Photonic Sampler for Millimeter-Wave Signals up to 70 GHz Using a 1-GHz Mode-Locked Laser and a Silicon Photonic Integrated Circuit

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***Abstract*—This work presents a photonic RF-sampling system using a silicon-photonic PIC and a 1-GHz 10.5-fs-jitter mode-locked laser, demonstrating photonic downconversion, sampling, and demodulation of complex QAM signals at millimeter-wave frequencies up to 70 GHz, with potential for satellite communications.**

***Index Terms*—Photonic ADC, Millimeter-wave sampling, low-jitter ADC**

I. Introduction

With the rise of 5G New Radio (5G NR) and non terrestrial networks (NTNs), satellite communications plays an increasingly critical role in global connectivity. Emerging mobile communications systems are required to leverage the enhanced bandwidth provided by millimeter-wave carrier frequencies. Therefore, high performance analogue-to-digital converters (ADCs) are required for RF signal digitization. However, with high-frequency sampling ADCs, jitter and distortion are exacerbated, producing critical limitations in conversion speed and resolution. To address these drawbacks, photonic ADC solutions [1], [2] can offer lower jitter and higher stability, while being compatible with photonic integration [3] where smaller size, weight and power are achieved [4].

This work focuses on a photonic-assisted ADC architecture for satellite communications based on integrated devices from silicon photonics technology and a mode locked laser (MLL) whose repetition frequency is 1 GHz. The system can optically down-convert and sample millimeter-wave carrier frequencies up to 70 GHz with typical RF signal bandwidths. In doing so, the reduced jitter enables sufficient resolution and an effective number of bits (ENoB) to successfully demodulate high modulation orders up to QAM-128.

II. System

The architecture of the system is presented in Fig. 1 (a) and it is mainly composed of: a MLL, Mach-Zehnder modulator (MZM) and a photodiode (PD). The MLL creates a train of pulses according to its repetition rate f_{rep} (Fig. 1 (b) (1)). Subsequently, the pulse train is used to optically sample a millimeter-wave signal via the MZM. The modulator is biased in quadrature and driven by the output of an arbitrary waveform generator (AWG) that generates the modulating signal at a carrier frequency f_c (Figure 1 (b) (2)). This process results in the representative spectrum shown in Fig. 1 (b) (3). Although the carriers are high-frequency signals and the repetition rate of the MLL laser is very low in comparison ($f_{rep} << f_c$), bandpass sampling can be applied because the signals are band-limited ($BW < f_{rep}/2$) and the modulation components will be located at $\Delta_f = f_c \mod f_{rep}$ from the MLL frequency component. Lastly, the on-chip PD converts the optical signal back into the electronic domain and filters the out-of-band signal. As a result, the final spectrum is solely composed of a component located in $f_{bb} = \Delta_f$, the baseband frequency. This signal is finally processed into the real time oscilloscope (RTO).

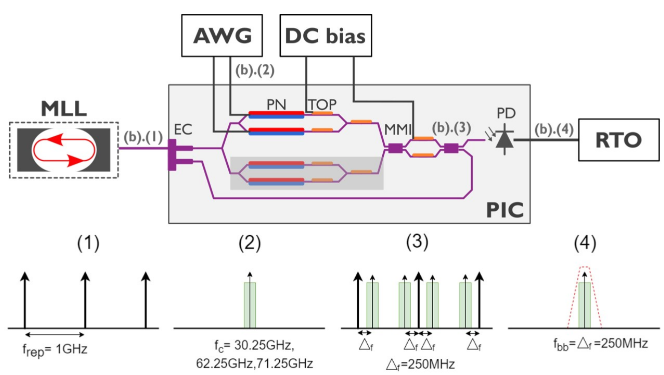

Fig. 1. System overview and spectrum representation for each step.

This procedure was tested using an MZM and a PD integrated on the same chip using imec's silicon photonics iSiPP50G technology. The PIC consists of two parallel MZMs, though only the top one is actively modulated in this experiment. The MZM achieves high-speed modulation through PN depletion phase shifters with traveling wave electrodes, while thermo-optic phase shifters (TOP) are used to bias the MZM. The TOP was tuned to bias the modulator in its quadrature point. The 3 dB bandwidth of the modulator was measured to be 37 GHz. Following the MZMs, a Mach-Zehnder interferometer (MZI) is implemented using 2x2 multimode interferometers (MMIs) and additional TOPs. The MZI is biased so that all optical power from the active MZM is directed toward the photodiode. Edge couplers (ECs) are utilized for efficient light coupling into the chip. The chip is packaged using a fiber array for optical interfacing and wire bonds for slow DC voltage connections. A 67 GHz ground-signal-signal-ground (GSSG) probe connects to the traveling-wave electrodes of the MZM. The MLL is the MENHIR-1550 model operating at 1.55 µm, featuring a clean sech²-shaped optical spectrum with a bandwidth of 1.5 THz at -3 dB and with a repetition rate of 1.0 GHz [5]. It operates in free-running mode and achieves a jitter of approximately 10.5 fs over the range of 1 kHz to 10 MHz. The modulated carriers were generated using the M8199B 256 GSa/s AWG. The result of the system was sampled and demodulated using the Keysight DSA-Z-634A RTO.

