Wavelength conversion technique for optical frequency dissemination applications

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We demonstrate coherent wavelength conversion capable to cover the entire C-band by modulating the incoming optical carrier with a compact Fabry-Perot cavity embedded phase modulator and by optical injection locking (OIL) a semiconductor laser to a tone of the generated optical frequency comb. The phase noise of the converted optical carrier over 1 THz frequency interval is measured to be -40 dBc/Hz at 10 Hz offset and the frequency stability is better than 2 × 10-17 level for averaging times >1000 s, making this technique a promising solution for comparisons of state-of-the-art optical clocks over complex fiber networks. © 2016 Optical Society of America

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Over the last few decades, the frequency stability and accuracy of optical atomic clocks has been steadily improved, with levels reaching a few parts in 1018 in less than <104 seconds. [1-3]. The comparison of these state-of-the-art optical clocks between distantly located national laboratories requires a frequency transfer technique capable of preserving such levels of stability and accuracy [4]. Traditionally, this has been achieved via geostationary satellite-based links [5]. However, the stability of these microwave-based systems, which operate at the low 10-15 level, is no longer sufficient to support the comparison of modern optical clocks. Performance improvement by several orders of magnitude can be achieved by using optical fiber-based, rather than satellite-based, links [6-11]. Several previous frequency transfer experiments have been reported, mostly using a dark fiber (i.e. not carrying any other optical signals apart from that used for transferring the optical frequency). This might not be the case for a widespread frequency dissemination scenario because of the high rental costs of dedicated fibers. A more likely viable solution is to use a single DWDM (dense wavelength division multiplexing) channel. In this arrangement the other available telecommunication channels are used for normal Internet data traffic. However, different branches of a frequency dissemination network could have different available channels, requiring the coherent wavelength conversion of the optical carrier across multiple channels, from a minimum of 50 – 100 GHz to several nm.

Several wavelength conversion scenarios have been previously studied in fiber optic communications, e.g. by using nonlinear phenomena such as cross-gain modulation (XGM) and four-wave mixing (FWM) in nonlinear media like semiconductor optical amplifiers (SOAs), highly nonlinear fibers (HNLFs), photonic crystals, and silicon waveguides [12,13]. However, in these methods, the phase coherence between the data-carrying optical carriers is not preserved, making all of these techniques unsuitable for frequency transfer applications. Recently, ultra-high stability phase locking of two optical carriers at different wavelengths was reported using a carrier envelope offset (CEO) stabilized optical frequency comb (OFC) [14-16]. However, CEO stabilized frequency combs are unlikely to be suitable for field implementation, where wavelength conversion might be required in several locations, because of their complexity, size and cost. Here we show that a very compact, low-cost resonant modulator can be used instead.

The proposed scheme is based on two key components: an electro-optic modulator with metallic mirrors (forming a Fabry-Perot cavity) (OptoComb from Optocomb Inc.) that generates a large number of coherent sidebands spaced by 25-GHz over the entire telecom C-band (1530 – 1565 nm) and an optical injection locking phase locked loop (OIPLL), employing a low cost semiconductor laser, for the extraction and amplification of the optical tone of interest [17].

The suitability of OIPLL for state-of-the-art frequency metrology was already characterized in our previous work [18]. Whilst the noise properties of the OptoComb have been the topic of several studies by other groups [19-22], these studies concentrated mainly on the temporal domain (i.e. jitter) in which all comb tones contribute to the performance. Here, we study the performance in the frequency domain, in which we characterize individual comb tones. This is necessary for full evaluation of our wavelength conversion system for frequency metrology applications that we carry out by analyzing noise sources in the frequency domain, enabling us to demonstrate suitability of this technique for the dissemination of ultra-stable optical carriers.

