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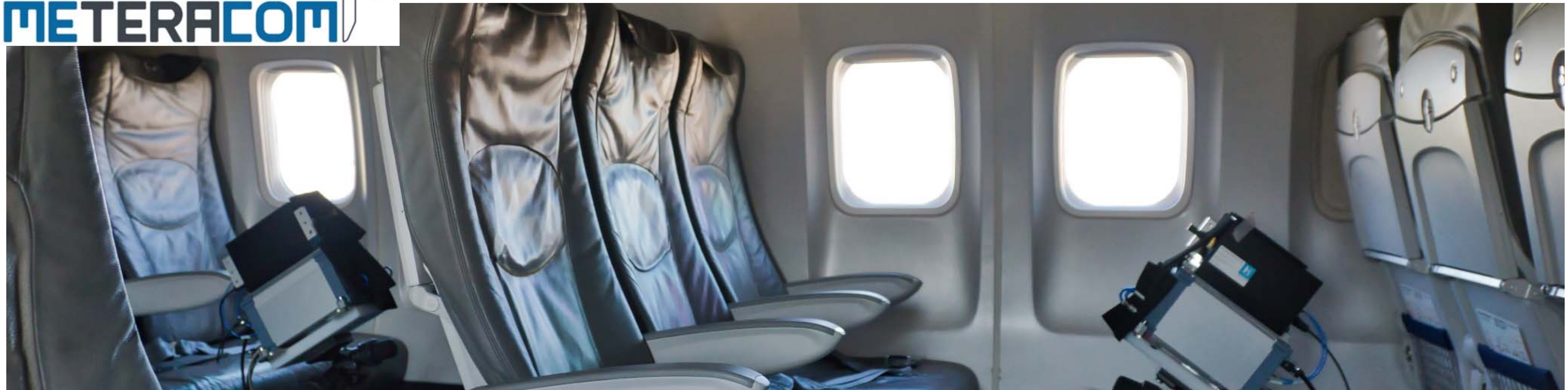
Metrology for THz Communications

2024 DUISBURG GeMiC German Microwave Conference



Review of Orthogonal Sampling for Terahertz Signal Processing

Younus Mandalawi, Souvaraj De, Thomas Kleine-Ostmann and Thomas Schneider

2nd International Workshop on Metrology for THz Communications, Duisburg, 12 March 2024

Outline

- Introduction
- Orthogonal Signal Processing
- Photonics-assisted DAC
- Photonics-assisted ADC
- Conclusion

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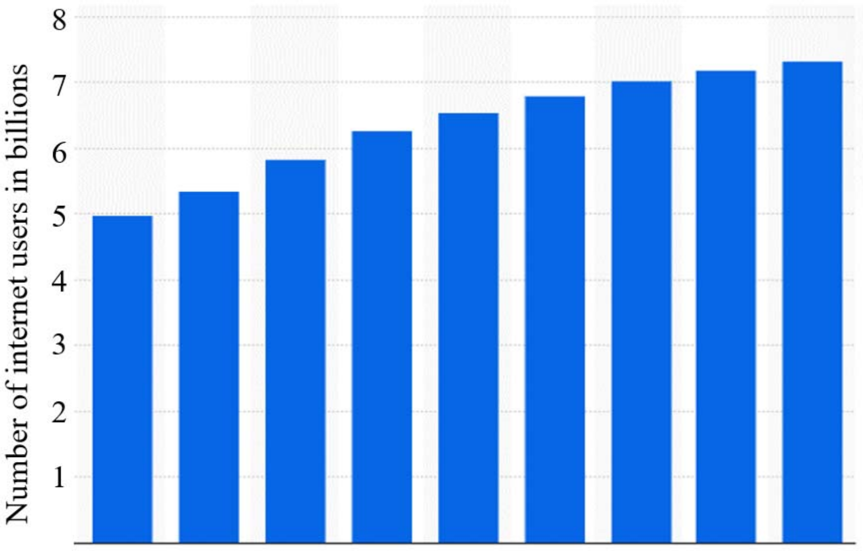
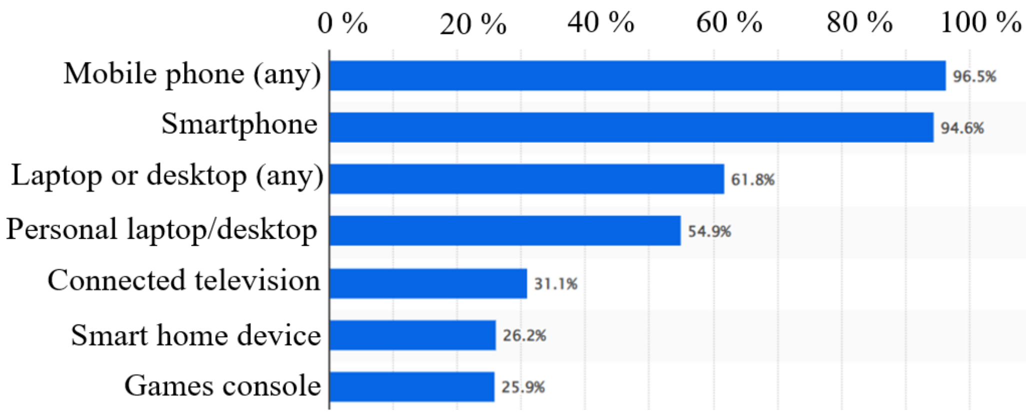
Introduction



Number of internet users worldwide from 2021 to 2029 [1]



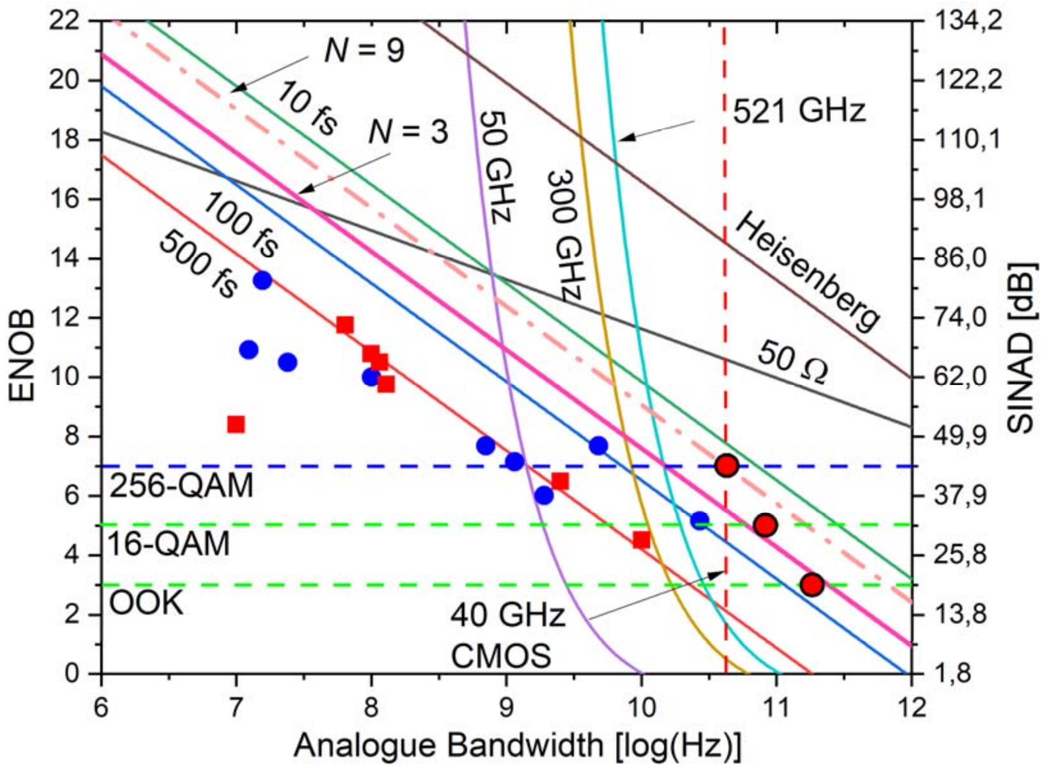
Global internet access Q3 2023, by device [2]

- Forecasted 7.2 billions internet users worldwide in 2029 [1]. 96.5 % of users have internet access via mobile phone [2].
- Measurement and processing of data with increasing bandwidths has been the spotlight of many researches.

[1] https://www.statista.com/forecasts/1146844/internet-users-in-the-world
[2] https://www.statista.com/statistics/1289755/internet-access-by-device-worldwide/

Introduction

- Conventional electronics-based digital-to-analog converters (EDAC) in the transmitter and analog-to-digital converters (EADC) in the receivers have become a bottleneck in meeting this demand.
- The next targeted data rate is around 1 Tbps [3].
- Fast electronic switches, beside the clock jitter it suffers from aperture jitter.
- The analog bandwidths and resolutions in effective number of bits (ENOB), or signal to noise and distortion ratio (SINAD) required to reach 1Tb/s signal (● red dots) are higher than what the state of the art electronic ADCs can provide as per the VLSI (● blue dots) and ISSCC (■ red squares) conferences in 2022 [4].



