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2024 DUISBURG GeMiC German Microwave Conference

Photonically Assisted Sampling Circuits

Maxim Weizel, J. Christoph Scheytt

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

Outline

- Motivation
- Selected Architectures
- Conclusion

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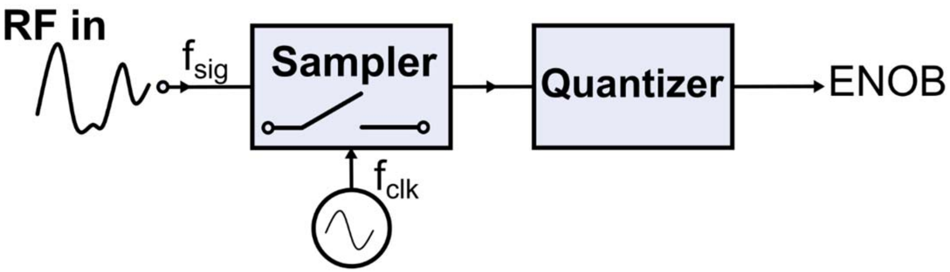
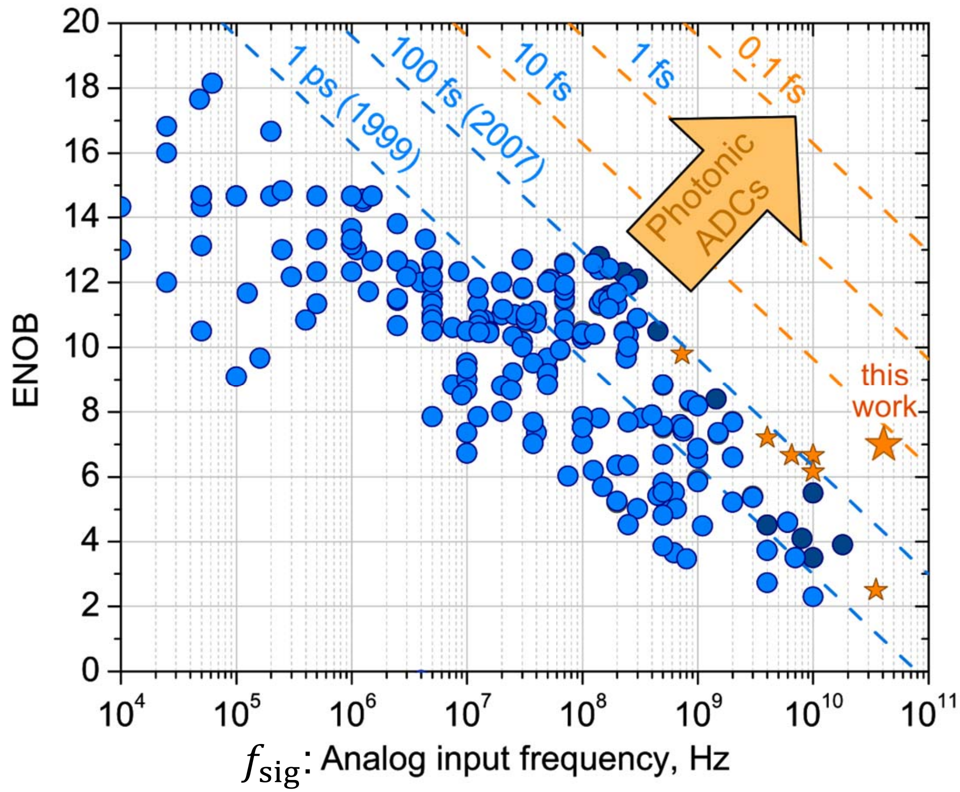
Motivation – Jitter in Data Converters



- Quantization Noise and SNR:

$$\mathrm{ENOB} = \frac{\mathrm{SNR_{dB}} - 1.76\ \mathrm{dB}}{6.02}$$

  - ENOB: Effective Number of Bits



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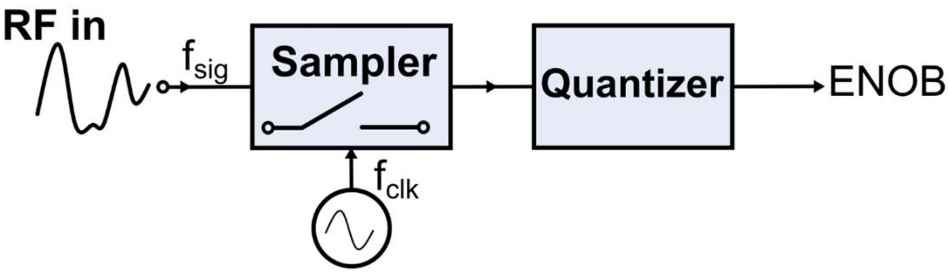