Fig. 1 shows the conceptual setup of the wavelength converter as it would be implemented in a real field application. We will assume that the wavelength conversion happens at some point along a fiber link between a transmitter and the user’s receiver. At the transmitter end of the link, the metrological optical carrier is modulated with a 25 GHz microwave frequency using a fast intensity modulator. The microwave signal for driving the OptoComb is extracted by means of a fast photodetector (PD) and then band-pass filtered and amplified. The optical carrier is then pre-amplified to be fed to the OptoComb modulator while the optical sidebands are suppressed by means of an OIPLL. In this case, since the OIPLL is sensitive to polarization, the injection light to the OIPLL would need to be automatically polarization-adjusted as in [9]. Then the OptoComb generates a large number of equally spaced (25 GHz) optical tones spanning more than 4 THz. For maximum efficiency of the modulation a polarization controller (PC-1) is used in front of the OptoComb. Also an optical isolator on each side of the OptoComb ensures the suppression of any unwanted reflections. The frequency comb generated by the OptoComb is directly fed to the OIPLL based wavelength selector without the use of any optical filters or additional optical amplifiers. The carrier frequency of the optically-injection-locked (OIL) laser is tuned (via control of its bias current and temperature) close to the chosen comb tone of the OptoComb output for wavelength conversion. Then, the OIL-process locks the carrier frequency of the OIL-laser, however, its phase can still drift () due to any drift in the temperature or current of the OIL-laser. In order to stabilize this phase difference a slow (<1 kHz) feedback loop is used as previously explained in [18]. The phase stabilization loop requires the injected light to be dithered at an RF frequency, which in our experiment was 1 GHz in order to be larger than the OIL-bandwidth, such that the dither tones are not affected by the OIL-process. In our previous work we have demonstrated that the frequency instability induced by the OIPLL was shown to be at the 10-16 level at 1 s averaging time and improving to less than 3×10-19 at 1000 s averaging time [18].

In the OptoComb, the noise of each generated comb tone is directly proportional to that of the microwave signal (25 GHz) used to drive the modulator. For a frequency separation by *N* tones the relative phase noise will be of that of the microwave signal [23]. The noise contribution from the OptoComb itself is extremely small (< 10 fs timing jitter) and thus can be neglected [22]. Although the OptoComb has a large insertion loss of 27 dB due to the fact that it is not operated at its maximum transmission in order to obtain a wide-enough spectrum [22] each optical tone still has a relatively high power (e.g. > -40 dBm in our experiment).



Fig. 1. Scenario of wavelength conversion based on the OptoComb and optical injection phase locked loop (OIPLL) for optical frequency dissemination applications (PC: Polarization Controller, BPF: Band-pass Filter, PD: Photodetector).

We characterized the OptoComb and the entire wavelength converter by comparing it to a CEO stabilized OFC from Menlo Systems (FC1500, 250 MHz repetition rate) as shown in Fig. 2. In this experiment only a very short (a few meters) link is employed in order to concentrate on evaluating the performance of the wavelength converter. The output of a 1557.3 nm laser (Orbits Lightwave) with a linewidth less than 1 kHz, was split into two paths. One of them was used for locking the Orbits laser to the Menlo OFC at 30 MHz offset frequency using a 5-kHz bandwidth PLL. The other was injected into the OptoComb at an input power of 13 dBm. The OptoComb modulation signal was obtained from an RF synthesizer (HP83712). A total optical power of -13.5 dBm was obtained at the OptoComb output. A portion of the spectrum of the generated optical comb tones is shown in Fig. 3.

For the phase noise characterization of the individual comb tones of the OptoComb we used a tunable optical band-pass filter (BPF, bandwidth of 0.15 nm) and erbium-doped fiber amplifiers (EDFA) to isolate and amplify the desired optical comb tone before photo-detection, see Fig. 2. As the frequency spacing of the OptoComb is an integer multiple of the OFC repetition rate (i.e. 250 MHz), a beat frequency of 30 MHz is obtained from interference of the *N-th* optical tone of the OptoComb with the nearest optical mode of the OFC. This beat note is directly compared with the 30 MHz beat signal for offset-locking the 1557.3 nm laser by using either a phase detector or a two channel dead-time free frequency counter. With this arrangement, the noise of the OFC becomes common-mode and thus is rejected, leaving only the excess phase noise of the wavelength converter.

The results for a selection of optical comb tones (N=0,1, 10, and 40) are shown in Fig. 4 and follow the between N=10 and 40. For the N=0 and 1 the phase noise is dominated by the noise generated in the EDFAs following the tunable optical BPF. The red trace shows the residual phase noise of the OptoComb and EDFAs when there is no frequency conversion, i.e. the 1557.3 nm carrier is beat against the OFC before and after the OptoComb and EDFAs. The small bump at around 300-Hz is attributed to the EDFA. The grey dashed trace shows the measurement noise floor that is obtained by comparing the 30 MHz beat notes between the 1557.3 nm laser carrier and the nearest mode of the OFC when the OptoComb and EDFAs are bypassed using a fiber patch cord.

