Optical comb for generation of continuously tunable coherent THz signal from 122.5 GHz to >2.7 THz

LALITHA PONNAMPALAM*, MARTYN FICE, HAYMEN SHAMS, CYRIL RENAUD, ALWYN SEEDS

Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom
**Corresponding author: l.ponnampalam@ucl.ac.uk*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We present a continuously tunable optical frequency comb generator (OFCG), with comb lines spanning over 3.8 THz, the widest span yet reported for a single phase modulator OFCG system. The line spacing, exactly determined by a microwave reference, can be continuously tuned, and by heterodyning two lines enables the generation of a continuously tunable electrical signal from 122.5 GHz to >2.7 THz. The composite noise of the heterodyne between two lines has been measured up to a record frequency of 300 GHz, and is -75 dBc/Hz at 10 kHz offset at 300 GHz, limited by the multiplied phase noise of the reference synthesizer.

OCIS codes: *(040.2840) Heterodyne; (300.6495) Spectroscopy, terahertz; (110.6795) Terahertz imaging.*

http://dx.doi.org/10.1364/OL.99.099999

Ultra high resolution terahertz spectroscopy is a fundamental technique used in many applications such as security checking, biomedical diagnosis and in the pharmaceutical industry where molecular structures are identified to ultra-high precision through spectral finger printing. As many molecular rotational and vibrational transitions are in the THz domain, it becomes essential to develop continuously tunable high spectral purity terahertz (THz) sources with exactly defined frequency, to be able to identify the closely spaced absorption lines. Photonics technology based high spectral purity tunable THz sources are promising in terms of compactness, bandwidth, power consumption and cost, and these are based on components such as waveguide uni-travelling carrier photodiodes (UTC-PD) [1, 2] and quantum cascade lasers [3]. In order to generate a high spectral purity THz signal, two suitably spaced comb lines from an optical frequency comb generator (OFCG) are selected using optical filters and the filtered signal is applied to a high bandwidth photodetector, such as an UTC photodiode (UTC-PD) [2]. The highly coherent THz signal generated by the UTC-PD can also be used to phase lock a quantum cascade laser [3]. For the generation of a continuously tunable THz signal with exactly defined frequency, it is essential to have an OFCG with a continuously tunable but exactly referenced line spacing.

Several semiconductor and fibre based OFCGs have been developed. The FM laser [4], the hybrid mode-locked laser [5] and the monolithically integrated passively mode-locked ring laser [6, 7], are examples of monolithic semiconductor based OFCGs with fixed comb line spacing, whose compactness can lead to thermally stable operation. Among the fibre-based systems, a single-mode laser modulated by a cascade of phase and intensity modulators driven by tailored RF waveforms has been shown to generate a very uniform optical comb [8] over a span of 380 GHz. In addition, successive phase modulation of the reference laser within an amplified recirculating fibre loop has been demonstrated with a span of <2 THz [9, 10]. In [10], fast step tuning of the comb line spacing with a resolution of 12.5 MHz has been demonstrated by varying the reference frequency to match the FSR of the loop. The phase noise of the heterodyne between two comb lines has also been measured up to 90 GHz, and is -80 dBc/Hz at an offset frequency of 10 kHz. An extension in the comb span to 2.8 THz has been achieved by the use of two cascaded phase modulators in a single recirculating loop OFCG [11] and, by injection seeding two recirculating loops, comb lines have been generated over a span of 4.56 THz, covering the C band [12]. However, the systems described in [11-12] have a fixed comb line spacing, and the spectral purity of the heterodyne between the comb lines was not reported. Further, to achieve phase coherence over the entire span in [11-12], the RF electronics driving each of the phase modulators has to be carefully phase matched, making the drive circuits and operation complex. Much broader span (10's THz) combs have been realized through the four wave mixing process in highly nonlinear fibres [13-14], however, these generally require high optical input powers in the 400 mW to 1500 mW [14] range, and the spectral purity of the heterodyne between the comb lines has not been reported.