- Quantization Noise and SNR:

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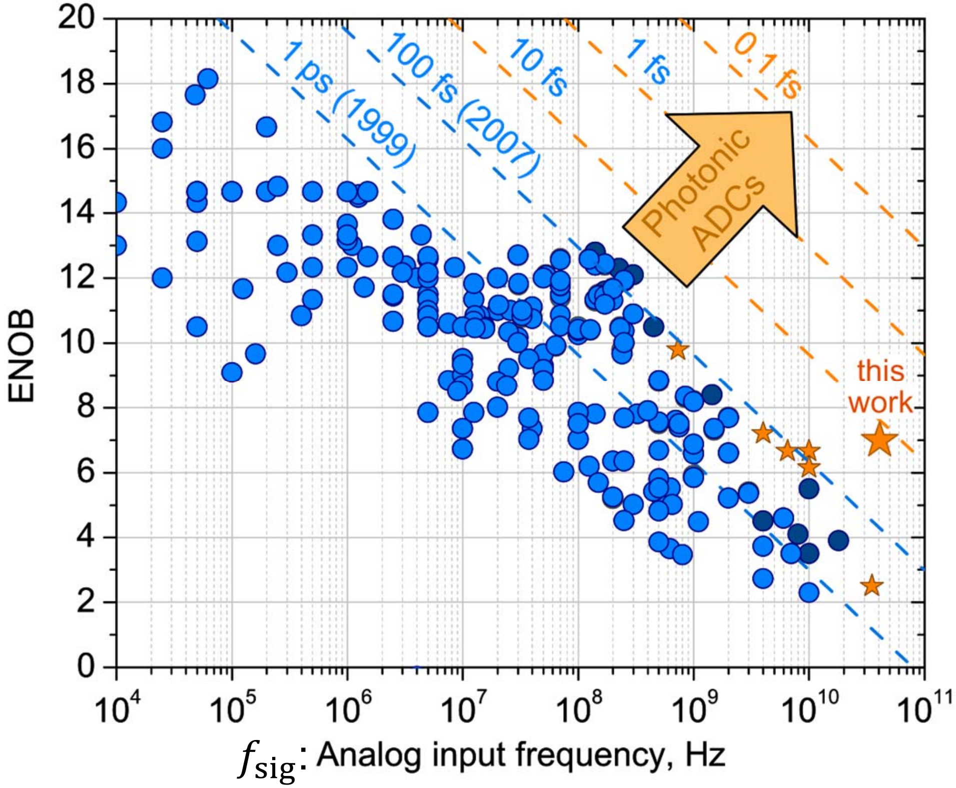
- RMS Jitter σ_{ji} is related to the SNR:

