Silicon Photonics for Millimeter-Wave Band Signal Generation

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ABSTRACT
Millimeter (mm-)wave band enables low-latency high-capacity wireless communications for 5G and 6G networks as well as high resolution imaging for advanced radar/sensing systems. The recent progresses in the development of compact RF signal synthesizers based on photonic integration technology using silicon on insulator platform are overviewed in this paper. Different architectures are discussed, and preliminary results confirms generation of a 100 GHz carrier wave starting from a 20 GHz reference oscillator with negligible excess phase noise, as well as the possibility of extending the operation over the whole mm-wave band.
Keywords: photonic integrated circuits, millimetre wave band signal generation, silicon photonics.

1. INTRODUCTION

Millimeter (mm)-wave frequencies (i.e., between 30 and 300 GHz) offer new opportunities for several RF systems applications. The latest generations of wireless communication systems are planning to leverage on the lower edge of the mm-wave band (e.g., up to about 100 GHz), for supporting broadband and low-latency services including vehicular connectivity, virtual and augmented reality, wireless backhauling, and industrial automation. Above 100 GHz, a large spectrum is available for operations such as short-range radar, THz imaging, chip-to-chip high throughput communications or again backhaul communications. With respect to conventional solutions based for instance on frequency multipliers in BiCMOS technology [1], photonics provides an alternative and flexible approach for generating carrier waves in the mm-wave band and above [2], with the additional advantage of permitting efficient distribution of the high-frequency carrier over the network or antennas segments through fiber links with negligible attenuation. To fully benefits from these features, and cope with available electronics-based solutions in terms of costs, complexity, and encumbrance, photonic integration using CMOS-compatible silicon on insulator (SOI) technology is a promisingly viable path. In the last recent years, we reported of different silicon-photonics-based circuits realizing several broadband RF processing functionalities with enhanced features in terms of band coverage and flexibility, including frequency scanning, programmable RF filtering, and low phase noise signal generation up to the sub-THz band [3]-[9].

Here, we discuss the operation and preliminary characterization of recently realized SOI photonic integrated circuits (PICs) for further improving the performance of frequency synthesis operation and for which functional electro-optic packaging with a printed circuit board (PCB) carrying the driving electronics is in progress [9].

2. SILICON PHOTONICS FREQUENCY SYNTHESIZER ARCHITECTURES

Different frequency synthesizer architectures have been considered and implemented using a SOI multi-user fabrication service [10]. The schemes typically operate as programmable frequency multipliers, permitting to overcome the bandwidth limitations of standard silicon photonics electro-optic devices.

2.1 Operation with single modulator and OF

In the architecture of Fig. 1(a), the light from an external laser source is injected into the PIC and split into two paths through a variable optical splitter (VOS). On one path, a phase modulator (PM) driven by an external

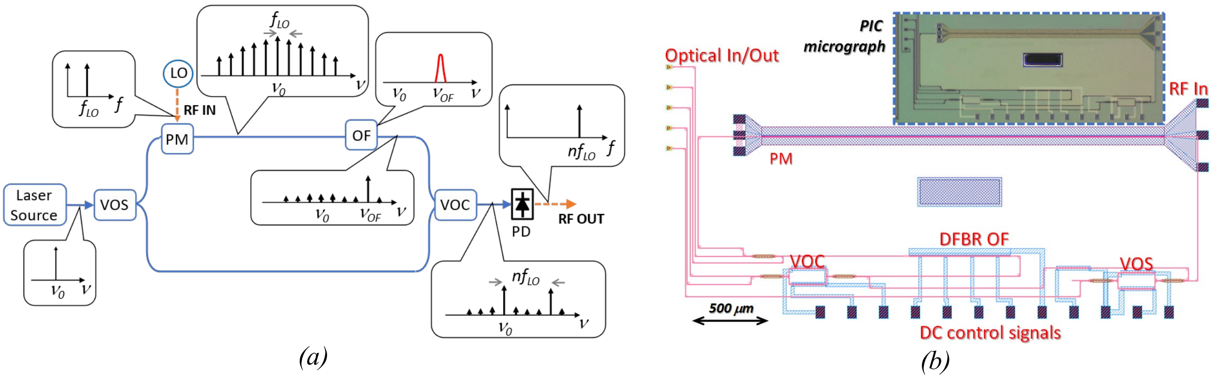
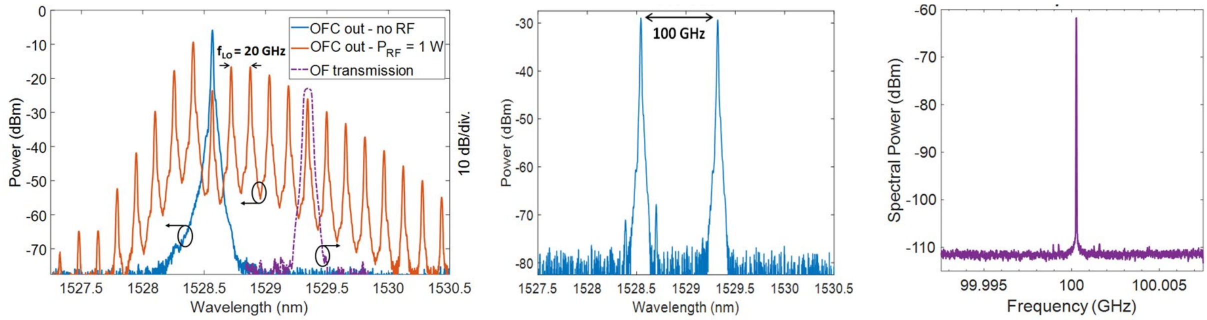