In this paper, we present a fibre re-circulating loop OFCG based on a single phase modulator within an amplified loop incorporating a variable optical delay line, allowing the spacing between the comb lines to be continuously tuned. This enables the generation of a continuously tunable high spectral purity heterodyne signal from 122.5 GHz to >2.7 THz subject to the availability of suitable heterodyne photodetectors. In previous work, heterodyne signal generation up to > 2 THz using an UTC-PD [15], and up to >6 THz using a photoconductive switch [16] has been demonstrated. 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. We also report detailed composite (amplitude and phase) noise measurements for the heterodyne signal between the comb lines up to a record frequency of 300 GHz. This single phase modulator system is substantially simpler than the dual phase modulator systems described in [11, 12]. We also show that the optical signal to noise ratio (OSNR) of the selected comb lines can be improved to 50 dB using optical injection locked filters, should this be required for particular applications.

The OFCG is shown in Fig. 1 and is based on the approach described in [9, 10]. It consists of a $LiNbO_3$ phase modulator with a 3dB bandwidth of 22 GHz, a 5 m long type M12 MetroGain Erbium doped fibre from Fibrecore, UK, and a 980 nm pump laser. This carefully selected length of highly doped fibre gives a relatively flat gain spectrum over the entire C-band [17], eliminating the need for an optical band pass filter to exclude the typical Erbium doped fibre amplifier (EDFA) gain peak at 1530 nm, which limited the comb span in [10]. Here, the total fibre loop length is approximately 20 m, giving an FSR of ~9.3 MHz.

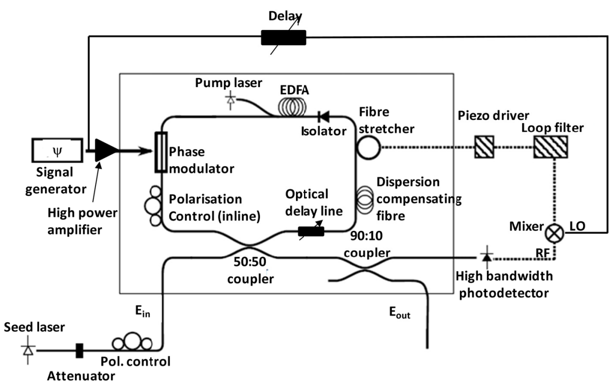

Fig. 1. Schematic of the fibre re-circulating loop OFCG.

For optimum operation, the frequency of the microwave reference must be a harmonic of the cavity mode spacing, and the operating frequency of the seed laser must be resonant with one of the cavity modes. The second condition can be relaxed by employing a broader linewidth seed laser, where a few cavity modes will be excited, generating groups of comb lines separated by the reference frequency [9]. However, for the generation of an heterodyne THz signal with high spectral purity, a seed laser with a narrow linewidth compared to the cavity mode spacing must be used, exciting only a single mode per comb line. Therefore, the OFCG described in this work includes a RIO-Orion laser with an FWHM linewidth of 15 kHz. Implementation with such a laser requires a feedback loop [10] to control the length of the loop actively, so as to maintain the resonance condition. The feedback loop controlling the piezo fibre stretcher (PZT) needs to compensate for the frequency fluctuations of the seed laser, and any variation in the loop length caused by temperature fluctuations.

A 2 m long dispersion compensating fibre (DCF) with a dispersion coefficient of -120 ps/(nm.km) has been included within the loop to maximise the comb span. Fig. 2 shows the optical spectrum of the OFCG, with comb lines over a span of 3.8 THz, with a -6 dB bandwidth of 2.7 THz. The isolator within the loop enforces propagation in one direction only, while also preventing the 980nm pump signal from circulating in the loop.

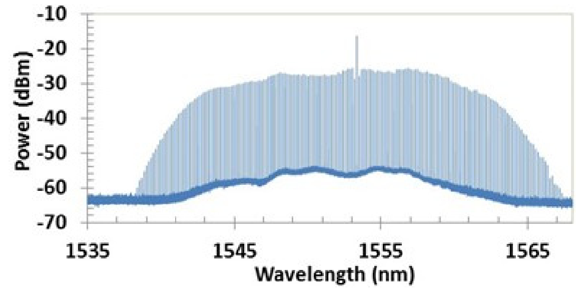

Fig. 2. Optical spectrum of the OFCG (optical resolution : 0.04 pm).

