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.](image-url) (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.

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].

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### References