Figure 1: (a) Operation scheme of RF frequency multiplier based on single PM and OF; (b) Mask layout for circuit implementation in SOI technology (inset: micrograph of fabricated PIC).



(a) (b) (c)

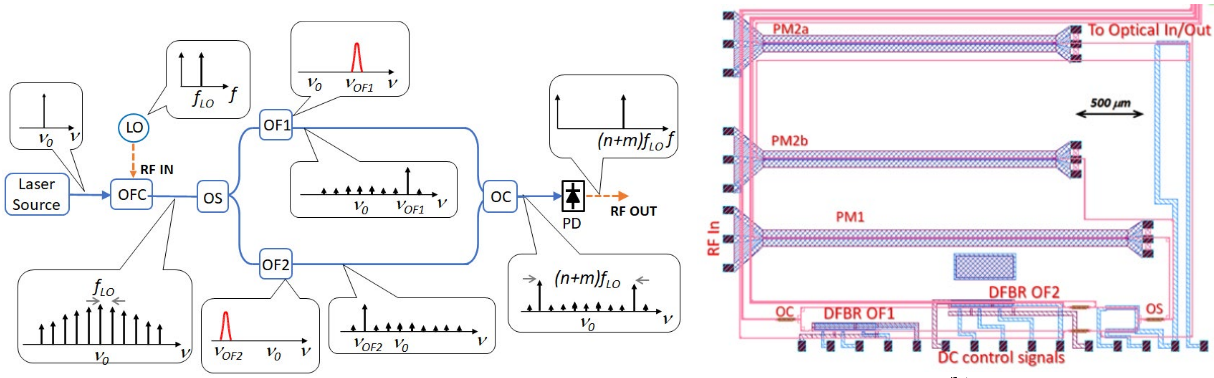
Figure. 2. Characterization results for the scheme in Fig. 1: (a) Optical frequency comb (OFC) source output spectra and OF transmission; (b) Optical spectrum at PIC output; (c) RF spectrum of generated 100 GHz clock.

reference signal at frequency f_{LO} with sufficiently large voltage level generates a comb of sidebands, and a subsequent passband optical filter (OF) selects a single harmonic in the comb spectrum, while suppressing all the other components. The filtered sideband is then recoupled with the original carrier emerging from the second path through an exit variable optical coupler (VOC), and the composite signal is delivered to an external photodiode (PD) (after an optional fiber link) to generate an RF signal at nf_{LO}, being n the order of the selected harmonic from the integrated OF. The corresponding mask layout, and a picture of the fabricated device are also illustrated in Fig. 1(b). The integrated passband OF is based on a 4^{th}-order distributed feedback resonator (DFBR) architecture [11], realized by embedding coupled cavities between waveguide Bragg grating mirrors (BGMs). Each of the cavities can be controlled through local phase shifters, allowing fabrication imperfections to be compensated and filter central frequency to be tuned within the mirrors' bandwidth.

