3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Photonic Synthesis of Mm-wave and THz Signals for 5G and Beyond

Stavros Iezekiel[(1)]
(1) EMPHASIS Research Centre, University of Cyprus, Nicosia 1678, Cyprus

Abstract

Low phase noise mm-wave oscillators are critical components for the implementation of emerging 5G and future 6G communication systems, both terrestrial and space-based. As carrier frequencies move into the V-band, W-band, D-band and the THz range, photonic synthesis of signals becomes more attractive, especially from the perspective of phase noise. Here, we review recent work in this field, with the focus on self-oscillating topologies derived from the optoelectronic oscillator.

1. Introduction

Radio-over-fiber techniques [1] and associated microwave photonics technology have played a pivotal part in the advancement of 5G and the development of 6G. In order to support the continued evolution to multi-Gb/s wireless communications, there has been a steady increase in carrier frequency, with interest in 60 GHz [2], W-band [3] and also the THz frequency range [4].

Although there are well-established electronic devices (especially diode-based) and circuit design techniques for the mm-wave regime, attaining low phase noise and significant power is a significant challenge. One reason for this is the phase noise degradation penalty that is incurred when using frequency multipliers to extend the oscillation frequency, coupled with the stringent requirements on phase noise performance in the mm-wave band for high-order modulation formats. For example, the minimum carrier phase noise is −96 dBc/Hz at 1 MHz offset for 64 QAM WiGig/IEEE802.11ad [5].

In contrast to electronic techniques, the optoelectronic oscillator (OEO) [6] offers a method of generating microwave signals in which the phase noise is lower, and crucially does not degrade as the operating frequency increases. However, with the exception of a W-band OEO employing a polymer modulator [7], most OEOs employ lithium niobate modulators, with the majority of reported results typically being below the Ka-band. In contrast, optical frequency combs (OFC) coupled with optical filtering allow much higher frequencies to be obtained [8], potentially through to the THz range.

2. Optoelectronic Oscillators

The OEO is a hybrid loop oscillator, comprising both microwave and optical components, thus allowing either a direct microwave output or the option of a modulated lightwave; the latter is attractive in systems that also employ microwave photonic mixing and signal filtering [9]. It is the low loss of optical fibre that enables a long loop delay, and thus a high-Q oscillator, but in the single loop topology (Fig.1(a)) this also leads to a small free spectral range and thus multimode operation. This may be overcome with either a dual-loop topology as illustrated in Fig.1(b), or by injection locking (Fig.1(c)).

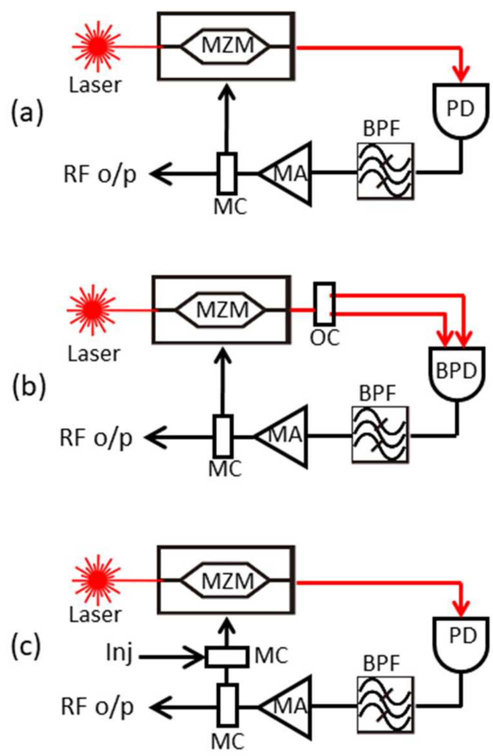

Figure 1. (a) Single-loop OEO (b) Dual-loop OEO (c) Injection-locked OEO. MZM = Mach-Zehnder modulator, PD = photodiode, BPD = balanced photodiode, MA = microwave amplifier, MC = microwave coupler, OC = optical coupler, BPF = bandpass filter. Note that many implementations also include optical amplifiers. Red lines indicate optical path.

By using injection locking, a W-band OEO has been demonstrated at 94.5 GHz [7]. The injection locking enabled a side-mode suppression in excess of 65 dB while a single-sideband (SSB) phase noise of -100 dBc/Hz at a carrier offset of 10 kHz was measured. To date, this is the highest recorded frequency for an OEO, although to achieve higher frequencies (up to 300 GHz) would rely on the use of emerging plasmonic modulator technology [10].

3. Self-Oscillating Frequency Combs

There are several techniques for generating optical combs; a relatively straightforward approach is based on the use of a dual-drive Mach-Zehnder modulator (DD-MZM) under appropriate bias and RF drive conditions [11]. In [12]-[13], the RF-drive signal was generated via a tunable OEO as shown in Fig.2 (a), resulting in an optical frequency generator (OFCG) capable of generating signals up to 242 GHz. A wavelength selective switch (WSS) was used to select a dual wavelength spectrum which was then heterodyne detected to generate the mm-wave signal.

