Optical Generation of Microwave Reference Frequencies

Lute Maleki and Andrey B. Matsko
OEwaves Inc., 2555 East Colorado Blvd., Pasadena, California 91107, USA; lute.maleki@oewaves.com

Abstract

Microwave photonics is promising for generation of spectrally pure high frequency RF signals. We review recent advances in photonic methods of generation of X-W band microwave references focusing on properties and capabilities of opto-electronic oscillators and optical frequency comb-based RF oscillators.

1 Introduction

Spectrally pure and stable microwave and mm-wave reference signals have widespread applications in diverse fields ranging from scientific investigations and metrology, to communications and radar. The need for high performance sources in this frequency range is growing at an increasing rate in response to advances in technology related to radio astronomy, mm-wave metrology, and high rate data transmission networks with associated wider bandwidth requirements. The traditional approach for generating spectrally pure signals rely on either multiplication of lower frequency signals generated with quartz or surface acoustic wave (SAW) oscillators, or direct generation using high quality factor (Q) microwave and mm-wave resonator oscillators. Both these approaches have limitations. In the case of multiplied signals, the multiplied noise of the high performance oscillator at 20log$N$, with N the multiplication factor, limits achievable performance; in the direct generation scheme, the high-Q cavity is bulky, highly sensitive to environmental perturbations, and requires cryogenic cooling for the highest performance, thus limiting applications where size, weight, and power are restricted. In this paper we argue that microwave photonics solves the mentioned above problems.

2 Opto-Electronic Oscillators

The most widespread approach of optical generation of microwave signals is based on the opto-electronic oscillator (OEO) where high-Q optical cavities replace high-Q microwave resonators [1]. The generic OEO consists of a laser, light modulator, optical cavity, and a photodiode, the output of which is fed back to the modulator to close the loop. This feedback loop oscillates if its overall gain is larger than the loss, and the waves circulating in it are added in phase. The former requirement can be met with insertion of proper gain in the loop, and the latter – by controlling the phase of the fed back microwave signal. Since waves circulating in the loop can add in phase, the oscillator is fundamentally multi-mode, with the mode spacing determined by the free spectral range of the cavity. The output of the oscillator can be obtained at desired frequency by adding a filter in the feedback loop. In this way, any frequency supported by the bandwidth of the components can be generated. The close-to-carrier noise of the OEO is determined by the Q of the optical cavity, and its white noise floor is determined by the shot noise of the optical power on the photodiode. Ultimately, the noise is limited by the $1/f$ noise of the amplifier and of the photodiode.

The OEO architecture and can be configured in a variety of ways with different optical and electrical components to optimize the performance. The gain, the filter, and the phase shifter can be placed either in the optical segment or the electrical segment of the loop. The laser can be of any suitable type, and modulation can be achieved directly with the current of the laser, or with an external modulator. The signal can be generated with phase, amplitude, or polarization modulation. The high-Q cavity can be a Fabry-Perot, whispering gallery mode (WGM) optical resonator, or a long fiber delay with an equivalent Q-factor. The operation frequency can be fixed by a fixed filter or tuned by changing the cavity's "optical length" by controlling dispersion, or the wavelength of the laser. Finally, even the light can be generated with a laser external to the loop, or in an optical loop with gain that can be coupled to the electrical loop through the

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

modulator shared by both loops. This latter configuration is known as the coupled opto-electronic oscillator or COEO [2].

The length of the fiber in the OEO loop L is related to the Leeson frequency of the oscillator as $f_L = c/(2\pi nL)$, where c is the speed of light in the vacuum, and n is the refractive index of the fiber material. A 16 km long fiber was used to obtain the highest achieved spectral purity of -163 dBc/Hz in a 10 GHz free-running oscillator, at 7 kHz from the carrier [3]. This performance was limited by the $1/f$ noise of the electronic amplifiers in the loop. OEO operation in Ka-band (39 GHz) [4] and U-band (50 GHz) [5] was also demonstrated. As the frequency of operation increases, the influence of laser noise and dispersion in the loop on the OEO phase noise must be taken into account [6].