The results of the bare-chip characterization are illustrated in Fig. 2, where the relevant signal spectra along the circuit and after a high-speed PD for the case of five-fold multiplication of a 20 GHz tone from the local oscillator (LO) up to 100 GHz are illustrated. By employing the tunable splitter and combiner at the input and output of the circuit, respectively, the quality of the generated RF signals can be optimized through proper balancing of the relative level of the two optical tones impinging on the PD, and a time jitter of 17 fs has been measured for the generated 100 GHz carrier against a value of 14 fs for the reference signal at 20 GHz, confirming limited excess phase noise added by the scheme.

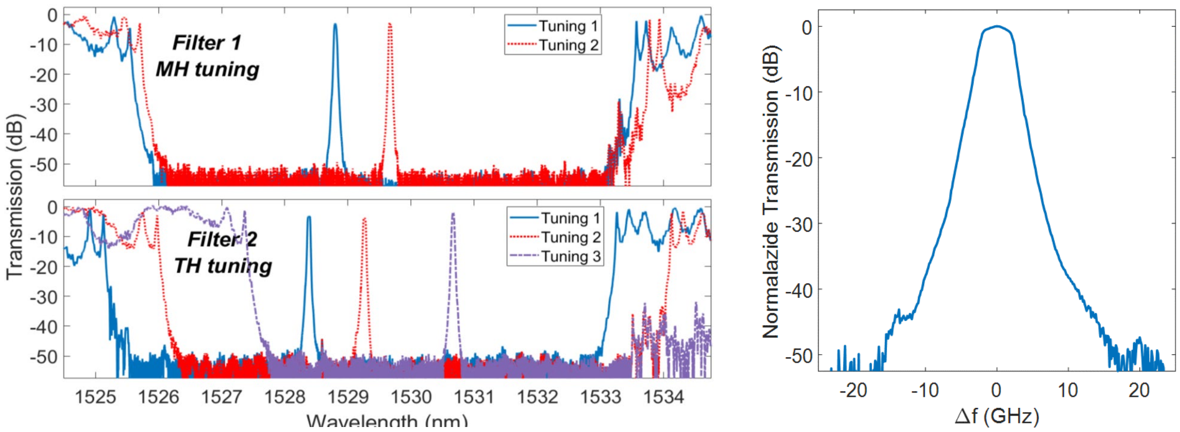
2.2 Operation with single or cascaded modulators and two OFs

In the architecture of Fig. 3(a), the injected light from the LS into the PIC is firstly delivered to the optical frequency comb (OFC) generator, and subsequently split into two paths, each comprising a 3^{rd}-order DFBR OF. The signals after the filters are then recoupled and delivered to the PIC output. The corresponding mask layout is reported in Fig. 3(b). To fully exploit the capability of this architecture to simultaneously select both lower- and higher-wavelength sidebands, and maximize the frequency multiplication factor, either a single PM or a cascade of two PMs, each connected to one port of the input 2×2 OS, can be used. To facilitate the relative tuning of the OFs central frequency, an additional tuning mechanism has been included in the DFBRs architectures, consisting in a second top heater (TH) covering the entire device length, thus allowing the Bragg wavelength, λ_b, of the distributed mirrors to be controlled [8]. In Fig. 4(a), different tuning settings for the two DFBR OFs are illustrated, and the typical passband details are also shown in Fig. 4(b). In particular, the top traces of Fig. 4(a) show the tuning results using local micro-heaters (MHs) acting on the isolated DFBR cavities, which leave almost unaffected the filter stop-band edges (i.e., the BGMs reflection band). On the other hand, using the TH,



(a) (b)

Figure 3: (a) Operation scheme of RF frequency multiplier based on single or two cascaded PM and two OFs; (b) Mask layout for circuit implementation in SOI technology. Two OFC source based on either the single PM1 or the cascaded PM2a and PM2b are independently connected to the parallel filter stage.