The linewidth of each of the comb lines is of the order of 10s of kHz, similar to that of the seed laser, and the heterodyne phase between the comb lines over the entire spectrum is correlated to the reference synthesizer. Fig. 3 shows the electrical spectrum of the heterodyne signal between two adjacent comb lines with a measured FWHM linewidth of < 10 Hz (electrical spectrum analyser (ESA) resolution bandwidth limited). More generally, the linewidth of the heterodyne between two selected lines will be N times the linewidth of the reference RF synthesizer, where N is the number of line spacings between the selected lines.

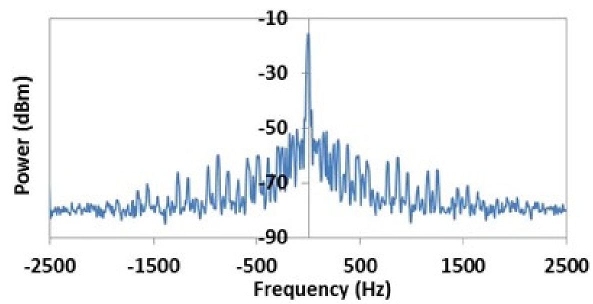

Fig. 3. Electrical spectrum of the heterodyne signal between two adjacent comb lines separated by 19.776 GHz. (RBW 10 Hz).

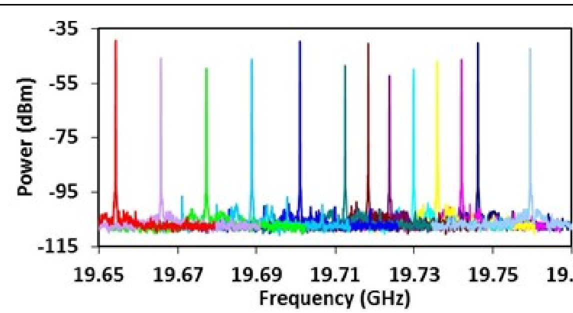

Fig. 4. Tuning of comb line spacing with optical delay line (RBW 1 kHz).

A 600 ps variable optical delay line is included within the loop to enable continuous tuning of the frequency spacing of the comb lines, eliminating the restriction of frequency step size to the loop FSR in previous work [10, 11]. Continuous tuning of the comb line spacing of 105 MHz was achieved when the OFCG was operating on a particular cavity mode (Fig. 4). However, to generate a continuously tunable heterodyne signal it is only necessary to adjust the delay over the FSR of 9.3 MHz, at which point the OFCG can be operated on the adjacent mode. This requires a change in loop length of only ~15 mm, in a 20 m loop (Fig. 5). The spacing between adjacent comb lines is exactly equal to the RF reference frequency and is tunable from 17.5 GHz-20 GHz, limited by the loop electronics. Heterodyne generation over the full comb span is achieved by selecting two suitably spaced lines using optical filters and applying the filtered signal to a high bandwidth photodetector, such as an UTC photodiode [2]. The electronic bandwidth limited tuning range of 2.5 GHz (17.5 GHz – 20 GHz) will give a heterodyne frequency continuous tuning range of 2.5*N GHz when two lines separated by N comb line spacing are selected. However, to obtain continuous frequency coverage, the minimum heterodyne frequency should correspond to a continuous tuning range equal to or greater than the comb spacing, requiring N ≥ 7 for 17.5 GHz comb line spacing. This gives a continuous frequency coverage range from 122.5 GHz to > 2.7THz, with additional gapped bands down to 17.5 GHz.

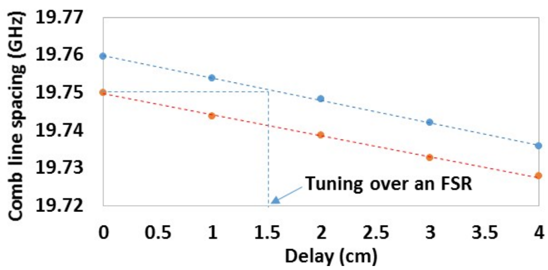

Fig. 5. Measurement of continuous tuning of two adjacent cavity modes.

In this work, the two comb lines spaced at the required frequency are selected either by a Finisar 4000S WaveShaper or by using two injection locked high power tunable digital supermode distributed Bragg reflector (DSDBR) lasers from Oclaro Technology, UK [18]. To minimise instability of the DBR laser, an optical filter was used to limit the number of comb lines injected into the DBR laser. Fig. 6 shows the spectrum of the selected lines separated by 2 THz using the injection locked DSDBR lasers filters. An improvement in the OSNR to greater than 50dB in 0.1 nm bandwidth is seen compared to about 25 dB when a line was selected using the wave shaper (inset), while the optical power of the selected comb line is amplified by >40 dB.