$$\text{SNR} = -20\log(2\pi f_{sig}\sigma_{ji})$$



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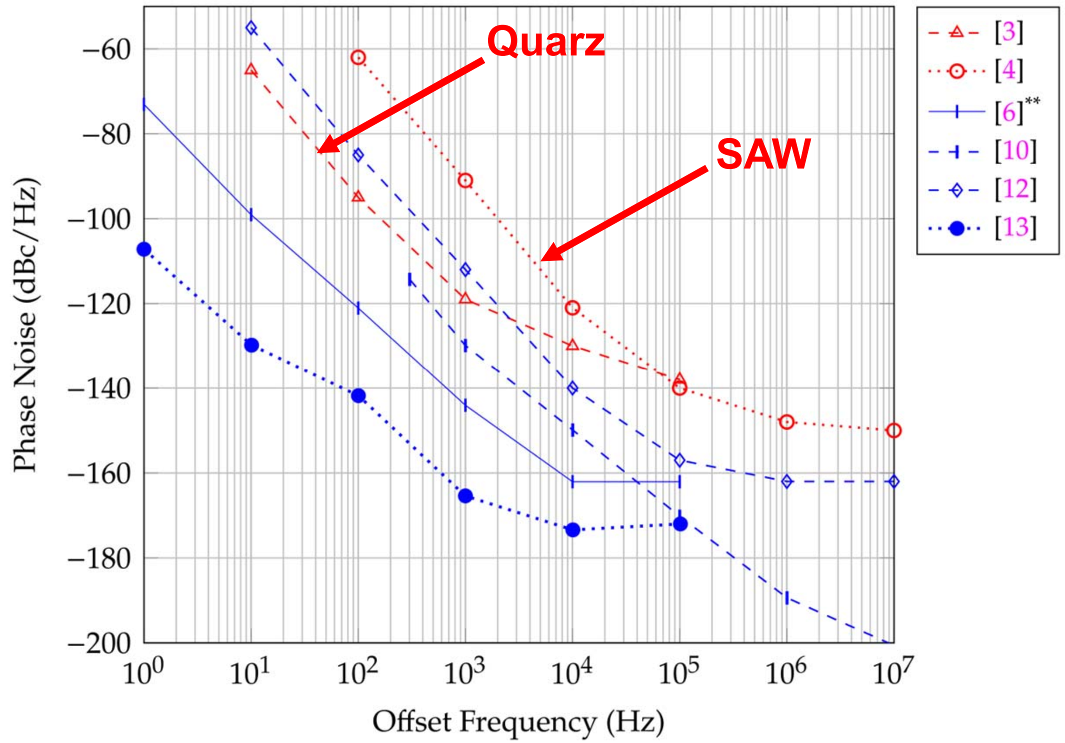
Motivation – Phase Noise in Electronic and Photonic Oscillators

- Electronic Oscillators

Comparison of the phase noise of electronic/photonic oscillators, normalized to 10-GHz carrier frequency



M. Bahmanian and J. C. Scheytt, "A 2–20-GHz Ultralow Phase Noise Signal Source Using a Microwave Oscillator Locked to a Mode-Locked Laser," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1635-1645, March 2021

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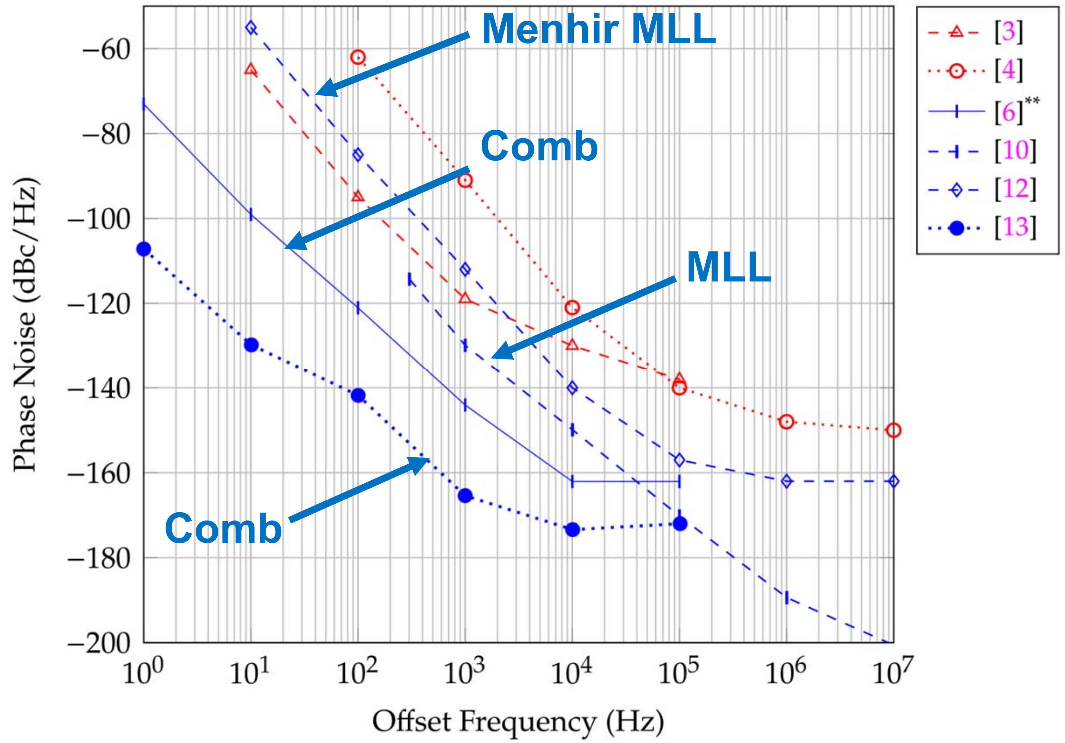