(a) (b)

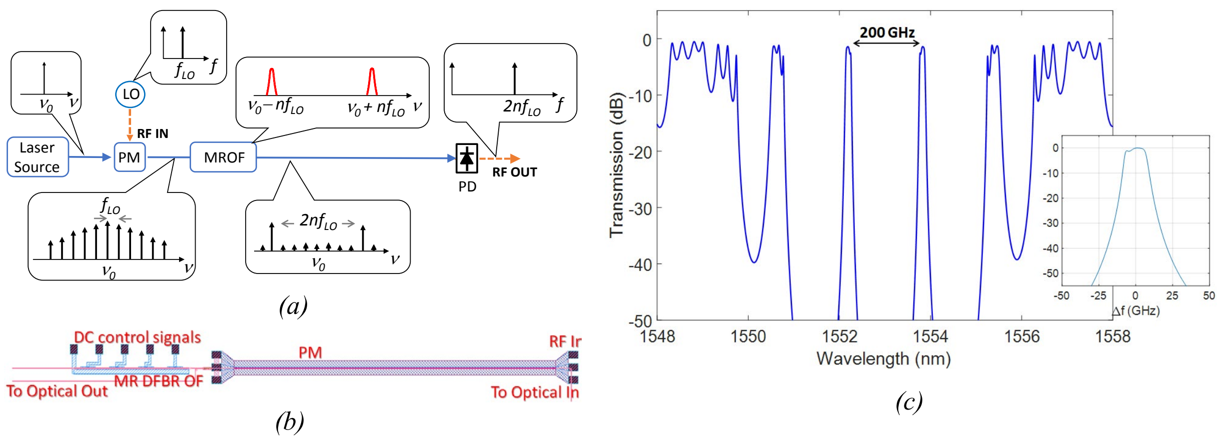
Figure 4: (a) Two DFBR filter tuning mechanisms, allowing either local control of the cavities phases through MHs, or acting on the distributed mirrors Bragg wavelength are illustrated; (b) Details of the passband window.

the tuning of λ_b results in a rigid translation of the overall spectral response. As shown, the combination of these tuning mechanisms permits flexible selection of widely spaced (up to well above 200 GHz) tones, for which the cascaded-PMs OFC source may be conveniently employed. However, the scheme suffers from the additional splitting and
coupling losses after the integrated PM and before PD, respectively.

2.3 Operations with single modulator and single multi-resonant OF and OEO-based

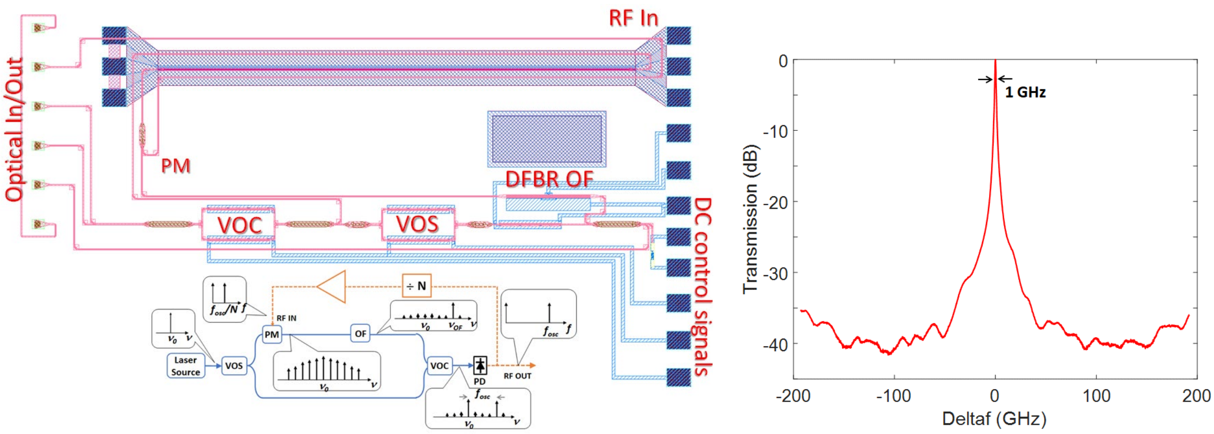
A different approach for extending the range of the synthesized carriers' frequency that preserve the simplicity of the architecture without increasing the number of required control signals, would be employing a double-resonant OF, as illustrated in the scheme of Fig. 5(a). The corresponding mask layout of Fig. 5(b) also highlights the compactness of this implementation, which on the other hand doesn't permit the full reconfigurability of the operation as in previous architectures, being the output synthesized frequency set by the spacing between filter's resonances. An example of a DFBR design with two 200-GHz spaced passband windows within its stop-band is also shown in Fig. 5(c).