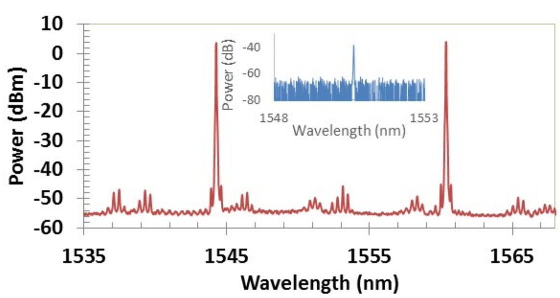

Fig. 6. Optical spectrum of the comb lines selected by injection locked DSDBR lasers compared to the line selected by the waveshaper (inset).

Fig. 7 shows the schematic of the noise measurement system, where the output of the OFCG was amplified, and the pairs of comb lines were selected using a WaveShaper (WS). The composite noise of the heterodyne signal between the two adjacent comb lines is shown in Fig. 8, and is less than -90dBc/Hz at an offset frequency of 10 kHz, but is higher than that of the reference synthesizer (REF). As will be explained later, this is due to the combined noise contribution from the OFCG, EDFA and the UTC-PD, which is dominant for heterodyne signals at lower frequencies. The performance characteristics of the UTC-PD utilized in this experiment are described in detail in [2]. There is also a noise penalty for offset frequencies <10 kHz, and similar noise penalty is seen in [10]; this may be due to imperfect stabilization of the loop length. Fig. 8 also shows the composite noise of the heterodyne signal between two adjacent lines when selected by the injection locked laser filters. This shows that the injection locked two high power laser filters improved the OSNR by amplifying the signal while preserving the phase coherence, without the need for an EDFA.

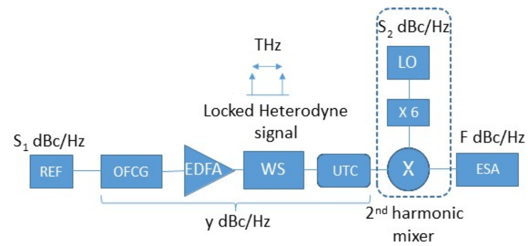

Fig. 7. Schematic of the phase noise measurement arrangement.

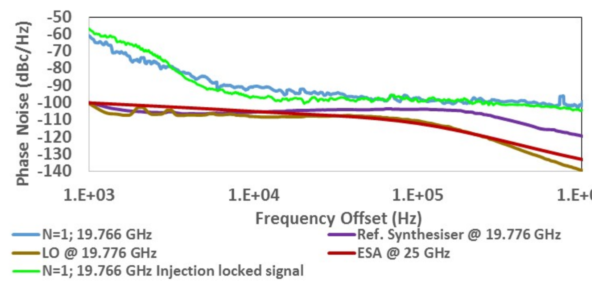

Fig. 8. Composite noise of the beat signal between two adjacent comb lines compared to the phase noise of the reference, LO and the ESA.

The composite noise of the heterodyne signal between pairs of comb lines separated by multiples of the reference signal frequency has also been studied. Fig. 9 shows the measured phase noise spectral densities of heterodyned signals between selected comb lines separated by up to 296.5 GHz (N = 15).

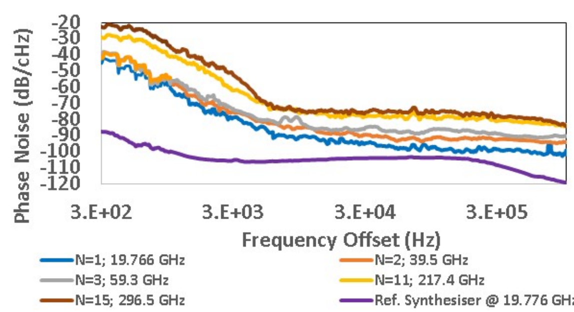

Fig. 9. Composite noise of the beat signal between pairs of comb lines separated by multiples of the comb line spacing.