[3] Schneider, T. (2023). Towards Terabit Receivers for Optical and Wireless Communications. IEEE Communications Magazine, 61(August), 169–174. https://doi.org/10.1109/MCOM.001.2200598

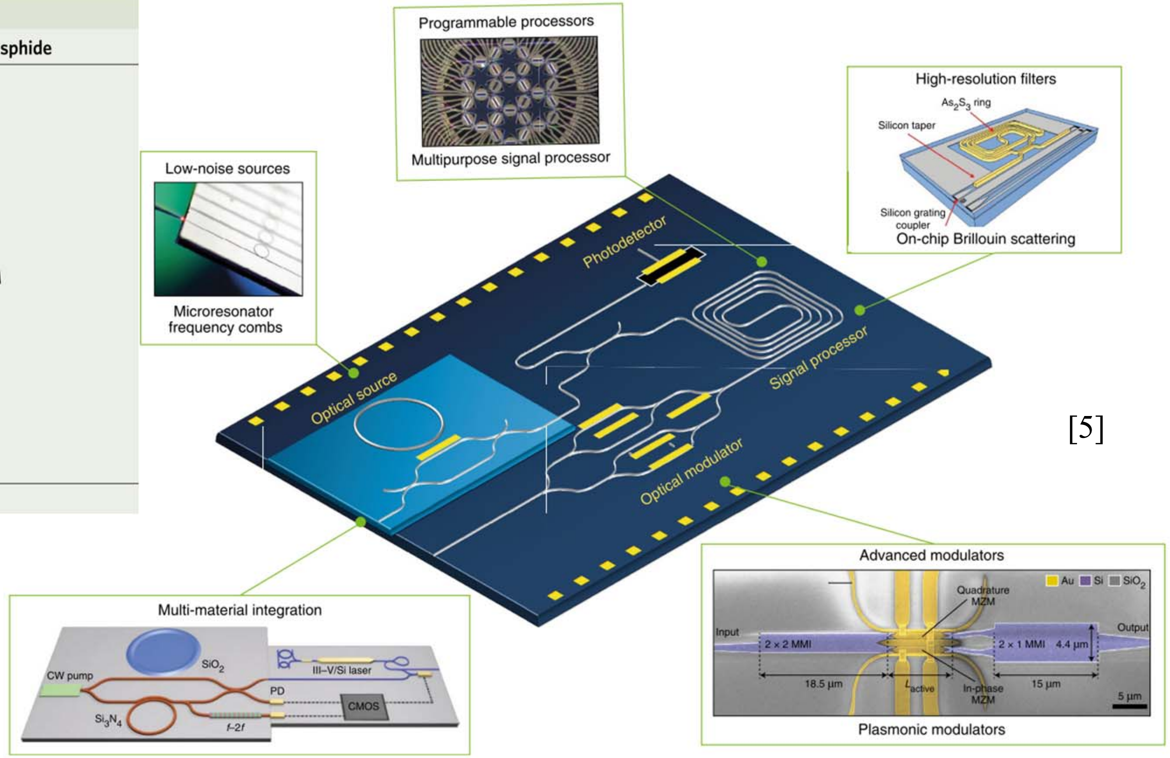
[4] B. Murmann, "ADC Performance Survey 1997–2022," available: http://web.stanford.edu/~murmann/adcsurvey.html; accessed 12-15-2022.

Introduction

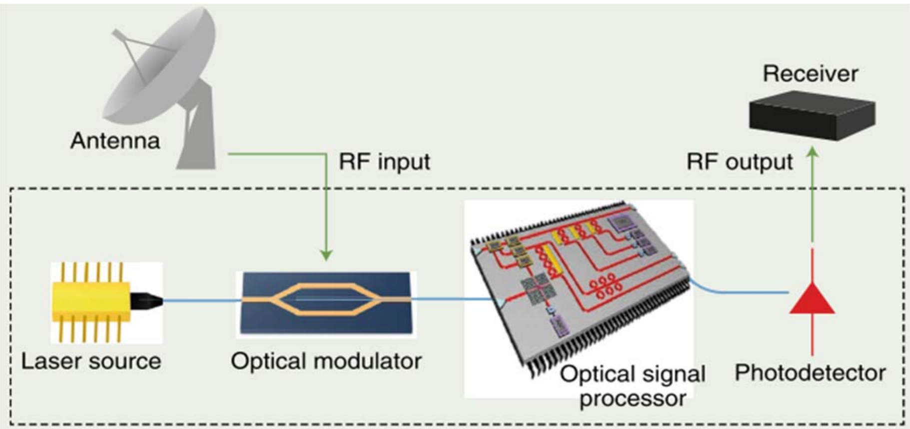
Table 1 | Parameters of the main material platforms relevant for MWP

	Silicon-on-insulator	Silicon nitride	Indium phosphide
Refractive index	3.5	2.1	3.1
Waveguide refractive index contrast (%)	>100	>25	10
Bending radius (μm)	5-100	50-150	100
Loss (dB cm^{-1})	0.1-3	0.01-0.2	1.5-3
Nonlinear index (m^2 W^{-1})	4.5×10^{-18}	2.6×10^{-19}	1.5×10^{-17}
Two-photon absorption (cm GW^{-1})	0.25	Negligible	60
Modulator technology (maximum speed)	Free-carrier plasma dispersion (30 GHz)	With graphene (30 GHz) With PZT (33 GHz)	QCSE-EAM (55 GHz)
Detector	Ge (50 GHz)	N/A	40 GHz
Laser output power	N/A	N/A	>20 mW
Fibre-to-chip coupling loss (dB)	2	0.5	3
CMOS compatibility	Excellent	Good	N/A
Optical amplification	N/A	N/A	>20 dB

EAM, electro-absorption modulator; PZT, lead zirconate titanate; QCSE, quantum-confined Stark effect. N/A, not applicable.



[5]



[6]

[5] D. Marpaung, J. Yao, and J. Capmany, “Integrated microwave photonics,” Nat. Photonics, vol. 13, no. 2, pp. 80–90, 2019.
[6] Zhou, Y.; Wang, L.; Liu, Y.; Yu, Y.; Zhang, X. Microwave Photonic Filters and Applications. Photonics 2023, 10, 1110.

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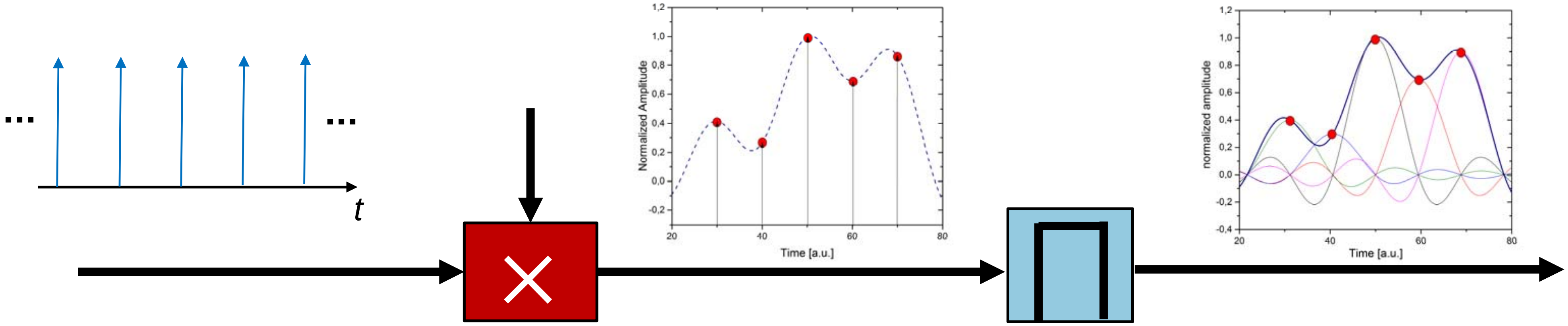
Orthogonal Signal Processing

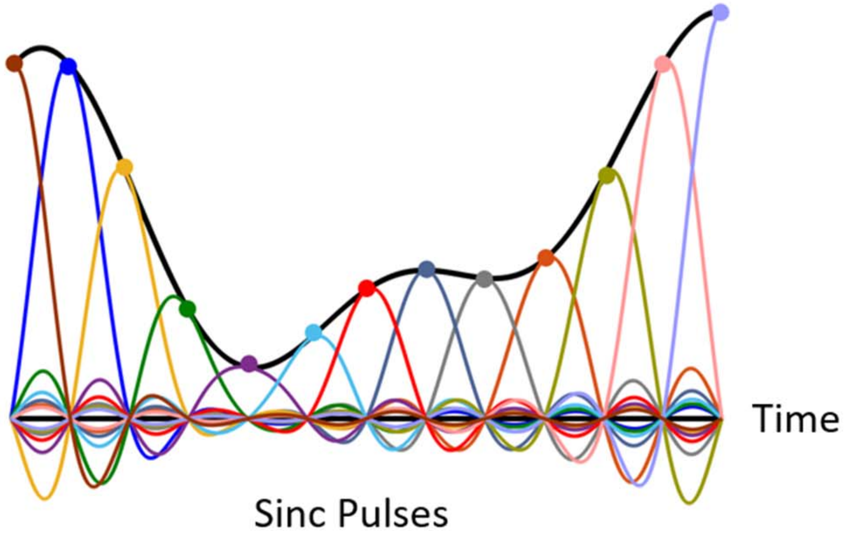
Concept of digital-to-analog conversion (DAC)