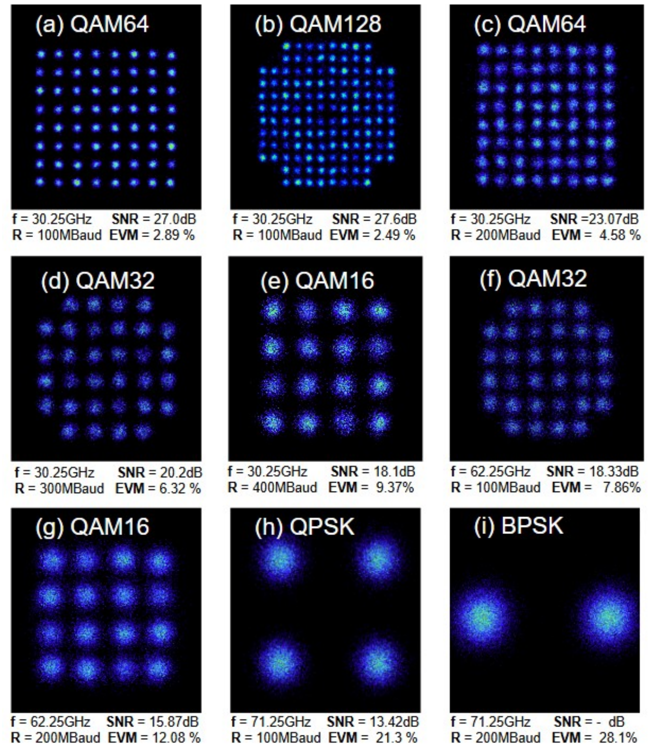

Fig. 2. Constellations diagrams for the demodulation results.

III. Experiment and results

The main goals were to downconvert, sample and demodulate a modulated high-frequency carrier. Several tests were done changing the carrier frequency, the modulation order and the data rate. Due to the 1 GHz repetition rate of the MLL and trying to avoid aliasing, the symbol rate was only selected between 100 $MBaud$ and 400 $MBaud$. The carrier frequencies were selected between 30 GHz and 70 GHz but results are presented for the frequencies $f_c = 30.25\ GHz,\ 62.25\ GHz$ or $71.25\ GHz$. The obtained constellations are presented in the Figure 2. For each case the signal-to-noise ratio (SNR) and the error vector magnitude (EVM) are shown. QAM32 with around 18 dB of SNR and 8% of EVM is achieved for $f_c = 62.25\ GHz$ with 100 $MBaud$, which in data rates is translated as 500 $Mbps$. $f_c = 71.25\ GHz$ QPSK and BPSK can also be obtained for 100 $MBaud$. For the case of $f_c = 30.25\ GHz$ higher modulation orders can be achieved for higher symbol rates, as it can be seen for the QAM128 for 100 $MBaud$ case with 27.6 dB of SNR or the QAM32 for 300 $MBaud$ and 20.2 dB of SNR. For these two last cases, speeds of 700 $Mbps$ and 1500 $Mbps$. For high-frequency signals and high symbol rates, it is more difficult to obtain high modulation orders due to the modulator bandwidth, even so, the system was able to handle with signals of up to 70 GHz.

IV. Conclusions

The system demonstrates the optical down-conversion and sampling of millimeter-wave carrier frequencies up to 70 GHz, while successfully demodulating high modulation orders up to QAM-128. The proposed architecture can find potential applications in the digitization of millimeter-wave carriers, particularly in satellite communications in K-band (18-27 GHz), Ka-band (27-40 GHz) and V-band (40-75 GHz), which are critical for enabling high capacity, low latency and high data rates. This scheme also highlights the potential of to overcome the jitter bottleneck associated with all-electronic down-conversion and sampling techniques.

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References

[1] J. Kim, M. J. Park, M. H. Perrott, and F. X. Kärtner, "Photonic subsampling analog-to-digital conversion of microwave signals at 40-GHz with higher than 7-ENOB resolution," *Opt. Express*, vol. 16, no. 21, pp. 16 509–16 515, Oct 2008. [Online]. Available: https://opg.optica.org/oe/abstract.cfm?URI=oe-16-21-16509

[2] G. C. Valley, "Photonic analog-to-digital converters," *Opt. Express*, vol. 15, no. 5, pp. 1955–1982, Mar 2007. [Online]. Available: https://opg.optica.org/oe/abstract.cfm?URI=oe-15-5-1955

[3] K. V. Gasse, Z. Wang, S. Uvin, B. D. Deckere, J. Mariën, L. Thomassen, and G. Roelkens, "Ka-band to L-band frequency down-conversion based on III–V-on-silicon photonic integrated circuits," *CEAS Space Journal*, vol. 9, no. 4, p. 531–541, Nov 2017.

[4] C. Deakin and Z. Liu, "Energy Efficiency Bounds for Photonic Analog to Digital Converters," *Journal of Lightwave Technology*, vol. 42, no. 6, pp. 1819–1828, 2024.

[5] H. Boerma, F. Ganzer, P. Runge, M. Schell, E. Fernandes, B. Rudin, and F. Emaury, "Microwave Photonic PS-Pulse and 140 GHz RF Comb Generator," *Journal of Lightwave Technology*, vol. 41, no. 11, pp. 3533–3538, 2023.