For the characterization of the phase noise of the entire wavelength converter including OIPLL we tuned the OIL-laser to 1549.3 nm, selecting the 40th tone to achieve the 1-THz wavelength conversion. The power of the 40th tone injected to OIL-laser was -38 dBm, and the output power of OIPLL was 0 dBm. This leads to a total insertion loss of the wavelength converter of 13 dB which could be further improved, e.g., by using an OIL-laser with a higher output power. The output optical spectrum is shown in Fig. 3. An optical signal-to-noise ratio (OSNR) is improved by 15 dB when using OIPLL instead of EDFAs and an optical BPF. This is because EDFAs exhibit non-negligible amplified stimulated emission (ASE) light when the injected optical power is below -30 dBm, whilst this does not happen in the OIL process. The phase noise of the wavelength converted optical signal is shown in Fig. 4, the cyan solid line. The measured phase noise is substantially the same for both the EDFA (black dashed line) and OIPLL (cyan solid line) and it was -40, -57, and -110 dBc/Hz at 10, 100 and 1 MHz respectively. And the phase error variance, that is the integrated phase noise from 1 Hz to 1 MHz, was about 5.5×10-3 rad2. The same level of jitter is introduced by propagation through 11 km of a phase-stabilized fiber [6]. It is worth mentioning that this is a significantly better result than that reported previously in [23,24], where high-purity RF signals were synthetized using a similar scheme to ours (OIL to optical comb generated by an electro-optic modulator). We attribute this to a low excess phase noise (e.g. < -70 dBc/Hz at 10 Hz) achieved by our OIPLL [18] while only OIL was used in [23,24]. We do not observe any bump around 300-Hz offset when using the OIPLL as compared to using the EDFA, confirming that this is attributed to the EDFA.



Fig. 2. Schematic drawing of our experimental setup for characterization of the wavelength converter using a carrier envelope offset (CEO) stabilized OFC (EDFA: Erbium Doped Fiber Amplifier, BPF: Band-pass Filter, OIPLL: Optical Injection Phase Locked Loop, PD: Photodetector).



Fig. 3. Measured optical spectra of Orbits laser output, OptoComb output, and wavelength converted light when the OptoComb was driven with a 25 GHz signal generated by the RF synthesizer.

The phase noise of a stabilized 146-km long fiber link [18] is shown for comparison in Fig. 4. The noise of the wavelength converter is lower over the entire measurement range (from 1 Hz) by up to 30 dB, suggesting the wavelength converter would not degrade the performance of fiber optic frequency transfer.

Temperature-induced changes of the OptoComb cavity length cause a mismatch between the cavity free spectral range and the frequency of the microwave signal used to drive the OptoComb. This mismatch can result in variations of the individual comb tone output powers, changing thus the injection power to the OIL-laser. In order to measure the influence of the ambient temperature variations on the performance of the wavelength conversion, the temperature of the OptoComb was varied from 27.5 °C to 52.5 °C using a TEC attached to the modulator whilst measuring the phase noise of the 40th comb tone. The phase noise measured as a function of the TEC temperature is shown in Fig. 5. Over the 25 °C temperature change (change in the power of 40th tone by < 1 dB) no appreciable changes in the measured phase was detected. In a field implementation, even if the temperature variation is substantially different from that found in our laboratory () temperature stabilization could easily be implemented given that the OptoComb modulator has a small volume. This stabilization would also ensure stable long-term operation.



Fig. 4. Measured single sideband (SSB) phase noise for various comb tones of the OptoComb using Erbium doped fiber amplifiers (EDFAs) and SSB phase noise of the wavelength converter using optical injection phase locked loop (OIPLL) (The phase noise 146-km stabilized fiber link adopted from [18] is also presented for the comparison) (OBPF: Optical Band-pass Filter, PTB: Physikalisch-Technische Bundesanstalt, LUH: Leibniz Universität Hannover).