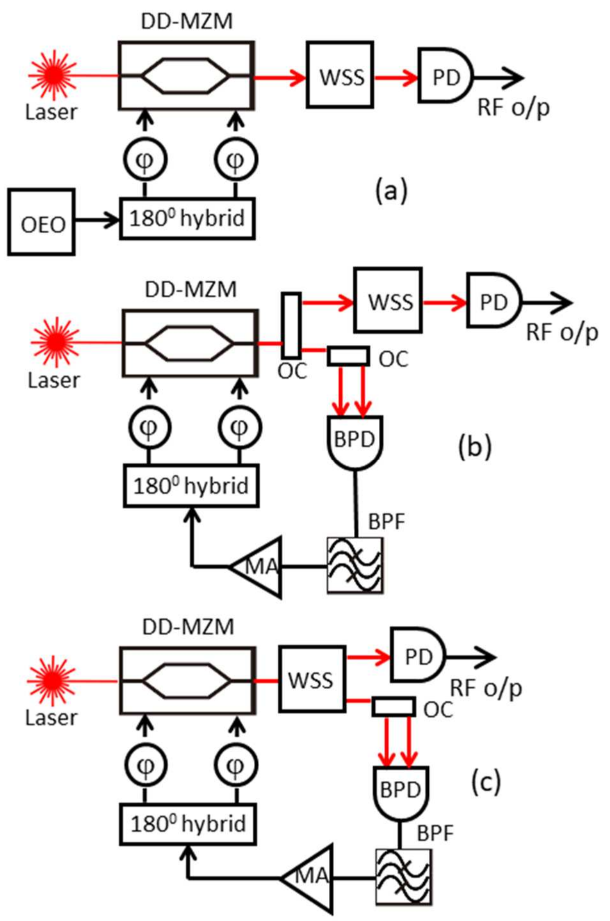

Figure 2. (a) OFCG driven by a tunable frequency OEO (b) Self-oscillating OFCG. (c). Modified self-oscillating OFCG in which the WSS is placed inside the oscillation loop. Note that the implementations above also include optical amplifiers in practice. Red lines indicate optical path.

However, if a tunable comb spacing is not required, it is possible to form a self-oscillating OFCG topology [14] as shown in Fig.2(b). This approach is essentially a modified dual-loop OEO, in which the modulator generates an optical comb rather than a double-sideband modulated lightwave. The balanced photodiode then beats the optical frequency comb, with the BPF selecting the lowest frequency (which corresponds to the comb spacing). A WSS is then employed as before in order to setup the heterodyne detection. With this approach, a W-band signal generator was developed, which was then applied to a W-band radio-over-fiber demonstrator [14]. The advantage of the self-oscillating OFCG is that it dispenses with the requirement for an external RF drive and offers better phase noise performance by virtue of the loop topology.

A minor modification to the self-oscillating OFCG may be made by placing the WSS inside the loop [15]. Apart from a reduction in component count and complexity, this also has the advantage in that it can select a dual wavelength input for both the BPD and PD, leading to optimised operation. Here, a 95 GHz signal was generated with a phase noise of – 86 dBc/Hz for a frequency offset of 10 kHz.

4. Conclusions

We have reviewed a number of approaches to the photonic synthesis of mm-wave and THz signals that are based on OEO-derived self-oscillating optical comb generators. This approach paves the way for low phase noise signal generators for demanding applications such as 5G and future 6G systems.

Although the intended applications include terrestrial radio-over-fiber systems, there is also an increased interest in the application of microwave photonics to high throughput telecommunication satellite payloads [16]. Here, a key driver apart from bandwidth is the requirement for reduced SWaP (size, weight and power) which has motivated the development of integrated microwave photonics [17].

5. Acknowledgements

Part of this work was supported by the European Union's Horizon 2020 research and innovation programme under Grant 642355.

References

[1] N.J. Gomes, M. Morant, A. Alphones, B. Cabon, J.E. Mitchell, C. Lethien, M. Csörnyei, A. Stöhr, and S. Iezekiel, "Radio-over-fiber transport for the support of wireless broadband services [Invited]," J. Opt. Netw., vol. 8, pp. 156-178, 2009, doi: 10.1364/JON.8.000156.

[2] P. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions," in IEEE Communications Magazine, vol. 40, no. 1, pp. 140-147, Jan. 2002, doi: 10.1109/35.978061..