One of the features of a fiber delay in the OEO is that oscillation at frequencies that are multiples of that associated with the length of fiber (the analog of longitudinal modes of a laser resonator) are also supported. This multi-mode oscillation, mentioned above, can be suppressed if the bandwidth of the RF filter in the loop is narrow enough so that a single mode of oscillation survives in the loop. This is not practical, especially when the length of the fiber is long. For example, for a 4 km length of fiber the frequency associated with these modes is about 90 kHz; an electronic filter with this bandwidth is hard to realize for microwave and mm-wave frequencies.

One approach to mitigate this problem is to utilize optical filters in the the OEO. This scheme is particularly attractive since Fabry-Perot cavities and WGM optical resonators can have very narrow bandwidth. A low noise OEO has been recently demonstrated with a Fabry-Perot as a filter in the optical loop [7]. A 39 GHz OEO utilizing a WGM resonator as an optical filter has also been demonstrated [8].

Another approach for reducing the amplitude of unwanted modes surviving the filter bandwidth and appearing as "supermodes" in the phase noise spectrum is to use multiple lengths of fiber as an optical filter [9]. This approach was recently somewhat modified to achieve the overall filtering effect in optics, rather than in combination with the electrical loop [10]. Finally, an OEO utilizing an atomic transition in rubidium was also demonstrated; this oscillator was designed to achieve high stability of operation derived from the atom [11].

Obviously, decreasing the length of the fiber and the associated increase in the frequency of the modes reduces the unwanted supermode noise by keeping them outside the filter bandwidth . This, however, reduces the desired high-Q associated with the fiber delay. A way around the problem is the COEO configuration [2,12]. In the COEO, the active optical loop essentially functions as a "Q multiplier" – shorter fiber length in the COEO leads to a lower phase noise than the same fiber length in the OEO. Finally, injection locking of two OEOs, one with a long length of fiber to produce low phase noise, and the other with a short fiber and the associated large supermode frequency spacing, has been proposed as a scheme to attain the best performance of the combined oscitllators [13].

Further improvement of OEO parameters can be achieved with optical microresonators. For example, optical WGM resonators are able to operate as the RF photonic filter, the high-Q element, and the modulator in the OEO loop. These OEOs have the added benefit of small size, and low operation power. There are two basic approaches for realization of the WGM resonator based OEO: direct modulation of the laser current, or external modulation using a resonator made with electro-optic material. In the former case, the resonator can be fabricated with crystalline material, such as calcium fluoride or magnesium fluoride, to achieve extremely high Qs. Optical resonators with Q exceeding 10^{11} have been demonstrated with these materials [14]. The phase noise corresponding to this high-Q is quite low, but the frequency of the oscillator is limited to the modulation bandwidth of the laser, and is typically limited to X-band frequencies. Given the growing interest in higher frequency oscillators, the WGM resonator serving as a modulator can be more attractive. Here, the resonator is fabricated with electro-optic material, such as lithium niobate or lithium tantalate, and provided with electrodes that can be used to apply the modulation voltage. The narrow resonance of the resonator serves to provide low phase noise in the oscillator circuit; it also leads to highly efficient modulation and thus reduction for needed amplification and resultant power consumption.

The latest advance in the technology of WGM-based OEO is the use of a both TE and TM modes of the WGM resonator. A modulator transferring photons from a single TE mode to a TM mode has been shown to perform as a true single sideband (SSB) modulator. The SSB modulator is fundamentally more efficient, and thus can improve the performance of the oscillator. Furthermore, since the indices of refraction of the modes respond differently to a forcing function, such as temperature change or an applied voltage, the modulation frequency can be tuned. This approach has been recently implemented, and a voltage controlled oscillator with a WGM resonator was demonstrated [15].

