However, to aid clarity, the beat signal spectrum for each of the drive current is offset vertically in the plot. When the heterodyne frequency ($|f_{REF} - f_{QCL}|$) was between 4 MHz and 10 MHz, the QCL frequency was pulled towards the THz reference by as much as 1 MHz, and when the heterodyne frequency was <4 MHz, the QCL acquired lock and the beat signal becomes no longer visible (Fig. 8). The narrower locking range of ±4 MHz compared to the estimated locking range of ±14 MHz from the simplified Adler's expression at this injection level may be due to non-optimised coupling of the THz signal into the QCL cavity. The -3-dB linewidth of the un-locked beat signal was measured to be 1 MHz. Nonetheless, 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.

The amplitude and phase of the locked QCL signal was measured using a lock-in amplifier (Fig. 9), by varying the relative phase between the signal from the QCL and the THz reference signal. When the QCL was well locked, the amplitude increased when the QCL frequency approached the edge of the locking range and remained the same within the locking range, while phase of the signal changed from –π/2 to +π/2 as expected [10].

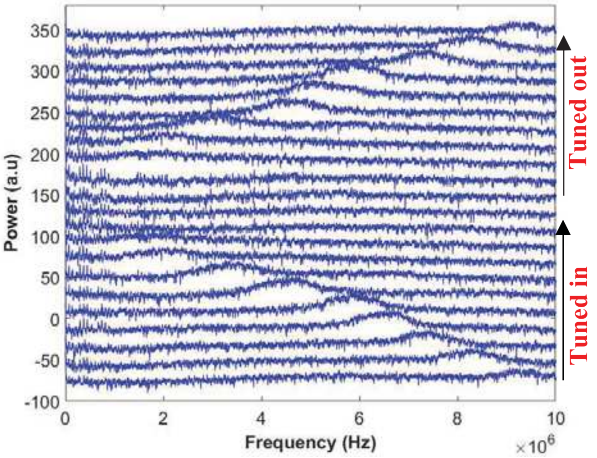

Fig. 8. The beat signal between the reference signal derived from the comb source and the QCL when the QCL drive current was adjusted to tune the QCL frequency towards and away from the reference frequency. To aid clarity, the beat signal spectrum for each of the QCL drive current is offset vertically in the plot.

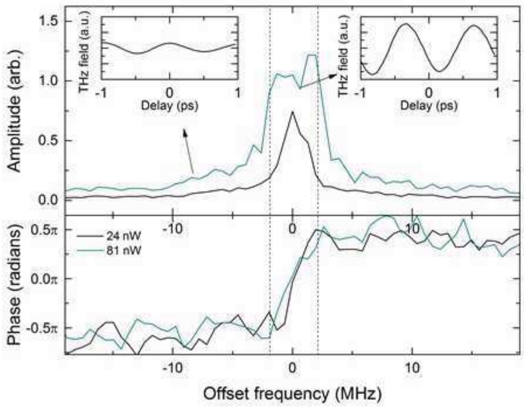

Fig. 9. The amplitude and phase of the locked signal measured using a lock-in amplifier when the QCL drive current was varied. [Green : QCL well-locked; Black : QCL partially locked; Inset : Sinusoidal waveform from the receiver].

Fig. 10 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.

VI. Conclusion

The results of measurements on an absolute frequency referenced continuously tuneable THz signal synthesizer based on a wide bandwidth OFCG have been presented. The frequency was continuously tuneable from 122.5 GHz to > 2.7 THz, with a spectral resolution of < 100 Hz at 2 THz. The composite noise was measured to be less than -75 dBc/Hz at 10 kHz offset at 300 GHz, and was shown to be limited by the scaled phase noise of the reference synthesizer. Laser locking techniques enabled the OSNR to be improved to greater than 50 dB with an increase in optical power by > 30 dB, while preserving the noise characteristics of the OFCG itself. However, due to the lower conversion efficiency of the available opto-electronic converters at high frequencies, only 80 nW of power was generated by the Toptica transmitter at 2 THz. Nonetheless, by direct injection locking a high power QCL to this 80 nW high resolution signal, has enabled the realisation of an absolute frequency referenced, high spectral purity 2 THz source with an output power of ~2 mW, with phase/frequency noise characteristics directly referenced to the microwave synthesizer, making it suitable for many high-resolution applications. This system has a great potential for photonic integration leading to compact and portable systems.

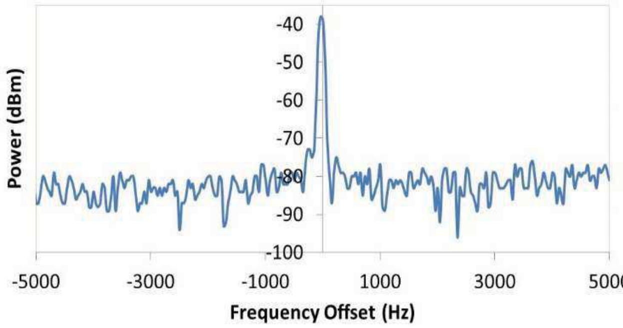

Fig. 10. Electrical spectrum of the heterodyne signal between the locked QCL and the THz reference signal at the modulation frequency of the transmitter (RBW : 50 Hz).

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