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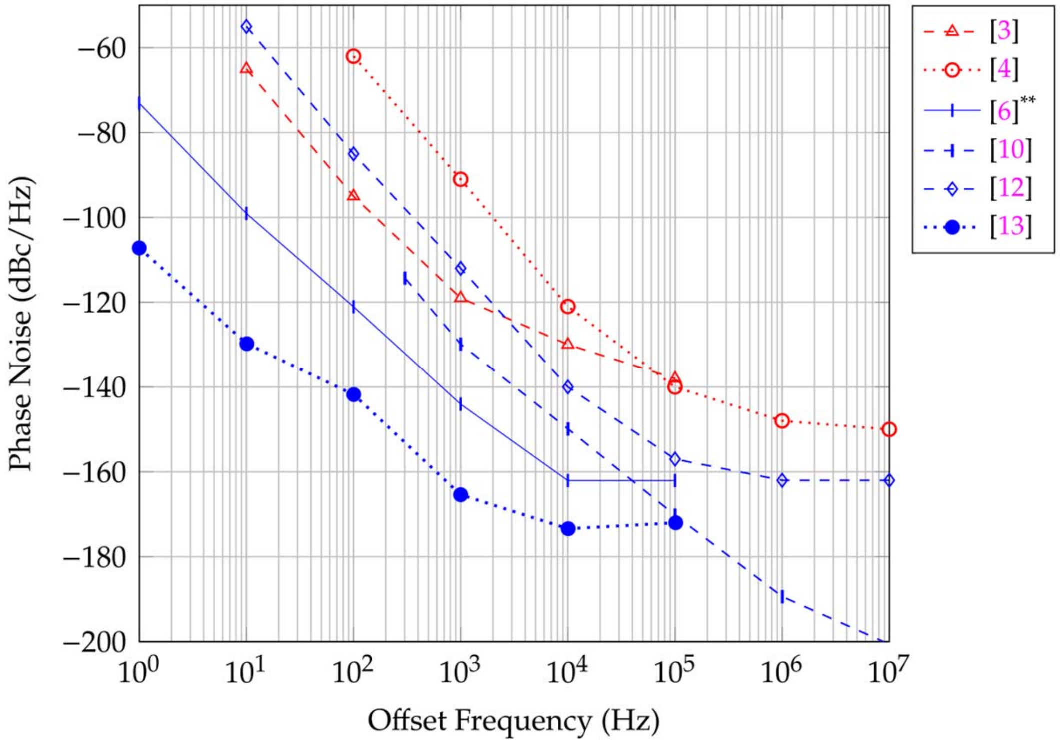
Motivation – Phase Noise in Electronic and Photonic Oscillators

- **Phase Noise of Optical Frequency sources is superior to their electronic counterparts**

Comparison of the phase noise of electronic/photonic oscillators, normalized to 10-GHz carrier frequency