The noise floor for the measurements, N=1 and N=2 in Fig. 8 and Fig. 9 are calculated as -107 dBc/Hz, from the difference between the internal noise power of the ESA, specified as -147 dBm/Hz for this frequency band and the carrier power, $P_{carrier}$ of -40 dBm. For the measurements with the external mixer (N ≥ 3),

$$Noise\ Floor = -174 + NF_{RX} - P_{Carrier} \quad \frac{dBc}{Hz} \qquad (1)$$

where NF_{RX} (dB) is the combined noise figure of the mixer and the ESA, calculated using Friis' formula for noise. From Eq. (1), the calculated noise floors for N = 3 and N = 11 to 15 were -108 dBc/Hz and -99 dBc/Hz respectively. There was a good agreement between the calculated and the measured noise, and the measurements in Fig. 8 and Fig. 9 were not limited by the measurement system.

The composite noise measurements in Fig. 9 have been verified by calculating the overall system noise (CN). For frequencies < 40 GHz, phase noise from the reference synthesizer (S_1 dBc/Hz), contributions from OFCG , EDFA and the UTC photo detector (y dBc/Hz) and the ESA (F dBc/Hz) have been combined as shown in Eq.(2).

$$CN = 10 * \log(10^{\frac{[S1+20\log(N)]}{10}} + 10^{\frac{[y]}{10}} + 10^{\frac{[F]}{10}}) \quad \frac{\text{dBc}}{\text{Hz}} \quad (2)$$

For measurement frequencies > 40 GHz, where down-conversion is required in the measurement system, scaled phase noise of the local oscillator (LO), [S2 + 20log(12)] dBc/Hz has been included for the second harmonic mixer with a X6 frequency multiplier (Virginia Diodes WR3.4MixAMC) (Fig. 7).

The phase noise of the reference synthesizer (S_1) was measured to be -104 dBc/Hz at 100 kHz offset while the phase noise of the spectrum analyser (F) varied from -124 dBc/Hz to -105 dBc/Hz, depending on the frequency band. As the measured composite noise at the fundamental frequency is -96 dBc/Hz at an offset frequency of 100 kHz (Fig. 8), the combined noise contribution, y dBc/Hz is derived from Eq. (2) as -97 dBc/Hz.

The estimated and the measured composite noise of the heterodyne signals at N times the reference frequency at 100 kHz offset are shown in Fig. 10 with the scaled phase noise of the reference synthesizer, [S1 + 20log(N)] dBc/Hz. As expected, the composite noise converges with the scaled phase noise of the reference synthesizer at higher multiplication factors, while at lower frequencies (N≤3), the combined contribution, y dBc/Hz is dominant. To achieve a noise level less than -90 dBc/Hz at 10 kHz offset at 2 THz, it is important to have an ultra-low noise reference synthesizer, with a phase noise less than -130 dBc/Hz at 10 kHz offset frequency [19].

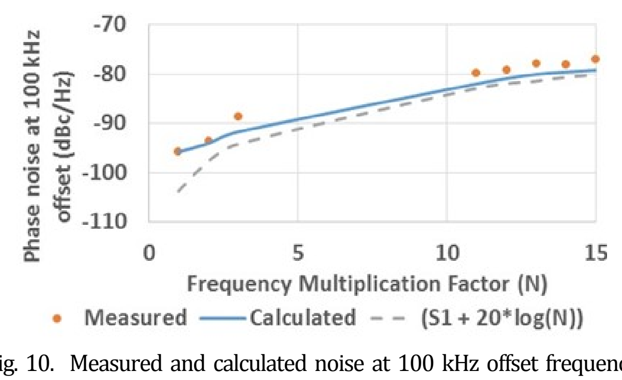

Fig. 10. Measured and calculated noise at 100 kHz offset frequency with the scaled phase noise of the reference synthesizer.