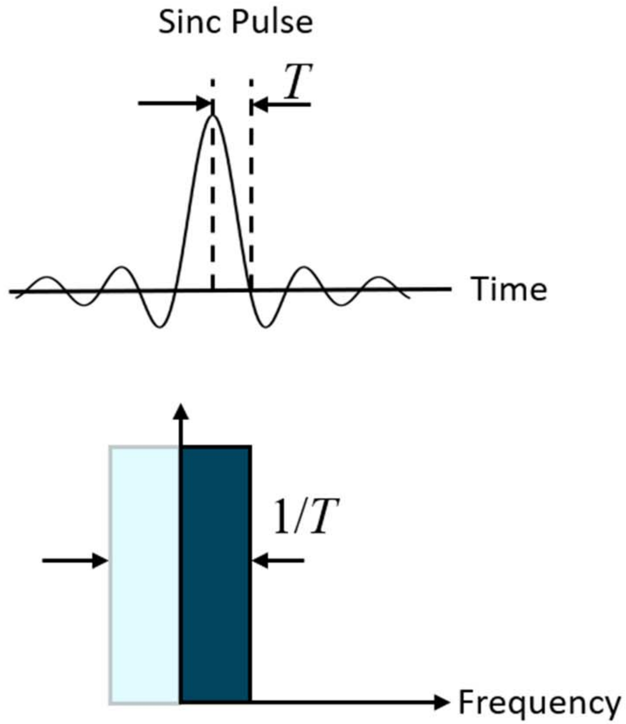
$$s(t) = \sum_{k=-\infty}^{\infty} s\left(\frac{k}{\Delta f_s}\right) sinc(\Delta f_s t - k)$$



[3] Schneider, T. (2023). Towards Terabit Receivers for Optical and Wireless Communications. IEEE Communications Magazine, 61(August), 169–174.
[7] J. Meier, *et. al.*, "Precise, High-Bandwidth Digital-to-Analog Conversion by Optical Sinc-Pulse Sequences," *GeMiC 2019 - 2019 Ger. Microw. Conf.*, pp. 166–169, 2019.
[8] J. Meier, *et. al.*, "Orthogonal Full-Field Optical Sampling," *IEEE Photonics J.*, vol. 11, no. 2, 2019.

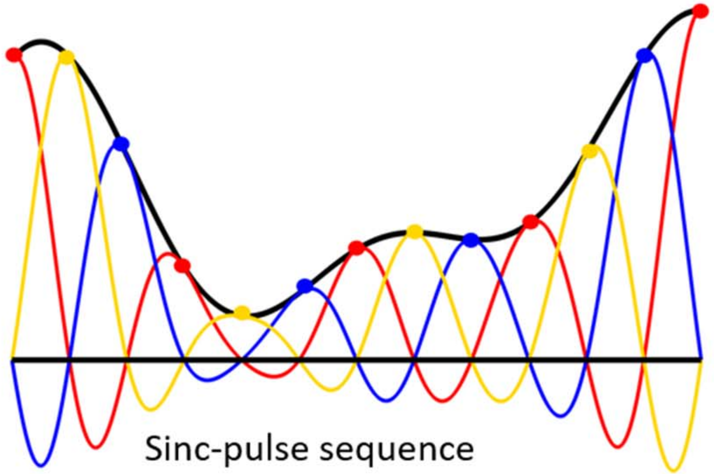
Orthogonal Signal Processing





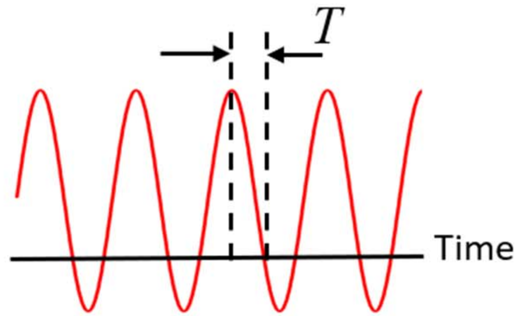
Orthogonal Signal Processing

- With two zero-crossing, each sinc-pulse sequence carries 1/3 of the total sampling points.

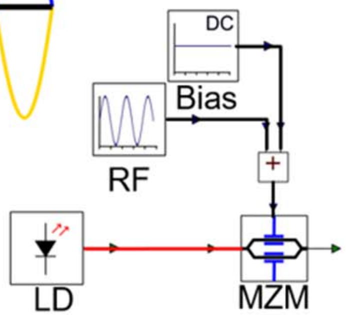


Sinc-pulse sequence

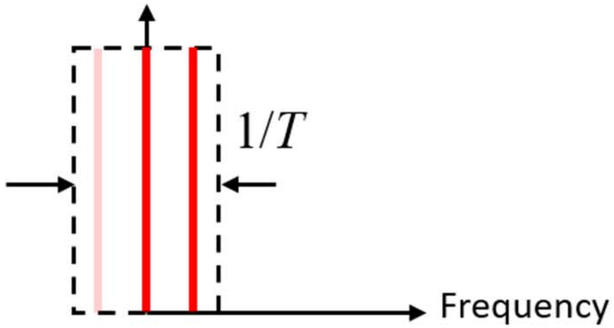
Two zero-crossings
Sine + addional dc bias



Sinc-pulse sequence



Optical sinc-pulse sequence generation



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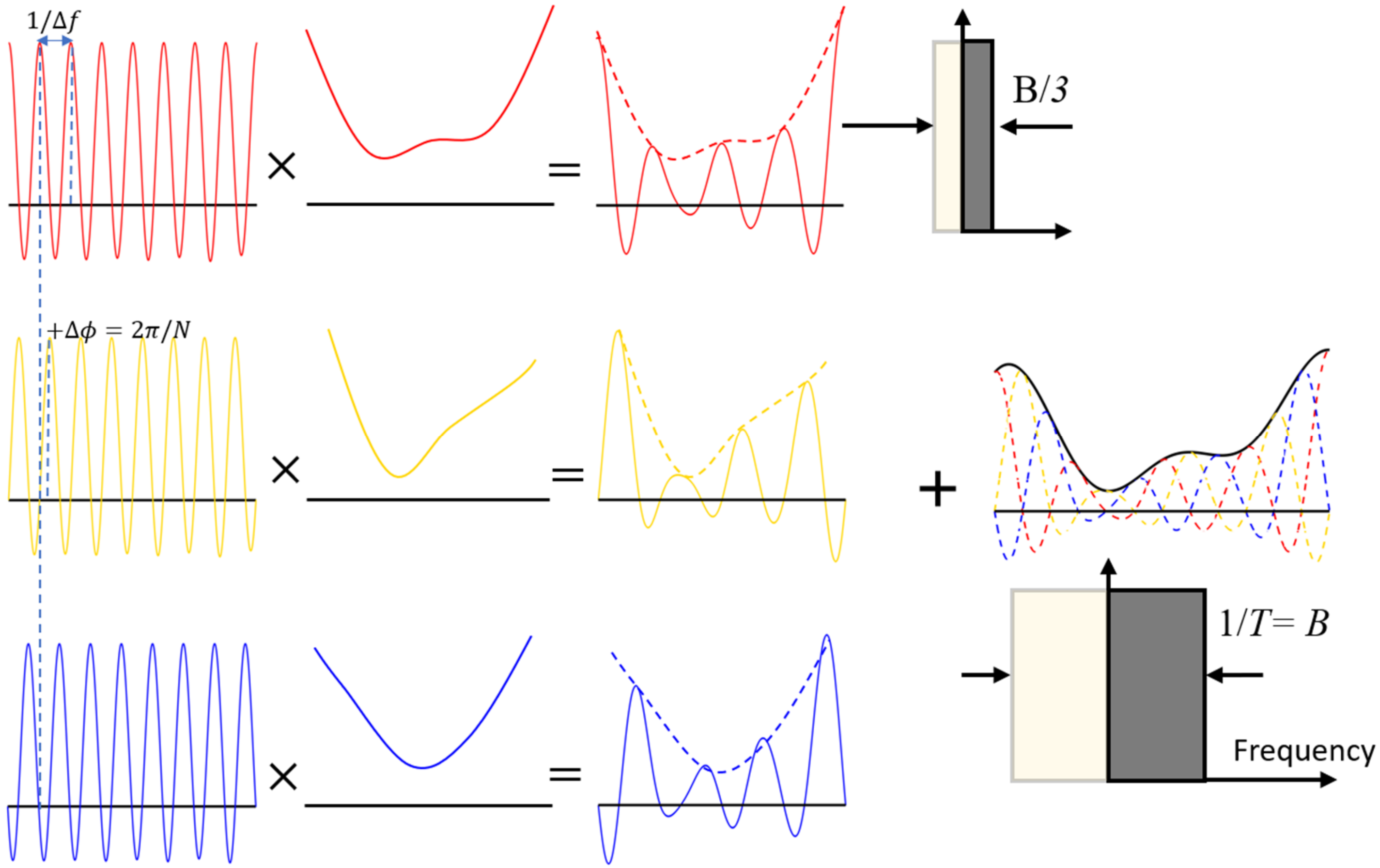
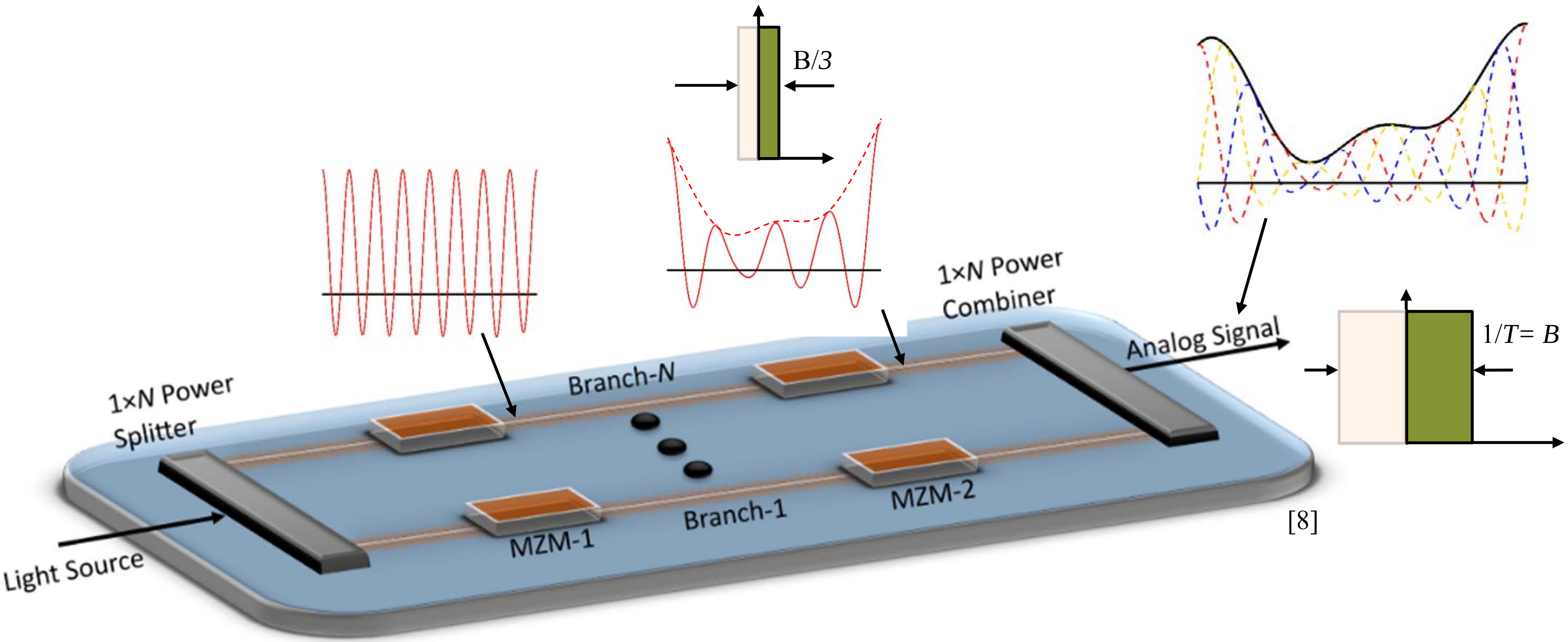
High-bandwidth signal generation from low-bandwidth electronics