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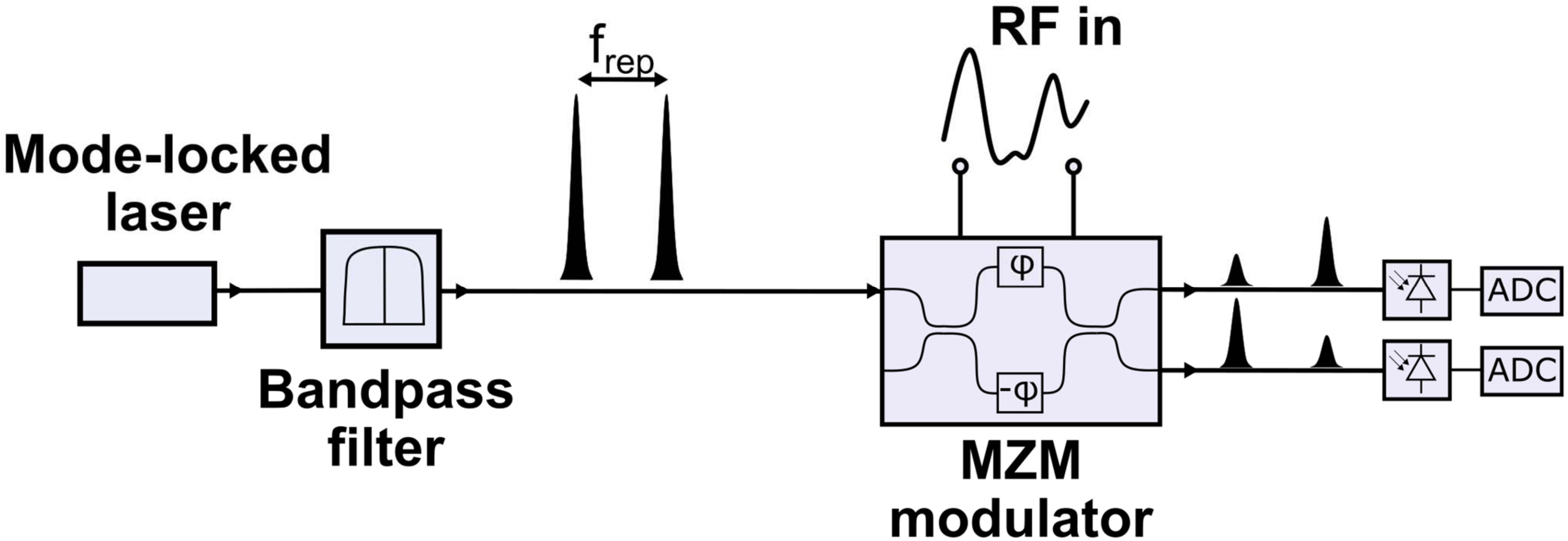
- Selected Architectures
  - MZM-based Sampling
  - MZM-based Sampling → Time Interleaved
  - MZM-based Sampling → Frequency Interleaved
  - Optically Clocked Electronic Sampling
  - Photonically Referenced Oscillator / Optoelectronic PLL (OE-PLL)

- Conclusion

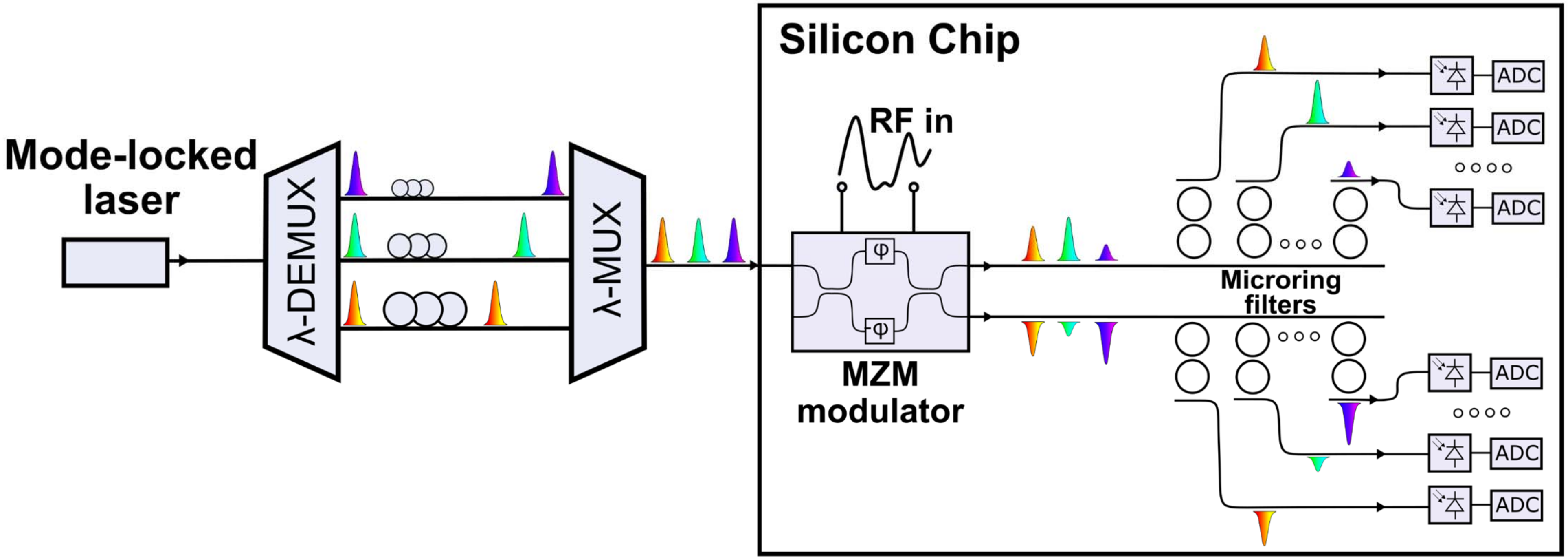
MZM-based Sampling



H. F. Taylor, M. J. Taylor, P. W. Bauer; Electro-optic analog-to-digital conversion using channel waveguide modulators. *Appl. Phys. Lett.* 1 May 1978; 32 (9): 559–561.