3 Optical Frequency Combs as RF Photonic Oscillators

A different photonic approach for generation of microwave and mm-wave signals takes advantage of the fact that an optical frequency comb generated with a femtosecond modelocked laser is essentially equivalent to a large number of phase locked lasers emitting at equally separated frequencies. Such a light source generates a single tone RF signal at the output of a fast photodiode. The signal has outstanding spectral purity because of the coherence of the comb lines, and can be combined with a stable optical reference to also provide high stability [16]. Recent work in this area has shown stand alone femtosecond combs producing unmatched spectral purity RF signals at 1 and 10 GHz [17].

The femtosecond comb setups are large, require a relatively high power pump laser, and are generally limited to application in the laboratory environment. They also produce signals at frequencies around 10 GHz and lower. A recent advance in the generation of optical frequency comb utilizing a WGM microresonator has opened the door for production of high spectral purity RF signals at virtually any desired microwave or mm-wave (and even THz) frequency. The approach is based on Kerr nonlinearity in the resonator material, which through the process of four-wave mixing allows excitation of many modes when one mode of the resonator is pumped with continuous wave light. Moderate laser powers combined with the high Q-factor of the resonator modes make this process feasible [18]. High spectrally pure mm-wave signals have been produced at 10 and 35 GHz [19] using the Kerr frequency combs. A clear advantage of this technique is the small size of the Kerr comb oscillator powered with a semiconductor laser that can support a wide variety of applications in science and engineering.

4 Conclusion

The technology of photonic generation of microwave and mm-wave signals has advanced considerably in the past few years. New schemes for realization of the OEO and use of optical combs promise to serve emerging applications where stringent performance is required.

5 References

1. X. S. Yao, and L. Maleki,"High frequency optical subcarrier generator," *Electron. Lett.*, **30**, Sep. 1994, pp. 1525 - 1526; *ibid.*, "Optoelectronic oscillator for photonic systems," *IEEE J. Quantum Electron.*, **32**, Jul. 1996, pp. 1141-1149; *ibid.*, "Optoelectronic microwave oscillator," *J. Opt. Soc. Am. B*, **13**, Aug. 1996, pp. 1725-1735.

2. X. S. Yao and L. Maleki, "Dual microwave and optical oscillator," *Opt. Lett.*, **22**, Dec. 1997, pp. 1867-1869; X. S. Yao, L. Davis, and L. Maleki, "Coupled optoelectronic oscillators for generating both RF signal and optical pulses," *J. Lightwave Tech.*, **18**, Jan. 2000, pp. 73-78.

3. D. Eliyahu, D. Seidel D, and L. Maleki, "RF amplitude and phase-noise reduction of an optical link and an opto-electronic oscillator," *IEEE Trans. Microwave Theory Tech.*, **56**, Feb. 2008, pp. 449-456.

4. D. H. Chang, H. R. Fetterman, H. Erlig, et al., "39-GHz optoelectronic oscillator using broad-band polymer electrooptic modulator," *IEEE Photon.Tech. Lett.*, **14**, Feb. 2002, pp. 191-193.

5. S. Fedderwitz, A. Stöhr, S. Babiel, V. Rymanov, and D. Jäger, "Opto-Electronic Dual-Loop 50 GHz Oscillator with Wide Tunability and Low Phase Noise," *2010 IEEE Topical Meeting on Microwave Photonics (MWP), Montreal, Quebec, Canada, 5-9 Oct. 2010*, **1**, Oct. 2010, pp. 224 - 226.

6. K. Volyanskiy, Y. K. Chembo, L. Larger, et al., "Contribution of Laser Frequency and Power Fluctuations to the Microwave Phase Noise of Optoelectronic Oscillators," *J. Lightwave Tech.*, **28**, Sept. 2010, pp. 2730-2735.