In order to evaluate the long-term stability of the wavelength converter with the OptoComb drive signal from the RF synthesizer, we measured the Allan deviation (ADEV) and modified Allan deviation (MDEV), with the experimental set-up in Fig. 2 using a frequency counter. The wavelength converter was running for more than 12 hours without losing the lock. The results are in Fig. 6, black squares. The ADEV averages as up to approximately 100 s and then reaches a plateau at for longer timescales. The MDEV averages as indicating that below 100 s the dominant noise process is white of phase from the 25-GHz RF synthesizer.

For comparison, and also for implementing the wavelength converter as it would operate in the field, we replaced the OptoComb RF drive signal with a 20 GHz signal that is generated by detecting the 40th harmonic of the OFC repetition rate (i.e. 250 MHz) and then doubling it with a passive non-linear frequency doubler. In this case, we selected the 50th tone of the OptoComb using the OIPLL, performing wavelength conversion by 1 THz identically to the previous experiment. The power of the 20 GHz RF signal delivered to the OptoComb was 20 dBm, which is 7 dB lower than the 25 GHz signal from the RF synthesizer, and could not be further increased because of the limited availability of high frequency amplifiers in our laboratory. This lower power converts to a lower optical power (by 12 dB) of the 50th comb tone injected into the OIL-laser. This made the experiment more sensitive to temperature-induced polarization changes in the injected optical signal to the OIL-laser which manifests itself as increased instability for time scales longer than 10 s (red circles in Fig. 6). Although the wavelength conversion system suffers from lower injection power to the OIL-laser, the result at short time scales improved by replacing the RF synthesizer with RF detection from the OFC thanks to the reduced phase noise of the microwave signal. For averaging time from 10 to 1000 s, better performance could be achieved by improving the thermal isolation of the wavelength converter and by using a higher injection power to the OIL-laser (i.e. higher RF power for driving the OptoComb). For longer averaging times >1000 s, however, we could achieve a frequency instability of <10-17 with the 20 GHz signal detected from the OFC. This is because, in the experimental-setup detecting the 20 GHz signal from the OFC, long period phase drift induced by fiber for OFC signal was compensated, making the wavelength converter the only source of fiber-induced noise.



Fig. 5. Measured single sideband (SSB) phase noise of 1-THz wavelength converted light using the OptoComb and optical injection phase locked loop (OIPLL) for various OptoComb temperatures.



Fig. 6 Measured frequency instability of the wavelength converter using the microwave signal of the RF synthesizer (black squares) and RF-signal detected from the carrier envelope offset (CEO) stabilized optical frequency comb (red circles) (ADEV: Allan Deviation, MDEV: Modified Allan Deviation)



Fig. 7. Bi-directional implementation of wavelength conversion for optical frequency dissemination applications.

In conclusion, we demonstrated a wavelength converter based on the optical injection phase locked loop (OIPLL) and an optical comb generated by a Fabry-Perot electro-optic modulator (OptoComb) with performance suitable for the transfer of ultra-stable frequencies. We show that the low phase noise performance of the wavelength converter (-40 dBc/Hz at 10 Hz) can be preserved over a large temperature range (25 degrees) making this technique suitable for in-field application where the temperature of the environment can be substantially worse than that of research laboratories. We have characterized the long term performance up to several thousand seconds demonstrating a fractional frequency stability for 1 THz converted light to better than 2 × 10-17. The technique can be extended to be used in a bidirectional way (Fig. 7), such as that needed for state-of-the-art optical carrier transfer experiments for optical clock comparisons that already operates bi-directionally over the same optical fiber. Please note that in this case a free running oscillator could be used as the driving signal for the OptoComb as its noise would be cancelled by the fiber phase noise cancellation feedback loop.