In conclusion, stable phase coherent optical comb lines over a record span of 3.8 THz have been demonstrated in a single phase modulator OFCG system. The comb line spacing was continuously tunable from 17.5 GHz to 20 GHz, limited by the loop electronics, and enables the generation of a continuously tunable heterodyne signal from 122.5 GHz to >2.7 THz for the first time in such a system. The linewidth of the heterodyne signal between two adjacent comb lines was < 10Hz (ESA limited), and the composite noise was less than -90 dBc/Hz at an offset frequency of 10 kHz. The composite noise was also measured for heterodyne frequencies up to 300 GHz and shown to be limited by multiplied phase noise of the reference source, emphasing the need for an ultra-low noise reference synthesizer for THz signal synthesis. Results of a tunable THz signal synthesizer with OSNR greater than 50 dB have also been presented where two high power widely tunable DSDBR lasers have been injection locked to two of the comb lines separated by the required frequency, while preserving the composite noise characteristics of the OFCG itself. The design described here could be translated to a monolithic integration platform by replacing the EDFA, fibre stretcher and DCF by semiconductor optical amplifier (SOA), passive phase sections [7] and chirped gratings respectively. This could lead to compact and portable systems, attractive for many applications that require highly coherent sources in the < 3 THz region.

Funding. Engineering and Physical Sciences Research Council [EP/J017671/1:COTS project, EP/P021859/1: HyperTHz project].

References

1. C. C. Renaud, M. Robertson, D. Rogers, R. Firth, P. J.Cannard, R. Moore,and A. J. Seeds, Proc. SPIE, 61940, 61940C (2006).
2. E. Rouvalis, M. Chtioui, F. van Dijk, F. Lelarge, M. J. Fice, C. C. Renaud, G. Carpintero, and A. J. Seeds, Opt. Express, 20, 20090 (2012).
3. J R Freeman, L Ponnampalam, H Shams, R A Mohandas, C C Renaud, P Dean, L Li, A G Davies, A J Seeds, E H Linfield, Optica, **4,** 1059 (2017).
4. C. C. Renaud, M. Pantouvaki, S. Grégoire, I. Lealman, P. Cannard, S. Cole, R. Moore, R. Gwilliam, and A. J. Seeds, J. Quantum Electron. **43,** 998 (2007).
5. J. S. Parker, A. Sivananthan, M. Lu, L. Johansson, and L. A. Coldren, *in Optical Fiber Communication and the National Fiber Optic Engineers Conference (OFC/NFOEC* 2012), p. 1.
6. V. Moskalenko, S. Latkowski, T. De Vries, L. M. Augustin, X. J. M. Leijtens, M. K. Smit, and E. a J. M. Bente, *in Optical Fiber Communication Conference* (2014), p. Tu2H3.
7. V. Corral, R. Guzman, C. Gordon, X. J. M. Leijtens and G. Carpintero, Opt. Lett. **41,** 1937 (2016).
8. R. Wu, V. R. Supradeepa, C. M. Long, D. E. Leaird, and A. M. Weiner, Opt. Lett., **35,** 3234 (2010).
9. S. Bennett, B. Cai, E. Burr, O. Gough, and A. J. Seeds, Photon. Technol. Lett., **11,** 551 (1999).
10. P. Shen, N. J. Gomes, P. A. Davies, P. G. Huggard and B. N. Ellison, J. Lightw. Techn., **25,** 3257 (2007).
11. J. Zhang, N. Chi, J. Yu, Y. Shao, J. Zhu, B. Huang, and L. Tao, Opt. Express **19,** 12891 (2011).
12. Junwen Zhang, Jianjun Yu, Ze Dong, Yufeng Shao, and Nan Chi, Opt. Express **19,** 26370 (2011).
13. M. Zajnulina, J. M. Chavez Boggio, M. Bohm, A. A. Rieznik, T. Fremberg, R. Haynes and M.M. Roth, Appl. Phys. B, **120,** 171 (2015).
14. T Yang, J Dong, S Liao, D Huang, and X Zhang, Opt. Express, **21,** 8508 (2013).
15. C.C Renaud, M. Natrella, C. Graham, J. Seddon, F. van Dijk and A. J. Seeds, IEEE J. of Sel. Topics in Quantum Electron., **24** (2018).
16. R. J. B. Dietz, B Globisch, H Roehle, D Stanze, T Göbel, and M Schell, Opt. Lett., **22,** 615 (2014)
17. S. Bhadra and A. Ghatak, CRC press, 145 (2013).
18. 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, M J Wale, IEEE J. of sel. topics in quantum electronics, **11,** 149 (2005).
19. T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C.W. Oates and S. A. Diddams, Nature Photonics, **5,** 425 (2011