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Photonics for high-frequency ultra-wideband and frequency-agile RF transmitters

G. Serafino[(1)], F. Scotti[(2)], D. Onori[(2)], F. Falconi[(2)], F. Amato[(1)] P.Ghelfi [(2)], A. Bogoni[(1)], [(2)]
(1) Sant'Anna School of Advanced Studies, TeCIP Institute, Via G. Moruzzi, 1, 56124 Pisa, ITALY
(2) CNIT, National Laboratory of Photonic Networks, Via G. Moruzzi, 1, 56124 Pisa, ITALY

Abstract

The main techniques of microwave signal generation based on photonics will be described, to provide high-quality and software defined RF signals with unprecedented frequency tuning in a very large RF spectrum including the millimeter wave spectral range.

1. Introduction

The new generation of radars are requiring microwave signals with higher frequencies, wider bandwidth, and increasing stability, in order to implement coherent radar systems with enhanced capabilities [1]. Moreover, the paradigm of "software defined" systems requires tunable carrier frequencies, without affecting its stability. The availability of adaptive radars (i.e. frequency agile and software defined) will also enable cognitive radars. Moreover, the possibility of dynamically changing the operating frequency allows to face the increasing erosion of the spectrum available for radar applications.

Similarly radio communications are migrating toward Ultra-wideband (UWB) and high-frequency systems. UWB is a radio technology where employed signals present a bandwidth exceeding 500 MHz or 20% of the center frequency, whether they are aggregation of narrow band carriers (e.g. in multiband orthogonal frequency-division multiplexing), etc. [2]. UWB communication offers not only the advantage of providing a very large transmission capacity, but also superior obstacle penetration, undercover operation, resistance to jamming, etc. [2]. The availability of multi-band UWB transmitters, able to provide frequency agility, flexibility, and reconfigurability, allows to envisage the development of new generation multi-protocol communication systems where the hardware sharing, among different communication standards, lead to a reduced size, weight, and power consumption (SWaP).

Nowadays, the main source of phase and amplitude noise, as well as non-linear distortions in the high-frequency radar/radio transmitters is the mixing process of up-conversion, which is necessary to shift the radio frequency (RF) signal from the baseband or intermediate frequency, to the desired carrier frequency.

The direct use of high frequency local oscillators also limits the quality of the RF signal, due to the performance of the RF oscillators that are degrading with the frequency increase. Moreover, multi-band operation is usually implemented through a stackable implementation due to the lack in tunability of state of the art electronic and microwave technology [3].

Finally high-frequency RF transmitters should be implemented on chip to reduce the system SWaP as well as the cost, and make the system suitable for large use in radar and communication fields. In this context, photonics help for producing high quality and tunable RF signals up to the mmW, thanks to its inherent high frequencies and high coherence of photonic sources (i.e. lasers). In fact, photonics is characterized by very high values of the carrier frequencies (10^{14} Hz) compared to the radio frequencies (10^9 Hz). This results in the capacity to generate RF signals tunable over several tens of GHz. As an example, a 40GHz tuning of an RF signal corresponds to an optical frequency variation in the order of 0.01% of the carrier frequency. Moreover integrated photonics allow for a chip implementation of the photonics-based transceiver. This make these solutions available for applications requiring low SWaP as on mobile platforms (i.e. satellites, unmanned air vehicles-UAVs etc..) and applications requiring low cost in mass production.

2. Photonics based mmW signal generation

With Reference to Figure 1, RF signals have been generated exploiting photonics based on the heterodyning of two independent lasers in a photodiode. The photodiode generates a current proportional to the square of the input optical signal. This process produces an RF tone, whose frequency is equal to the detuning between the two lasers. If one of the two laser is modulated with the RF waveform at intermediate frequency, this waveform is replicated at the generated RF tone, by the laser heterodyning process. Unfortunately, the use of two independent lasers do not allow for a stable RF generation, due to the phase noise of the two involved lasers, which changes the laser detuning, i.e. changes the generated RF frequency. This results in RF signals noisy and not useful for real applications both in radar and communication field. In order to improve the RF stability, phase locking of the beating lasers is mandatory. Three different approaches can be used for generating phase locked lasers: (a) to exploit photonics techniques for the locking of continuous wave (CW) lasers, (b) to exploit laser combs with laser lines inherently locked, (c) to exploit opto-electronic oscillators.