[3] R. Puerta, S. Rommel, J. J. V. Olmos, and I. T. Monroy, "Optically Generated Single Side-Band Radio-over-Fiber Transmission of 60Gbit/s over 50m at W-Band," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017), paper M3E.4. doi:10.1364/OFC.2017.M3E.4

[4] H. Song and T. Nagatsuma, "Present and Future of Terahertz Communications," in IEEE Transactions on Terahertz Science and Technology, vol. 1, no. 1, pp. 256-263, Sept. 2011, doi: 10.1109/TTHZ.2011.2159552.

[5] T. Siriburanon et al., "A Low-Power Low-Noise mm-Wave Subsampling PLL Using Dual-Step-Mixing ILFD and Tail-Coupling Quadrature Injection-Locked Oscillator for IEEE 802.11ad," in IEEE Journal of Solid-State Circuits, vol. 51, no. 5, pp. 1246-1260, May 2016, doi: 10.1109/JSSC.2016.2529004.

[6] X. S. Yao and L. Maleki, "Optoelectronic oscillator for photonic systems," in IEEE Journal of Quantum Electronics, vol. 32, no. 7, pp. 1141-1149, July 1996, doi: 10.1109/3.517013.

[7] G.K.M. Hasanuzzaman, S. Iezekiel and A. Kanno, "W-Band Optoelectronic Oscillator," *IEEE Photonics Technology Letters*, vol. 32, no. 13, pp. 771-774, July 2020, doi: 10.1109/LPT.2020.2996277.

[8] M. Kourogi, K. Nakagawa and M. Ohtsu, "Wide-span optical frequency comb generator for accurate optical frequency difference measurement," in IEEE Journal of Quantum Electronics, vol. 29, no. 10, pp. 2693-2701, Oct. 1993, doi: 10.1109/3.250392.

[9] J. Capmany, B. Ortega and D. Pastor, "A tutorial on microwave photonic filters," in Journal of Lightwave Technology, vol. 24, no. 1, pp. 201-229, Jan. 2006, doi: 10.1109/JLT.2005.860478.

[10] M. Burla, C. Hoessbacher, W. Heni, C. Haffner, Y. Fedoryshyn, D. Werner, T. Watanabe, H. Massler, D.L. Elder, L.R. Dalton, and J. Leuthold, “500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics”, APL Photonics, vol. 4, no. 5, p.056106, 2019, doi: 10.1063/1.5086868.

[11] T. Sakamoto, T. Kawanishi, and M. Izutsu, “Asymptotic formalism for ultraflat optical frequency comb generation using a Mach-Zehnder modulator. Optics letters”, vol. 32, no.11, pp.1515-1517, 2007, doi: 10.1364/OL.32.001515

[12] G.K.M. Hasanuzzaman, H. Shams, C. C. Renaud, J. Mitchell, A. J. Seeds and S. Iezekiel, "Tunable THz Signal Generation and Radio-Over-Fiber Link Based on an Optoelectronic Oscillator-Driven Optical Frequency Comb," *Journal of Lightwave Technology*, vol. 38, no. 19, pp. 5240-5247, Oct. 2020, doi: 10.1109/JLT.2019.2953070..

[13] G.K.M. Hasanuzzaman, H. Shams, C. C. Renaud, J. Mitchell, A. J. Seeds and S. Iezekiel, "Cascaded Microwave Photonic Filters for Side Mode Suppression in a Tunable Optoelectronic Oscillator applied to THz Signal Generation & Transmission," in IEEE Photonics Journal, vol. 13, no. 1, pp. 1-11, Feb. 2021, doi: 10.1109/JPHOT.2020.3044342.

[14] G.K.M. Hasanuzzaman, A. Kanno, P. T. Dat and S. Iezekiel, "Self-Oscillating Optical Frequency Comb: Application to Low Phase Noise Millimeter Wave Generation and Radio-Over-Fiber Link," *Journal of Lightwave Technology*, vol. 36, no. 19, pp. 4535-4542, Oct.1, 2018, doi: 10.1109/JLT.2018.2844344.

[15] A. Kanno, G.K.M. Hasanuzzaman, N. Yamamoto, and S. Iezekiel "Optical frequency comb applied optoelectronic oscillator for millimeter-wave signal generation and its application", Proc. SPIE 10634, Passive and Active Millimeter-Wave Imaging XXI, 106340E, 2018, doi: 10.1117/12.2304821.

[16] G. Charalambous and S. Iezekiel "Microwave photonic frequency generation and conversion unit design for Ka-band satellite payloads", Proc. SPIE 11852, International Conference on Space Optics — ICSO 2020, 1185243, 2021, doi:10.1117/12.2599638

[17] S. Iezekiel, M. Burla, J. Klamkin, D. Marpaung and J. Capmany, "RF Engineering Meets Optoelectronics: Progress in Integrated Microwave Photonics," IEEE Microwave Magazine, vol. 16, no. 8, pp. 28-45, Sept. 2015, doi: 10.1109/MMM.2015.2442932.