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REFERENCES

1. I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, Nat. Photonics **9**, 185 (2015).
2. B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, and J. Ye, Nature **506**, 71 (2014).
3. N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke, K. Beloy, M. Pizzocaro, C. W. Oates, and A. D. Ludlow, Science **341**, 1215 (2013).
4. H. Margolis, Contemp. Phys. **51**, 37 (2010).
5. H. Hachisu, M. Fujieda, S. Nagano, T. Gotoh, A. Nogami, T. Ido, St. Falke, N. Huntemann, C. Grebing, B. Lipphardt, Ch. Lisdat, and D. Piester, Opt. Lett. **39**, 4072 (2014).
6. P. A. Williams, W. C. Swann, and N. R. Newbury, J. Opt. Soc. Am. B **25**, 1284 (2008)..
7. O. Lopez, A. Haboucha, B. Chanteau, C. Chardonnet, A. Amy-Klein, and G. Santarelli, Opt. Express **20**, 23518 (2012).
8. S. Droste, F. Ozimek, Th. Udem, K. Predehl, T. W. Hänsch, H. Schnatz, G. Grosche, and R. Holzwarth, Phys. Rev. Lett. **111**, 110801 (2013).
9. S. M. F. Raupach, A. Koczwara, and G. Grosche, Opt. Express **22**, 26537 (2014).
10. O. Terra, G. Grosche, and H. Schnatz, Opt. Express **18**, 16102 (2010).
11. C. Clivati, G. Bolognini, D. Calonico, S. Faralli, A. Mura, and F. Levi, Opt. Express **23**, 10604 (2015).
12. Y. Liu, E. Tangdiongga, Z. Li, Shaoxian Zhang, Huug de Waardt, G. D. Khoe, and H. J. S. Dorren, J. Lightw. Technol. **24**, 230 (2006).
13. M. Matsuura, O. Raz, F. Gomez-Agis, N. Calabretta, and H. J. S. Dorren, Opt. Express **19**, B551 (2011).
14. J. Stenger, H. Schnatz, C. Tamm, and H. R. Telle, Phys. Rev. Lett. **88**, 073601 (2002).
15. D. Nicolodi, B. Argence, W. Zhang, R. L. Targat, G. Santarelli, and Y. L. Coq, Nat. Photonics **8**, 219 (2014).
16. N. Scharnhorst, J. B. Wübbena, S. Hannig, K. Jakobsen, J. Kramer, I. D. Leroux, and P. O. Schmidt, Opt. Express **23**, 19771 (2015).
17. J. Kim, D. S. Wu, G. Marra, D. J. Richardson, and R. Slavík, *in EPS-QEOD Europhoton Conference*, pp. ThB–T1–O–02 (2014).
18. J. Kim, H. Schnatz, D. S. Wu, G. Marra, D. J. Richardson, and R. Slavik, Opt. Lett. **40**, 4198 (2015).
19. T. Saitoh, S. Mattori, S. Kinugawa, K. Miyagi, A. Taniguchi, M. Kourogi, and M. Ohtsu, J. Lightw. Technol. **16**, 824 (1998).
20. R. P. Kovacich, U. Sterr, and H. R. Telle, Appl. Opt. **39**, 4372 (2000).
21. I.-L. Gheorma and R. M. Osgood, IEEE Photon. Technol. Lett. **14**, 795 (2002).
22. S. Xiao, L. Hollberg, N. R. Newbury and S. A. Diddams, Opt. Express **16**, 8498 (2008).
23. G. J. Schneider, J. A. Murakowski, C. A. Schuetz, S. Shi, and D. W. Prather, Nat. Photonics **7**, 118 (2013).
24. W. Chen, X. Qi, L. Yi, K. Dong, Z. Wang, J. Chen, and X. Chen, Opt. Lett. **33**, 357 (2008).