Finally, the ability of synthesising RF carriers up to the mm-wave band without the need of a reference microwave source would introduce relevant advantages in terms of equipment costs. To this scope, the opto-electronic-oscillator (OEO) architecture illustrated in Fig. 5(a) has been realized. The operation exploits the phase-to-amplitude modulation conversion originated by slicing a portion of a PM sideband and subsequent reinserting the optical carrier, similarly to the scheme of Fig. 1(a). The oscillating frequency is defined by the relative detuning of the optical carrier and the central frequency of the slicing filter. To overcome the silicon photonics PM bandwidth limitations (cut off frequency around 20 GHz) end extend the operation well within the mm-wave band, a frequency divider is required in the RF feedback loop for sustaining the oscillation at an harmonic of the PM driving signal. A 1st-order DFBR filter has been designed for this operation. The measured spectral characteristic of the fabricated filter is reported in Fig. 5(a) and illustrates a wide stop-band of more than 400 GHz (required for operation in high-order harmonic mode), and a filter Q-factor of 2×10^5.



(a) (b) (c)

Figure 5. (a) Operation scheme of RF frequency multiplier based on multi-resonant (MR) OF; (b) Mask layout for circuit implementation in SOI technology; (c) Designed MR DFBR transmission spectra.



(a) *(b)*

Figure 5. (a) Mask layout and operation of a silicon-photonics OEO encompassing high Q-factor DFBR OF.

3. CONCLUSIONS

An overview of currently implemented photonic-integrated approaches for RF synthesizers designed to operate from the *K* band up to the millimeter-wave and sub-THz bands using silicon-on-insulator technology has been provided. Preliminary on-chip experimental characterizations have been performed for some of the realized architectures, with an observed overall performance in accordance with design targets. The level of chips functionality will be improved by wedge bonding the photonic core with on-board driving electronics matched circuitry to provide a compact packaged solution.

4. ACKNOWLEDGEMENTS

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REFERENCES

[1] A. Siligaris *et al.*: A 270-to-300 GHz sub-harmonic injection locked oscillator for frequency synthesis in sub-mmW systems, *Microw. Wirel. Compon. Lett.*, vol. 25, pp. 259-261, April 2015.
[2] A. J. Seeds, H. Shams, M. J. Fice, and C. C. Renaud: Terahertz photonics for wireless communications, *J. Lightwave Technol.*, vol. 33, pp. 579–587, Feb. 2015.
[3] C. Porzi *et al.*: Fast-reconfigurable microwave photonics phase shifter using silicon microring resonators, *J. Quantum Electron.*, vol. 57, pp. 1-9, Feb. 2021.
[4] C. Porzi *et al.*: Flexible millimeter-wave carrier generation up to the Sub-THz with silicon photonics filters, *J. Lightwave Technol.*, vol. 39, pp. 7689-7697, Dec. 2021.
[5] F. Falconi *et al.*: UWB fastly–tunable 0.5–50 GHz RF transmitter based on integrated photonics, *J. Lightwave Technol.*, vol. 40, pp. 1726-1734, March 2022.
[6] C. Porzi, F. Falconi, M. Sorel, A. Bogoni: Broadband and high-capacity silicon photonics single-sideband modulator, *J. Lightwave Technol.*, vol. 40, pp. 538-546, Jan. 2022.
[7] A. Malacarne *et al.*: Reconfigurable low phase noise RF carrier generation up to W-band in silicon photonics technology, *J. Lightwave Technol.*, vol. 40, pp. 6891-6900, Oct. 2022.
[8] C. Porzi *et al.*: Silicon-on-insulator microwave photonic filter with widely tunable and reconfigurable flat-top bandpass functionality, *J. Lightwave Technol.*, vol. 40, pp. 6666-6675, Oct. 2022.
[9] A. Malacarne, L. Roselli, M. Chiesa, A. Bigongiari, M. Reza, A. D'Errico, A. Bogoni and C. Porzi: Electro-optic packaging of silicon photonics-based RF multiplier for clock signal generation in the millimeter-wave band", in *Proc. ECIO,* Enschede, The Netherlands, Apr. 2023, paper M2G.
[10] https://europractice-ic.com/mpw-prototyping/siphotonics/imec/.
[11] C. Porzi, G. J. Sharp, M. Sorel, and A. Bogoni,: Silicon photonics high-order distributed feedback resonators filters, *J. Quantum Electron.*, vol. 56, pp. 1-9, Feb. 2020.