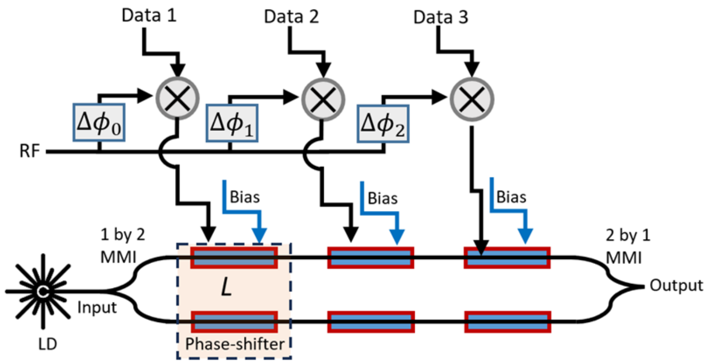


High-bandwidth signal generation from low-bandwidth electronics

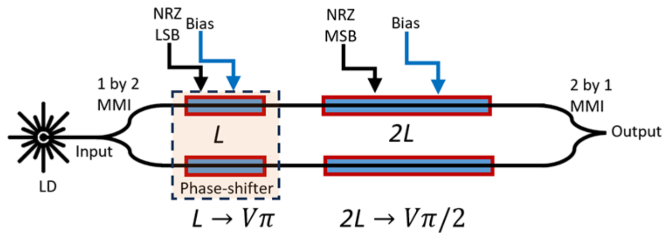


[7] J. Meier, *et. al*., "Precise, High-Bandwidth Digital-to-Analog Conversion by Optical Sinc-Pulse Sequences," *GeMiC 2019* ,pp. 166–169, 2019.
[10] K. Singh *et al*., "Emulation of integrated high-bandwidth photonic AWG using low-speed electronics," in *Next-Generation Optical Communication*, 2022, p. 29.
[11] K. Singh, *et. at*., "Photonic Arbitrary Waveform Generation with Three Times the Sampling Rate of the Modulator Bandwidth," *IEEE Photonics Technol. Lett*., vol. 32, no. 24, pp. 1544–1547, 2020.

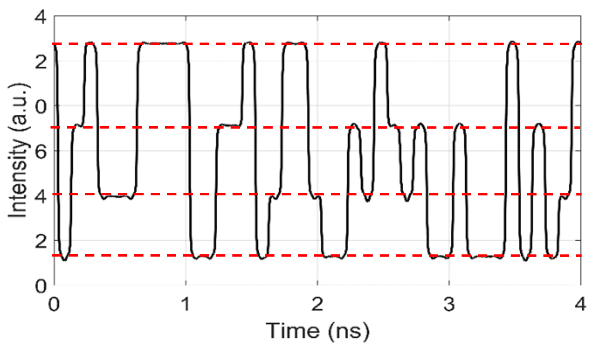
Concept of segmented modulator



LD: laser diode
MMI: multi-mode interference
RF: radio-frequency oscillator
$\Delta\phi$: phase shift
L : length

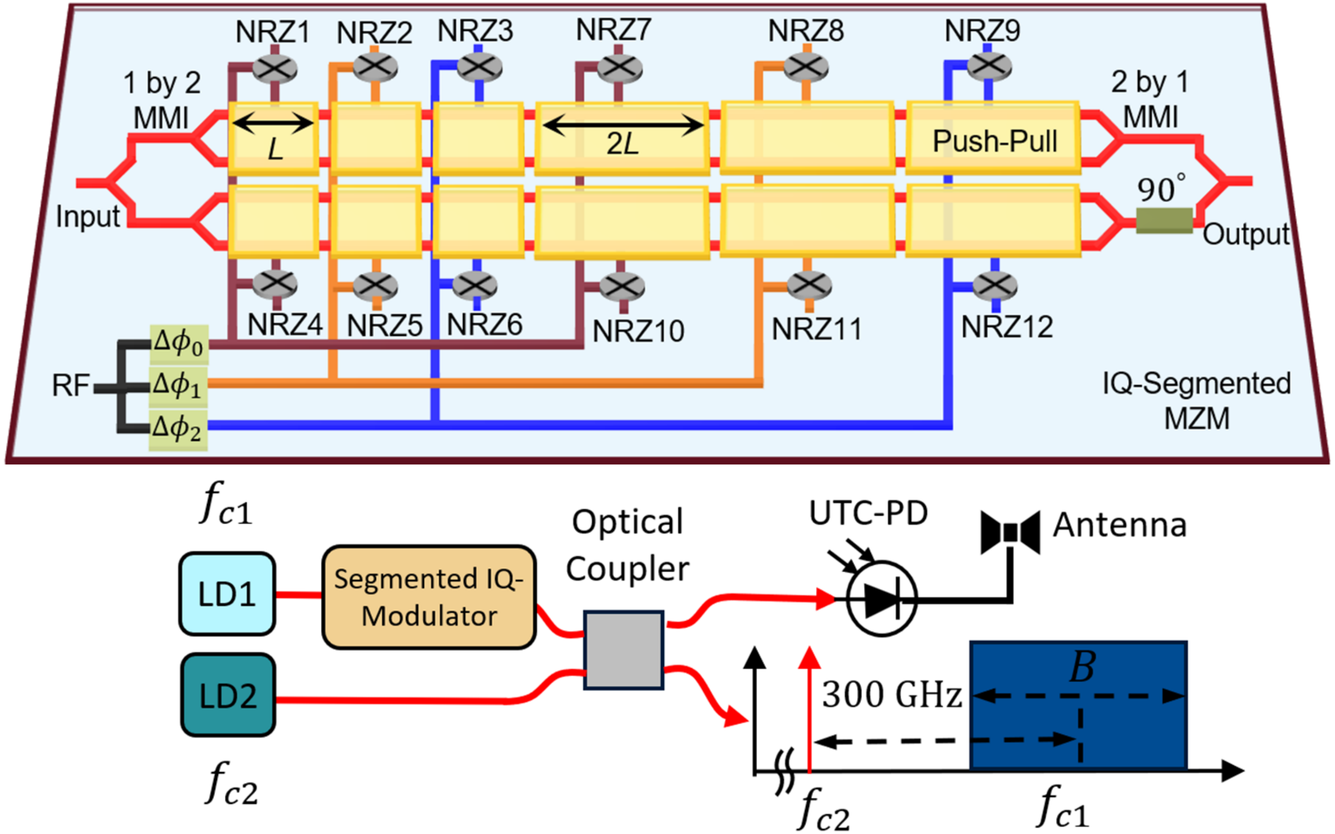


- PAM 4 can be generated using 2 NRZ signals.
- Implemented using 2 segments MZM



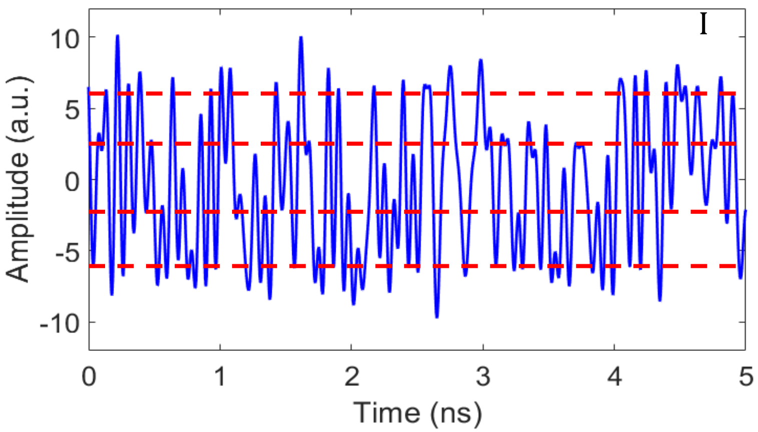
Time domain

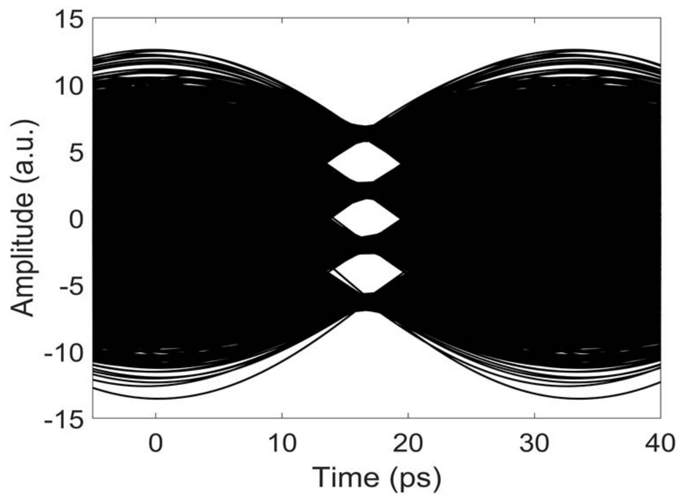
Segmented IQ-Modulator for Orthogonal Sampling and High-Data Rate Signal Generation