M. Weizel, F. X. Kaertner, J. Witzens and J. C. Scheytt, “Photonic analog-to-digital-converters—Comparison of a MZM-sampler with an optoelectronic switched-emitter-follower sampler,” in Proc. 21st ITGSymp. Photon. Netw., 2020, pp. 119–124.

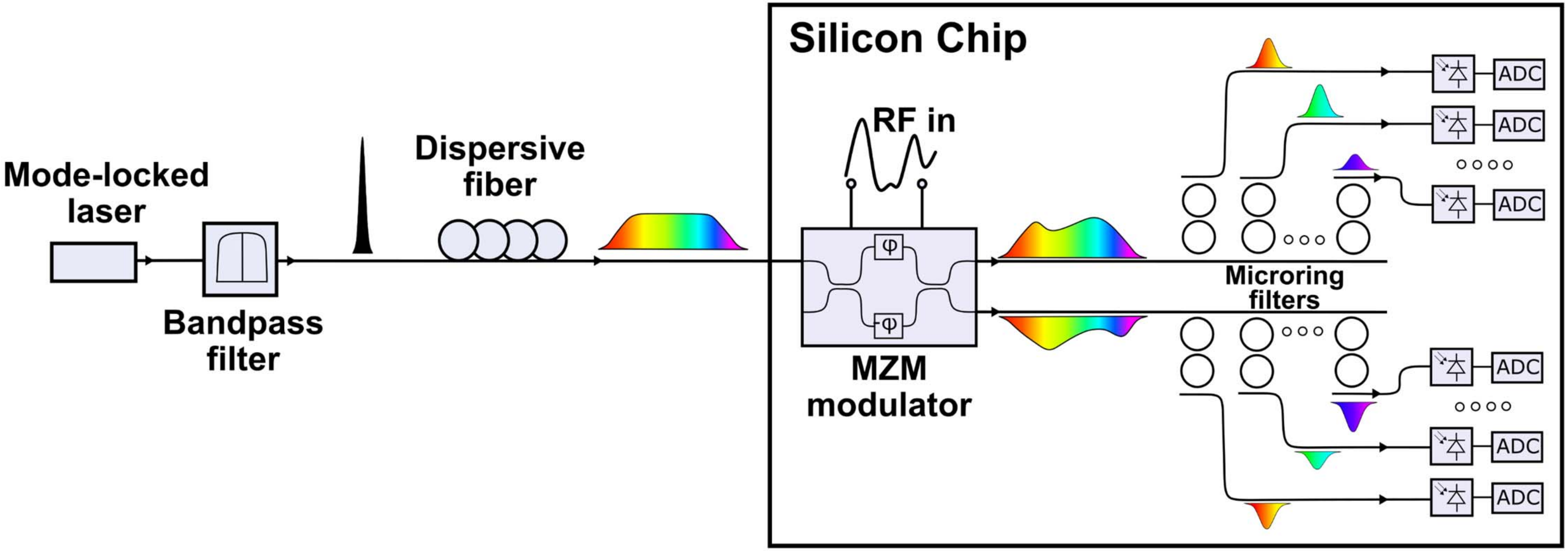
MZM-based Sampling → Time Interleaved



Anatol Khilo et al., "Photonic ADC: overcoming the bottleneck of electronic jitter," Opt. Express **20**, 4454-4469 (2012)