7. I. Ozdur , D. Mandridis, N. Hoghooghi , et al., "Low Noise Optically Tunable Opto-Electronic Oscillator With Fabry-Perot Etalon," J. Lightwave Tech., **28**, Nov. 2010, pp. 3100-3106; J. M. Kim, D. Cho, "Optoelectronic oscillator stabilized to an intra-loop Fabry-Perot cavity by a dual servo system," *Opt. Express*, **18**, Jul. 2010, pp. 14905-14912.

8. S. Fedderwitz, A. Stohr, S. Babiel, et al., "Optoelectronic K -Band Oscillator With Gigahertz Tuning Range and Low Phase Noise" *IEEE Photon. Tech. Lett.*, **22**, Oct. 2010, pp. 1497-1499.

9. X. S. Yao and L. Maleki, "Multiloop optoelectronic oscillator," *IEEE J. Quantum Electron.*, **36**, 2000, pp. 79-84.

10. J. Yang, Y. Jin-Long, W. Yao-Tian, Z. Li-Tai, and Y. En-Ze. "An Optical Domain Combined Dual-LoopOptoelectronic Oscillator," *IEEE Photon. Tech. Lett.*, **19**, Jun. 2007, pp. 807-812.

11. D. Strekalov, D. Aveline, N. Yu, et al., "Stabilizing an optoelectronic microwave oscillator with photonic filters," *J. Lightwave Tech.*, **21**, Dec. 2003, pp. 3052-3061.

12. D. Eliyahu and L. Maleki, "Modulation response (S21) of the coupled opto-electronic oscillator," *IEEE International Frequency Control Symposium/PDA Exhibit, Vancouver, BC, Canada*, 2005, pp.850-856; E. Salik, N. Yu, and L. Maleki, "An ultralow phase noise coupled optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, **19**, Mar. 2007, pp. 444-446; F. Quinlan, S. Gee, et al., "Self-Stabilization of the Optical Frequencies and the Pulse Repetition Rate in a Coupled Optoelectronic Oscillator" *J. Lightwave Tech.*, **26**, Aug. 2008, pp. 2571-2575.

13. W. M. Zhou, G. Blasche, " Injection-locked dual opto-electronic oscillator with ultra-low phase noise and ultra-low spurious level," *IEEE Trans. Microwave Theory Tech.*, **53**, Mar. 2005, pp. 929-933.

14. L. Maleki, V. S. Ilchenko, A. A. Savchenkov, and A. B. Matsko, in A. B. Matsko (ed.) *Practical Applications of Microresonators in Optics and Photonics*, CRC Press, 2009, chap. 3.

15. A. A. Savchenkov, V. S. Ilchenko, W. Liang, D. Eliyahu, A. B. Matsko, D. Seidel, and L. Maleki, "Voltage-controlled photonic oscillator," *Opt. Lett.*, **35**, May 2010, pp. 1572-1574.

16. A. Bartels, S. A. Diddams, C. W. Oates, G. Wilpers, J. C. Bergquist, W. H. Oskay, and L. Hollberg, "Femtosecond-laser-based synthesis of ultrastable microwave signals from optical frequency references," *Opt. Lett.*, **30**, March 2005, 667-669.

17. S. A. Diddams, M. Kirchner, T. Fortier, D. Braje, A. M. Weiner, and L. Hollberg, "Improved signal-to-noise ratio of 10 GHz microwave signals generated with a mode-filtered femtosecond laser frequency comb," *Opt. Express*, **17**, Mar. 2009, pp. 3331-3340.

18. A. B. Matsko, A. A. Savchenkov, D. Strekalov, V. S. Ilchenko, and L. Maleki, "Optical hyper-parametric oscillations in a whispering gallery mode resonator: threshold and phase diffusion", *Phys. Rev. A*, **71**, 033804 (2005).

19. L. Maleki, V. S. Ilchenko, A. A. Savchenkov, W. Liang, D. Seidel, and A. B. Matsko, "High Performance, Miniature Hyper-parametric Microwave Photonic Oscillator," *2010 IEEE International Freq. Control Symp.*, June 2010, pp. 558-563.