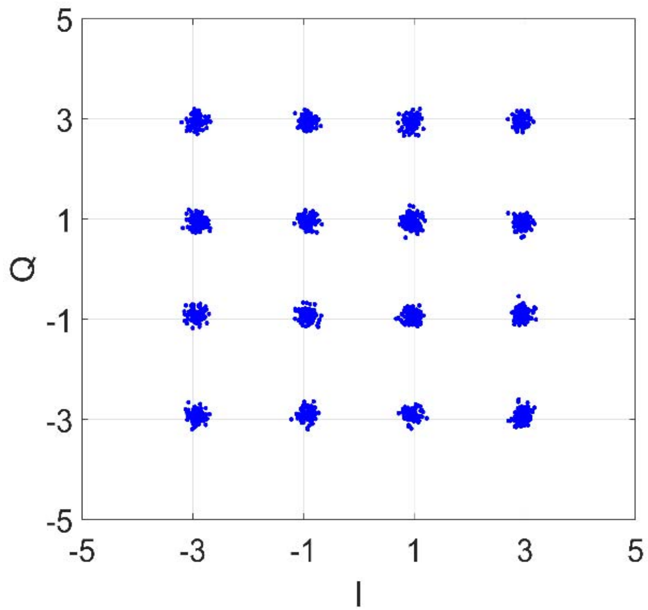


[12] Y. Mandalawi, *et. al*., "Integrated Segmented IQ-Modulator for Orthogonal Sampling and Multi-Level High-Bandwidth Signal Generation," Optics letter, 2024 (submitted)

16-QAM 30 GBd generated from 5 GHz NRZs







- 30 GBd 16-QAM signal from 5 GHz Nyquist filtered NRZ input signals .

Q-factor = 19.59 dB
BER = 7.21E-22

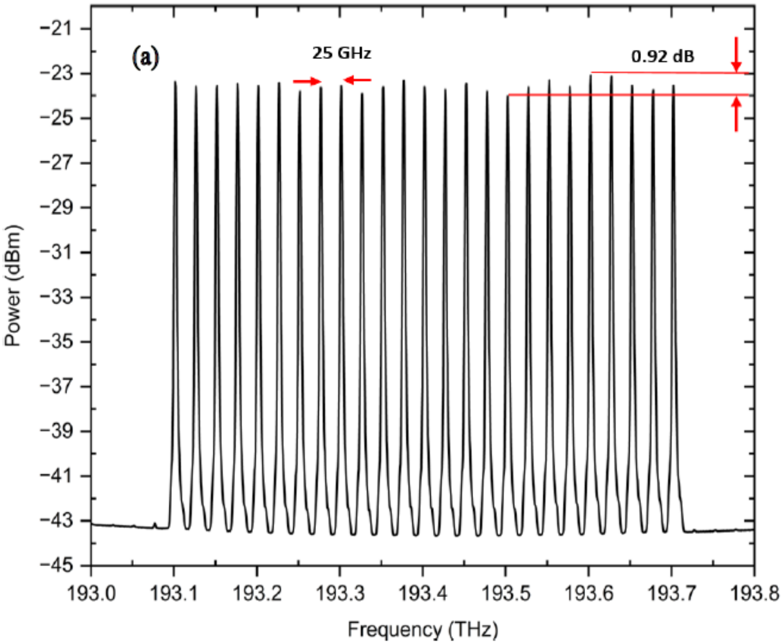
Constellation diagram of 16-QAM

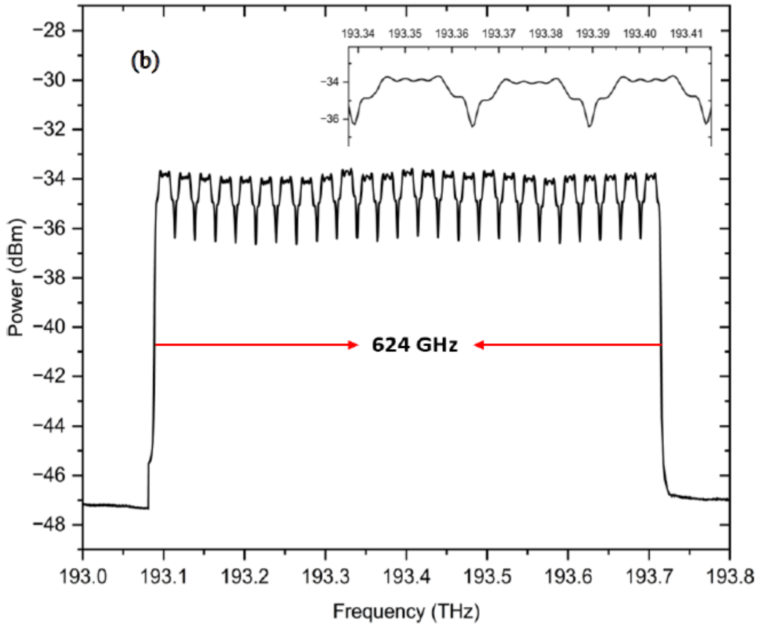
Simulated using Lumerical from Ansys

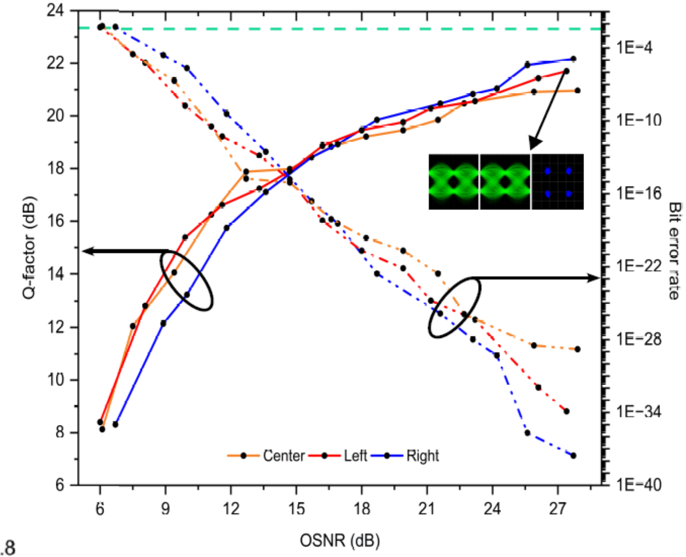
[12] Y. Mandalawi, *et. al.*, “Integrated Segmented IQ-Modulator for Orthogonal Sampling and Multi-Level High-Bandwidth Signal Generation,” Optics letter, 2024 (submitted)

Processing of High-Bandwidth Signals

Detection of a 624 GHz, QPSK, 1.2 Tbit/s rectangular bandwidth channel with 4 GHz electronics







[17] A. Venugopalan, P. Mandal, J. Meier, K. Singh, and T. Schneider, “Detection of a 624 GHz, QPSK, 1.2 Tbit/s rectangular bandwidth channel with 4 GHz electronics,” *2023 IEEE Photonics Conf.*, pp. 1–2, 2023.