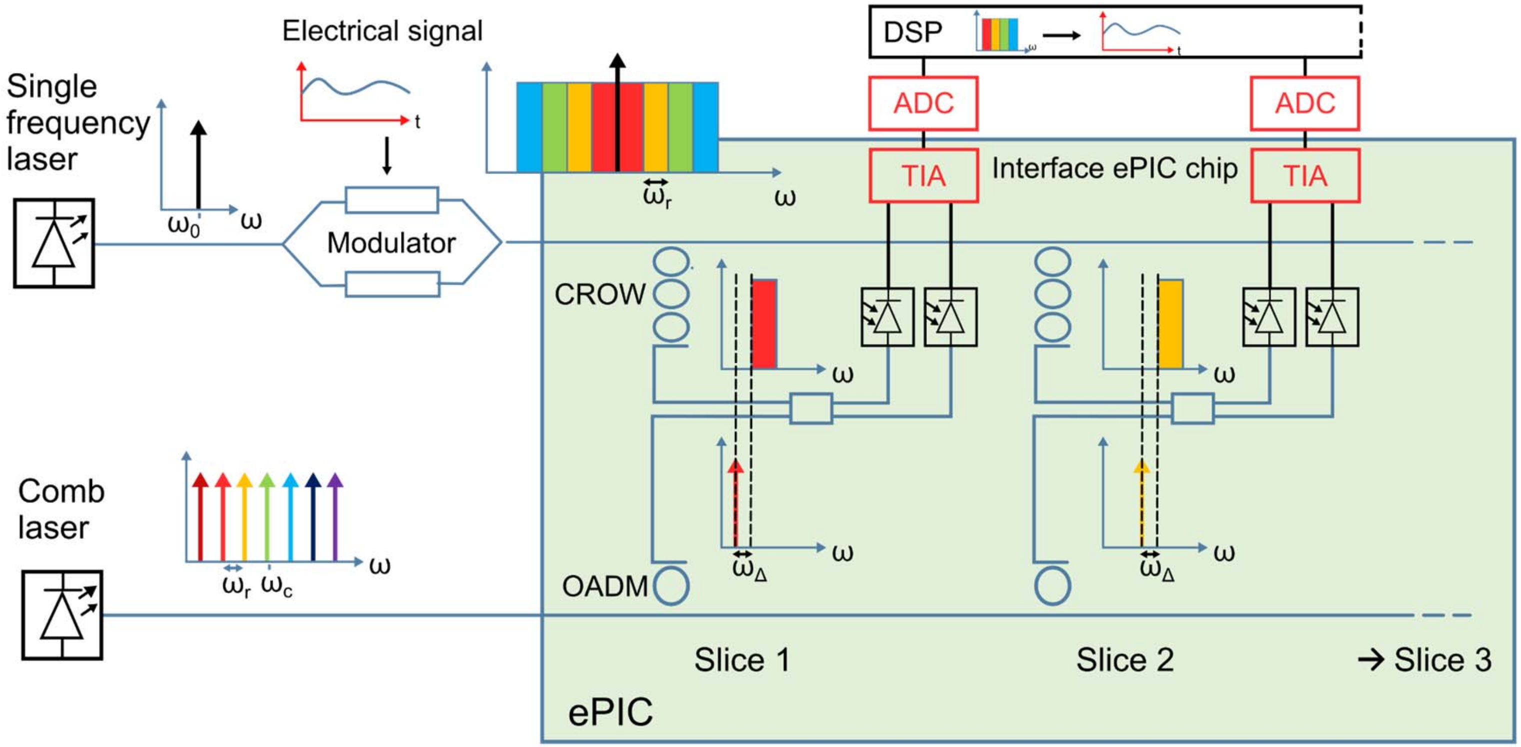
A. H. Nejadmalayeri *et al*., "A 16-fs aperture-jitter photonic ADC: 7.0 ENOB at 40 GHz," *CLEO: 2011 - Laser Science to Photonic Applications*, Baltimore, MD, USA, 2011, pp. 1-2,

MZM-based Sampling → Time Interleaved



Holzwarth, C. W. et al. “High speed analog-to-digital conversion with silicon photonics.” Silicon Photonics IV. Ed. Joel A. Kubby & Graham T. Reed. San Jose, CA, USA: SPIE, 2009. 72200B-15.

MZM-based Sampling → Frequency Interleaved



A. Zazzi *et al*., "Optically Enabled ADCs and Application to Optical Communications," in *IEEE Open Journal of the Solid-State Circuits Society*, vol. 1, pp. 209-221, 2021, doi: 10.1109/OJSSCS.2021.3110943.