In all the cases, the phase noise of the obtained RF signals has been demonstrated to be significantly better than the phase noise of the signals generated by the state-of-the-art RF synthesizers.

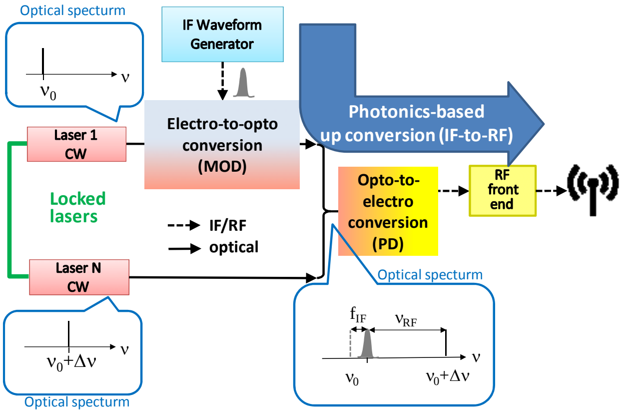

Figure 1 Working principle of a photonics-based RF signal generation

The first approach can be achieved by controlling a slave laser through injection locking. More in details a master laser is sinusoidally modulated to create a sideband tone that injects a slave laser working at a similar frequency (but different compared to the master frequency). The injection forces the slave to phase lock to the sideband tone and consequently to the master, if the injected tone frequency is within the slave injection locking range. This technique offers very low phase noise and the capacity to continuously tune the generated RF signal.

The second approach is based on a laser comb and it exploits the optical filtering of two laser lines of the comb at the desired RF. The laser comb can be quite easily obtained using a mode locked laser (MLL) [4][5]. MLLs are pulsed lasers whose optical spectrum is composed of several modes at a detuning equal to the pulse rate, and intrinsically locked in phase to each other. Another technique to obtain a laser comb with inherently coherent laser lines is based on the modulation of a CW laser through a cascade of phase or amplitude modulators [6]. The possibility of selecting laser modes of the comb with variable wavelength detuning also allows to produce RF carriers with tunable frequency, potentially generating any multiple frequency of the comb repetition rate. This results in a discrete tuning of the generated RF signals.

The third approach for generating stable phase locked laser lines, is the use of an opto-electronic oscillator (OEO). This technique consists on modulating the light of a CW laser, and feeding back the detected signal as RF modulating signal to the input port of the modulator itself. The OEOs have shown extremely low phase noise, thanks to the ultra-low losses of the optical cavity implemented by optical fiber or waveguide. The first examples of OEOs exploited an amplitude modulator and RF filters in the feedback to fix the oscillation frequency. This approach has the drawback of not allowing the tuning of the generated RF frequency [7].

More recently, OEOs have been implemented replacing the amplitude modulator with a phase modulation and a phase-to-amplitude modulation conversion [8]. This has been obtained by substituting the RF filter with an optical filter. This new implementation has the advantage of a large frequency tuning. Moreover the use of a phase modulator introduces a lower insertion loss improving the scheme performance and avoid the use of a bias voltage for setting the working point, simplifying the operation.

3. Integrated photonics technologies

From a technological point of view, many efforts have been spent for implementing the described solutions on chip through photonics integrated circuits. In the last decade, CMOS compatible silicon photonic technologies have undergone a substantial development. In particular, integrated photonics circuits have been widely developed for optical communications. Currently, microwave photonic systems are also under investigation and development. Many efforts have been done for example, in the field of development of microwave photonic filters, with a narrow band (few GHz) and high Q factor requirements needful for microwave application [9] or in the field of RF optical beamforming networks [10]. Commercial OEOs are already on the market produced by a US company [11]. Tunable OEOs developed as a bench top instruments are available, as well as OEOs on chip working at a fixed frequency of 35GHz.

6. Acknowledgements

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