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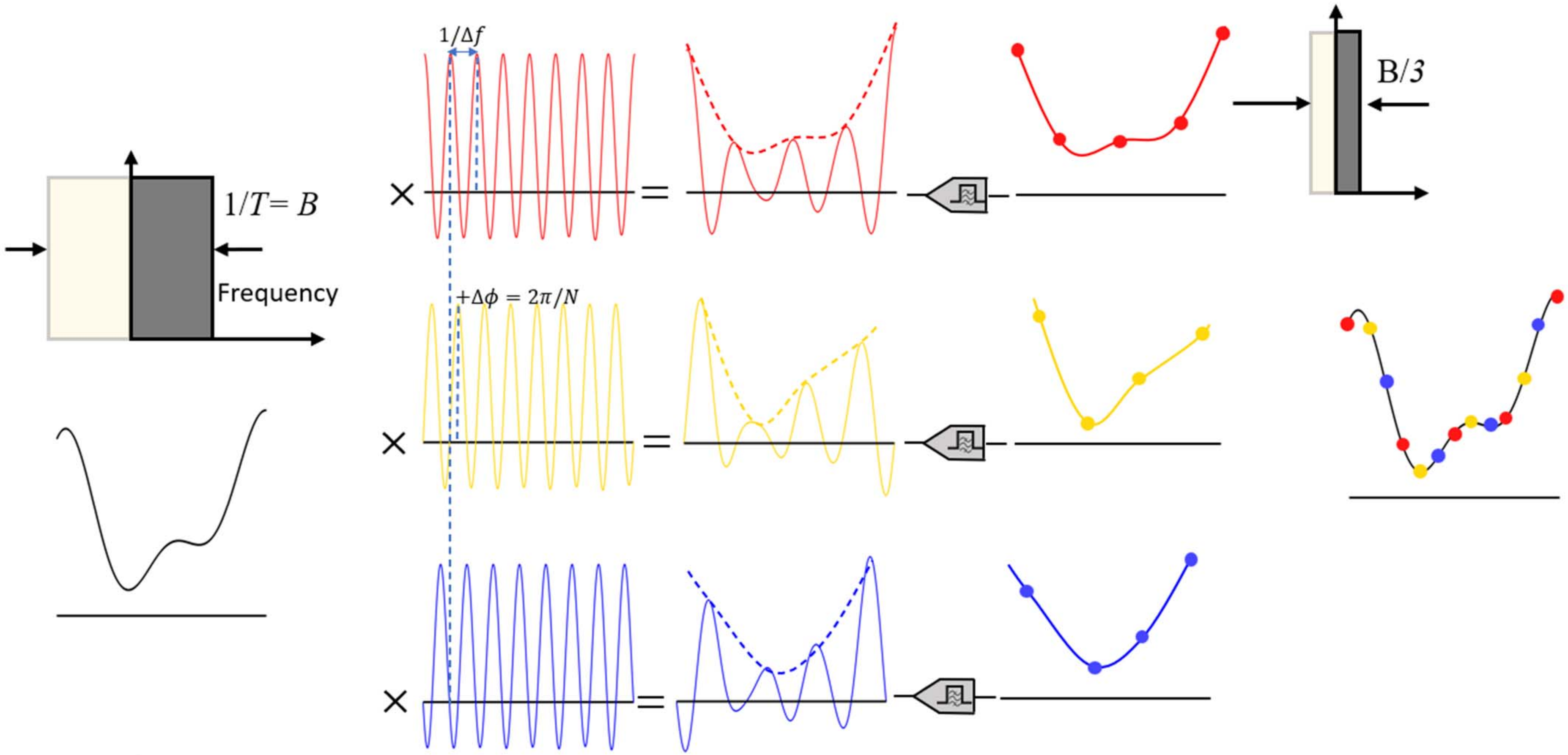
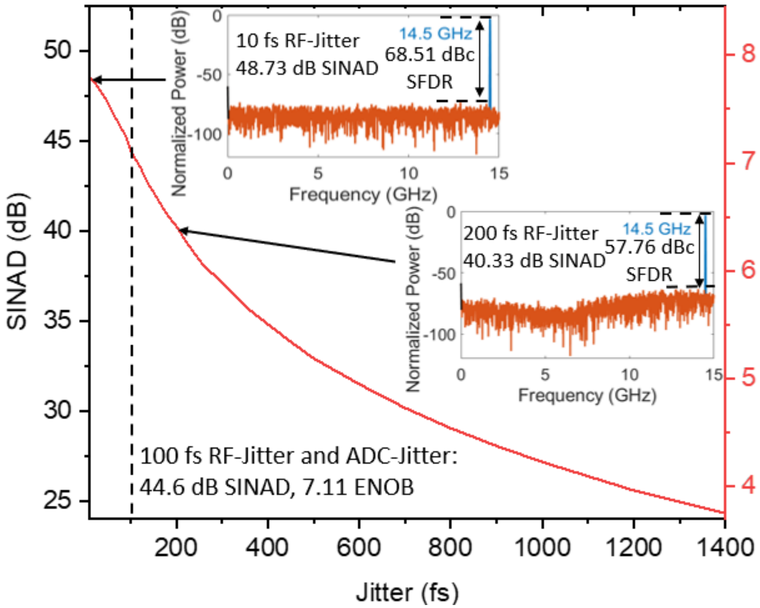
Photonics-Assisted ADC with High-Bandwidth and Improved Resolution

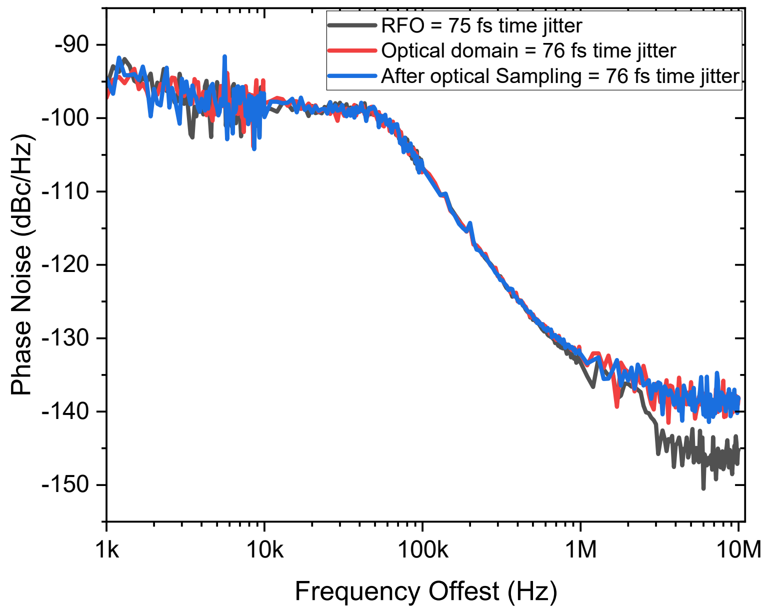


Analysis of Resolution Improvement of Photonics-Assisted ADC



SINAD and ENOB vs RF jitter

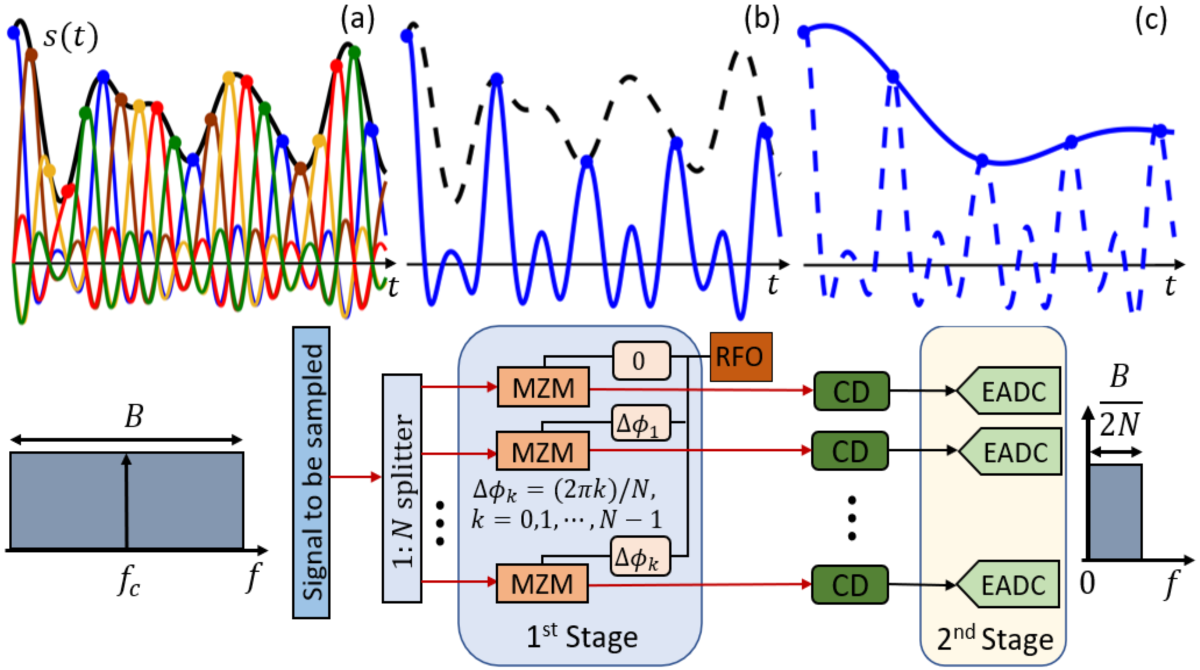
RIN level = -160 dBc/Hz, EADC jitter = 100 fs
LW= 100 Hz , Comb B= 30 GHz
N= 3 lines, Signal-to-sample= 14.5 GHz



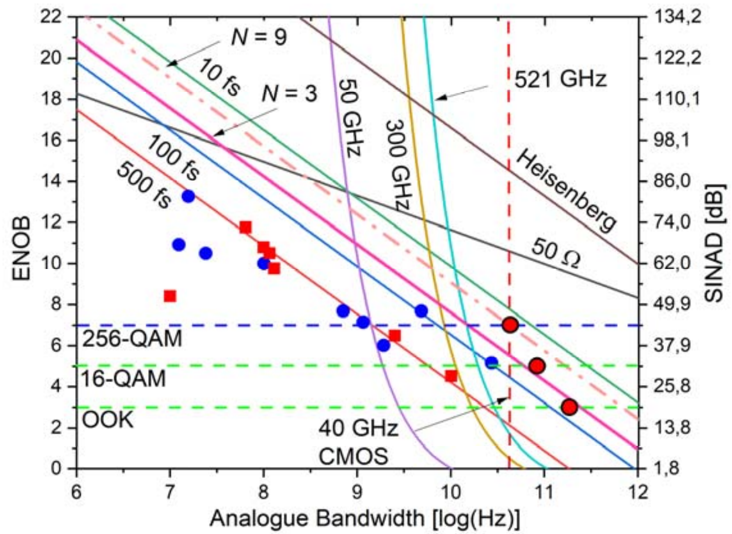
- No additional phase noise is added to the RFO source.
- While the current EADC have a total jitter of around 100 fs, even on integrated platform frequency oscillators can show jitter values of 20 fs [15].