FULL REFERENCES

1. I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, “Cryogenic optical lattice clocks,” Nature Photonics **9**, 185–189 (2015).
2. B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, and J. Ye, “An optical lattice clock with accuracy and stability at the 10-18 level,” Nature **506**, 71–75 (2014).
3. N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke, K. Beloy, M. Pizzocaro, C. W. Oates, and A. D. Ludlow, “An Atomic Clock with 10-18 Instability,” Science **341**, 1215–1218 (2013).
4. H. Margolis, “Optical frequency standards and clocks,” Contemporary Physics **51**, 37-58 (2010).
5. H. Hachisu, M. Fujieda, S. Nagano, T. Gotoh, A. Nogami, T. Ido, St. Falke, N. Huntemann, C. Grebing, B. Lipphardt, Ch. Lisdat, and D. Piester, “Direct comparison of optical lattice clocks with an intercontinental baseline of 9000 km,” Optics Letters **39**, 4072–4075 (2014).
6. P. A. Williams, W. C. Swann, and N. R. Newbury, “High-stability transfer of an optical frequency over long fiber-optic links,” Journal of Optical Society of America B **25**, 1284 (2008).
7. O. Lopez, A.  Haboucha, B. Chanteau, C. Chardonnet, A. Amy-Klein, and G. Santarelli, “Ultra-stable long distance optical frequency distribution using the Internet fiber network,” Optics Express **20**, 23518–23526 (2012).
8. S. Droste, F. Ozimek, Th. Udem, K. Predehl, T. W. Hänsch, H. Schnatz, G. Grosche, and R. Holzwarth, “Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link,” Physics Review Letters **111**, 110801 (2013).
9. S. M. F. Raupach, A. Koczwara, and G. Grosche, “Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier,” Optics Express **22**, 26537–26547 (2014).
10. O. Terra, G. Grosche, and H. Schnatz, “Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber,” Optics Express **18**, 16102–16111 (2010).
11. C. Clivati, G. Bolognini, D. Calonico, S. Faralli, A. Mura, and F. Levi, “In-field Raman amplification on coherent optical fiber links for frequency metrology,” Optics Express **23**, 10604–10615 (2015).
12. Y. Liu, E. Tangdiongga, Z. Li, Shaoxian Zhang, Huug de Waardt, G. D. Khoe, and H. J. S. Dorren, “Error-Free All-Optical Wavelength Conversion at 160 Gb/s Using a Semiconductor Optical Amplifier and an Optical Bandpass Filter,” Journal of Lightwave Technology **24**, 230–236 (2006).
13. M. Matsuura, O. Raz, F. Gomez-Agis, N. Calabretta, and H. J. S. Dorren, “UItrahigh-speed and widely tunable wavelength conversion based on cross-gain modulation in a quantum-dot semiconductor optical amplifier,” Optics Express **19**, B551 – B559 (2011).
14. J. Stenger, H. Schnatz, C. Tamm, and H. R. Telle, “Ultraprecise Measurement of Optical Frequency Ratios,” Physical Review Letters **88**, 073601 (2002).
15. D. Nicolodi, B. Argence, W. Zhang, R. L. Targat, G. Santarelli, and Y. L. Coq, “Spectral purity transfer between optical wavelengths at the 10-18 level,” Nature Photonics **8**, 219–223 (2014).
16. N. Scharnhorst, J. B. Wübbena, S. Hannig, K. Jakobsen, J. Kramer, I. D. Leroux, and P. O. Schmidt, “High-bandwidth transfer of phase stability through a fiber frequency comb,” Optics Express **23**, 19771--19776 (2015).
17. J. Kim, D. S. Wu, G. Marra, D. J. Richardson, and R. Slavík, “Wavelength Conversion by Injection Locking to an Optical Comb for Optical Frequency Transfer Applications,” *in EPS-QEOD Europhoton Conference*, pp. ThB–T1–O–02 (2014).
18. J. Kim, H. Schnatz, D. S. Wu, G. Marra, D. J. Richardson, and R. Slavik, “Optical injection locking-based amplification in phase-coherent transfer of optical frequencies,” Optics Letters **40**, 4198–4201 (2015).
19. T. Saitoh, S. Mattori, S. Kinugawa, K. Miyagi, A. Taniguchi, M. Kourogi, and M. Ohtsu, “Modulation Characteristic of Waveguid-Type Optical Frequency Comb Generator,” Journal of Lightwave Technology **16**, 824–832 (1998).
20. R. P. Kovacich, U. Sterr, and H. R. Telle, “Short-pulse properties of optical frequency comb generators,” Applied Optics **39**, 4372–4376 (2000).
21. I.-L. Gheorma and R. M. Osgood, “Fundamental Limitations of Optical Resonator Based High-Speed EO Modulators,” IEEE Photonics Technology Letters **14**, 795 (2002).
22. S. Xiao, L. Hollberg, N. R. Newbury and S. A. Diddams, “Toward a low-jitter 10 GHz pulsed source with an optical frequency comb generator,” Optics Express **16**, 8498–8508 (2008).
23. G. J. Schneider, J. A. Murakowski, C. A. Schuetz, S. Shi, and D. W. Prather, “Radiofrequency signal-generation system with over seven octaves of continuous tuning,” Nature Photonics **7**, 118–122 (2013).
24. W. Chen, X. Qi, L. Yi, K. Dong, Z. Wang, J. Chen, and X. Chen, “Optical phase locking with a large and tunable frequency difference based on a vertical-cavity surface-emitting laser,” Optics Letters **33**, 357 (2008).