[13] Y. Mandalawi, *et. al*., "Analysis of Bandwidth Reduction and Resolution Improvement for Photonics-Assisted ADC," J. Light. Technol. 41, 6225–6234 (IEEE, 2023).
[18] S. Levantino, "Recent Advances in High-Performance Frequency Synthesizer Design," in Proceedings of the Custom Integrated Circuits Conference, IEEE, Apr. 2022, pp. 1–7.

Photonics-Assisted ADC



[13]

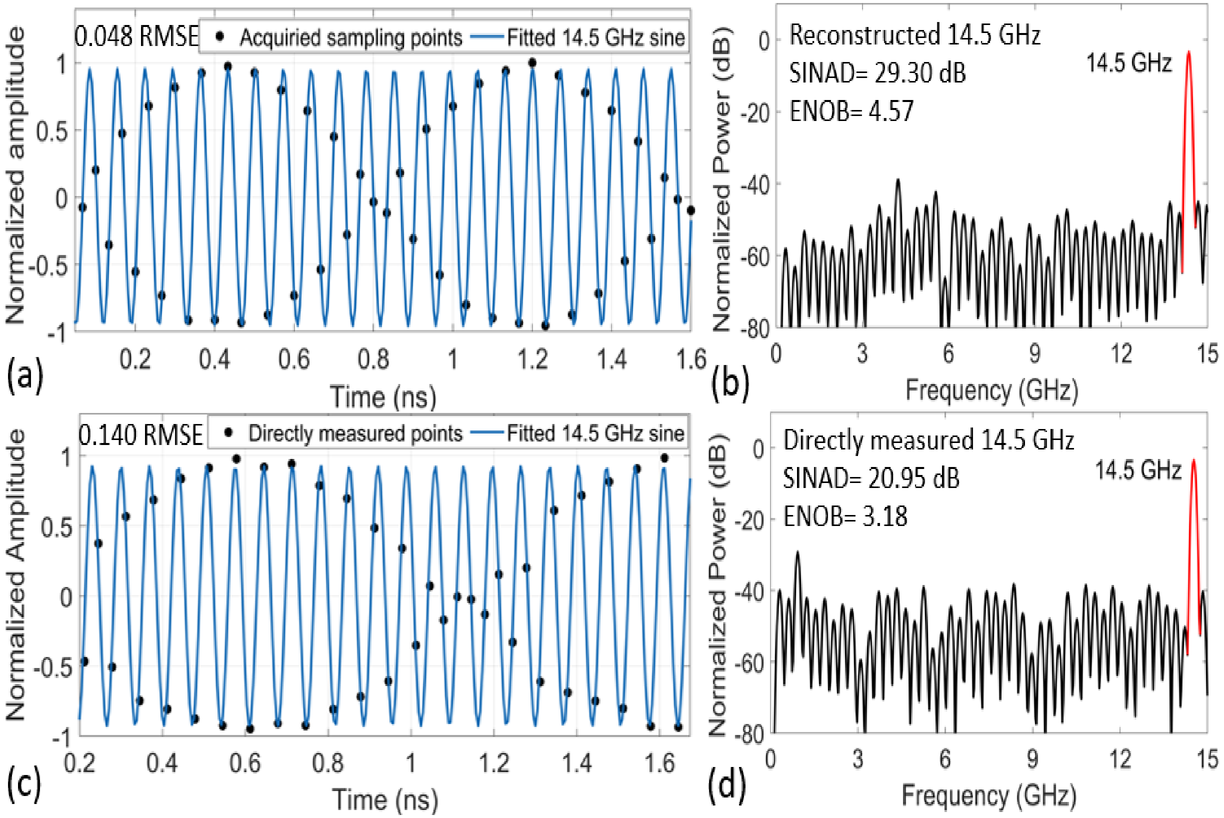


[3]

RFO: Single tone radio-frequency oscillator
MZM: Mach–Zehnder modulator
CD: Coherent detection
EADC: Electronic analogue-to-digital converter

[3] Schneider, T. (2023). Towards Terabit Receivers for Optical and Wireless Communications. IEEE Communications Magazine, 61(August), 169–174. https://doi.org/10.1109/MCOM.001.2200598
[13] Y. Mandalawi, *et. al.*, "Analysis of Bandwidth Reduction and Resolution Improvement for Photonics-Assisted ADC," J. Light. Technol. 41, 6225–6234 (IEEE, 2023).

Experimental Validation of Photonics-Assisted ADC



[13]

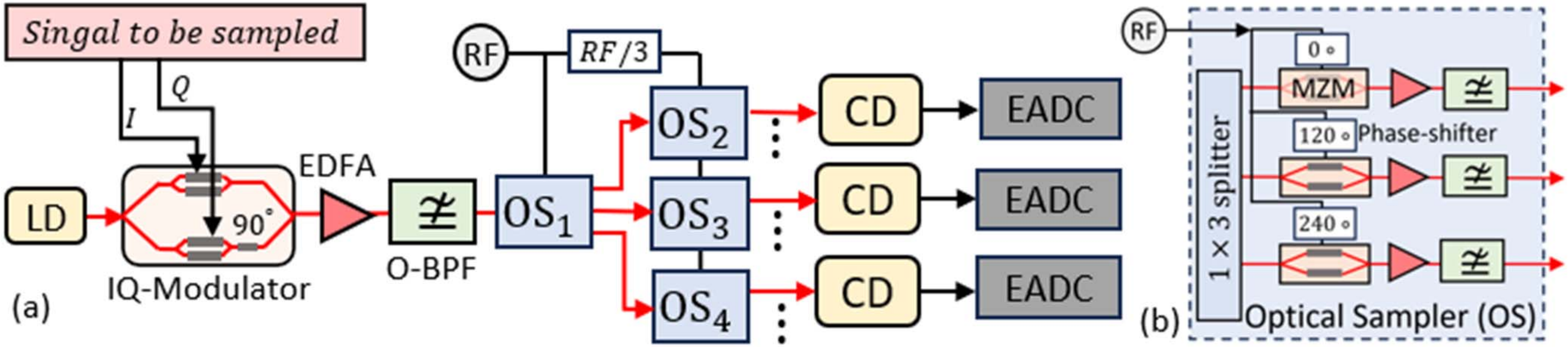
Sampling with only EADC
SINAD = 20.95 dB
ENOB = 3.18
Sampling with photonic-assisted ADC
SINAD = 29.30 dB
ENOB = 4.57

+ 8.35 dB SINAD
+ 1.4 ENOB

RF jitter= 75 fs
EADC jitter = 1 ps
RIN level = -135 dBc/Hz
LW= 100 Hz
Comb B= 30 GHz
N= 3 lines
Signal-to-sample= 14.5 GHz
Tested sampling points = 1000

[13] Y. Mandalawi, *et. al*., "Analysis of Bandwidth Reduction and Resolution Improvement for Photonics-Assisted ADC," J. Light. Technol. 41, 6225–6234 (IEEE, 2023).

Photonics-Assisted ADC Scalability and Reconfigurability



[15]

- Easy system scaling to higher number of branches.
- Easier to design integrated system with unified optical sampling block.
- The required electro-optic bandwidth of the modulator is reduced after each stage. Only three modulator required to be high bandwidth.

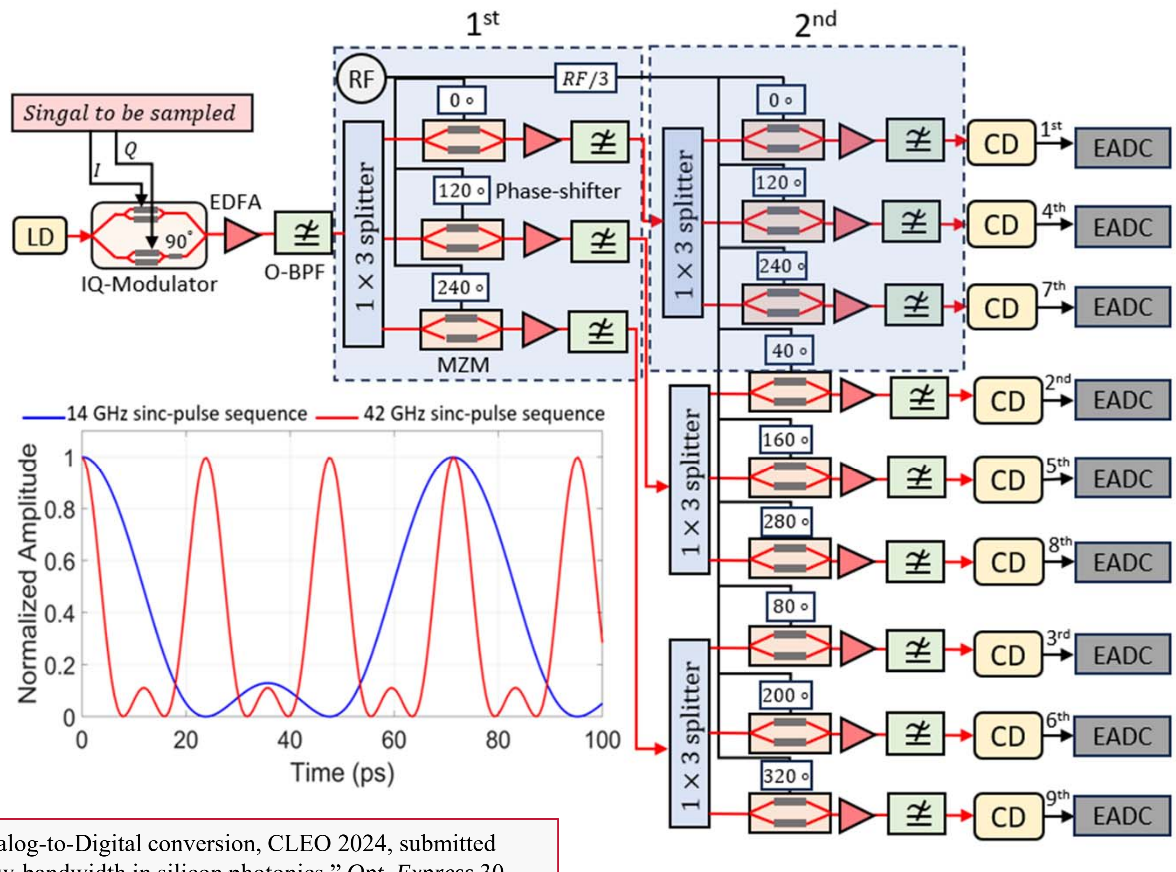
[15] Y. Mandalawi, *et. al.*, Multi-stage Optical Sampling for Photonics-assisted Wideband Signal Analog-to-Digital conversion, CLEO 2024, submitted

Photonics-Assisted ADC Scalability and Reconfigurability

- Two stages optical sampler with 126 GSs and 63 GHz bandwidth.
- First with 3-branche using 3-line comb of 42 GHz spacing.
- Second with three 3-branche using 3-line comb of spacing 14 GHz
- With the available 100 GHz 3 dB electrical bandwidth integrated optical modulator, 300 GS is possible.
- With 16 GHz 3 dB bandwidth modulator, 90 GHz 3-line comb was generated [10].

OptiSystem
Optiwave

Simulated using OptiSystem from Optiwave



Two-stages optical sampling

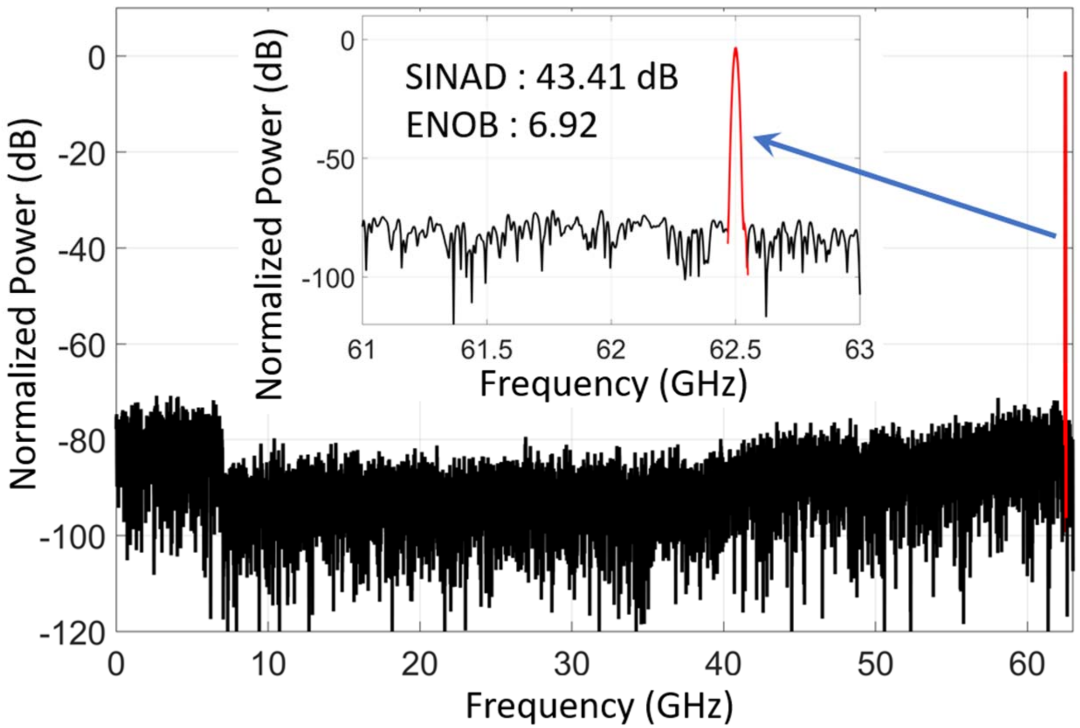
[15] Y. Mandalawi, *et. al*., Multi-stage Optical Sampling for Photonics-assisted Wideband Signal Analog-to-Digital conversion, CLEO 2024, submitted
[16] A. Misra, *et. al*., "Reconfigurable and real-time high-bandwidth Nyquist signal detection with low-bandwidth in silicon photonics," *Opt. Express* 30, 13776 (2022).

Photonics-Assisted ADC

A 62.5 GHz sine is sampled with 126 GSs.

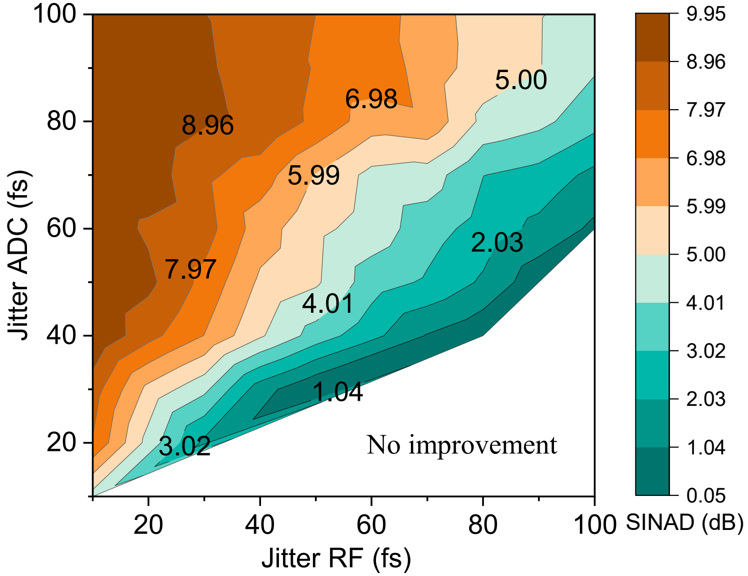
Sampling with only EADC
SINAD = 27.04 dB
ENOB = 4.20
Sampling with photonic-assisted ADC
SINAD = 43.41 dB
ENOB = 6.92

+ 16.37 dB SINAD
+ 2.72 ENOB

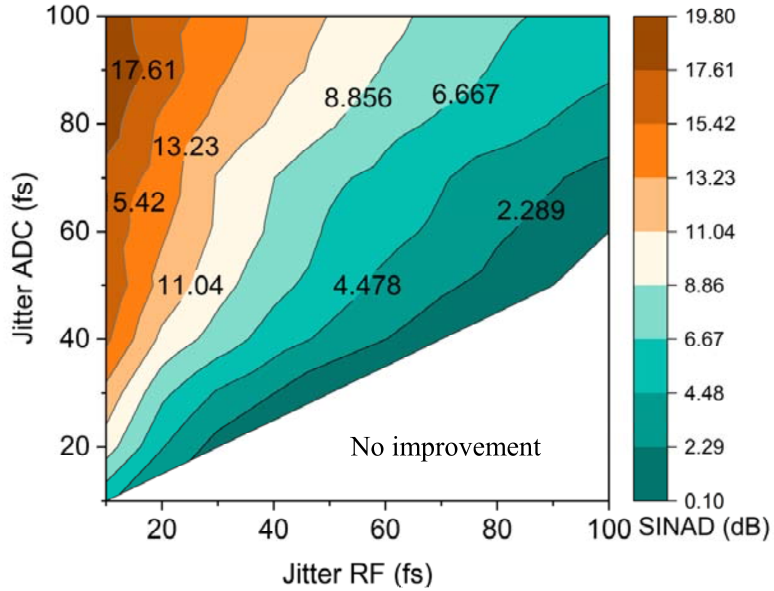


RF jitter= 10 fs
EADC jitter = 100 fs
RIN level = -160 dBc/Hz
LW= 100 Hz
Comb B= 126 GHz
N= 9 lines
Signal-to-sample= 62.5 GHz
Tested sampling points = 8190

Photonics-Assisted ADC with High-Bandwidth Modulated Data



At 20 fs RF jitter and 100 fs EADC jitter, around 9 dB SINAD improvement is expected from PADC EADC when sampling 62 GHz with 126 GSs using 3-branch



At 20 fs RF jitter and 100 fs EADC jitter, around 16.5 dB SINAD improvement is expected from PADC EADC when sampling 62 GHz with 126 GSs using 9-branch

$$SINAD = 10Log_{10}\left(\frac{1}{(\pi f \sigma_{RF})^2 + (2\pi \frac{f}{3}\sigma_{ADC})^2}\right), ENOB = \frac{SINAD - 1.76}{6.02}$$

[11] Y. Mandalawi, *et. al.*, “Analysis of Bandwidth Reduction and Resolution Improvement for Photonics-Assisted ADC,” J. Light. Technol. 41, 6225–6234 (IEEE, 2023).

Conclusion

- Increasing data rates require high analog bandwidth digital signal processing.
- The standard CMOS has a restricted bandwidth due to some impairments such as time jitter.
- The presented orthogonal sampling method using sinc-pulse sequences works error free for ideal components.
- The proposed parallelization base orthogonal sampling photonics-assisted DAC and ADC system can generate or receive high-bandwidth signal with low-bandwidth electronics with improvement resolution.
- With the assistance of the mature integrated photonics which is compatible with CMOS platform, much higher signal bandwidths can be processed in wireless and THz applications.

Thank you very much for your Attention

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