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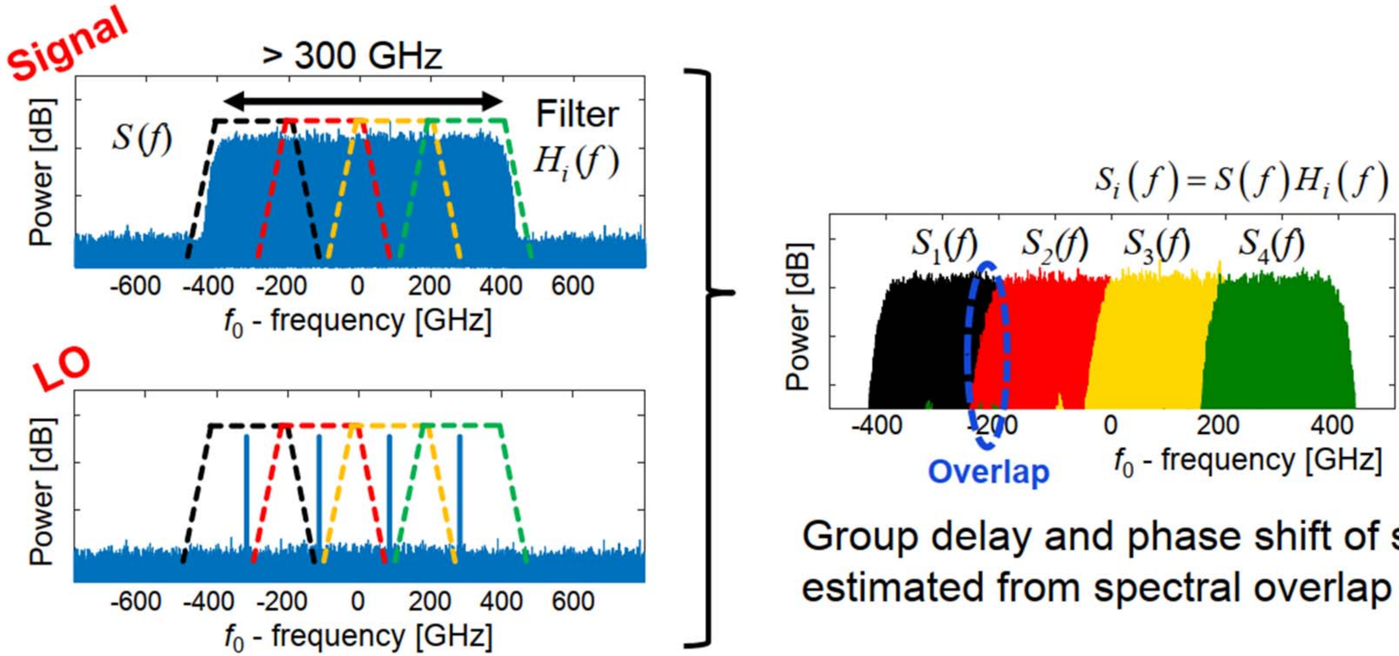
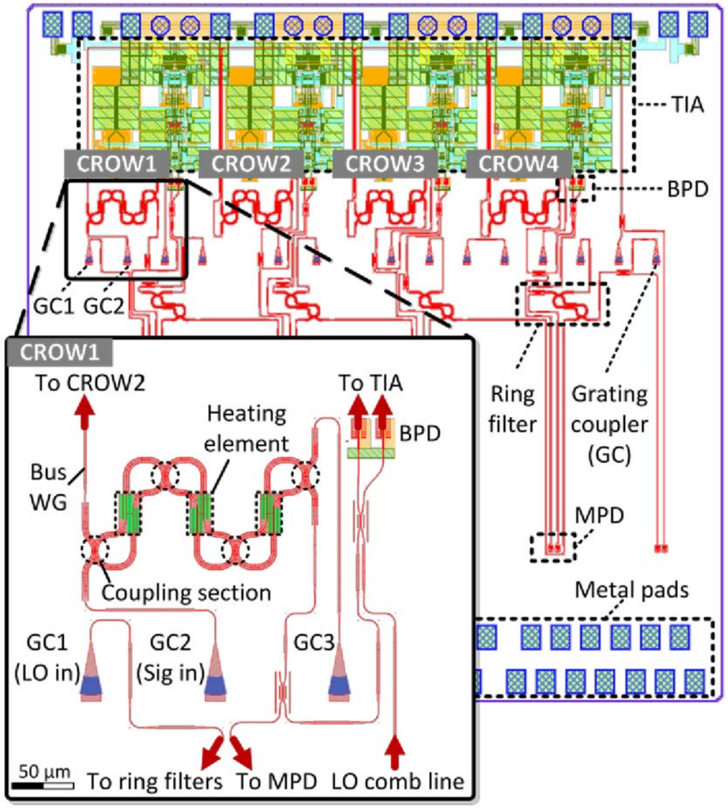
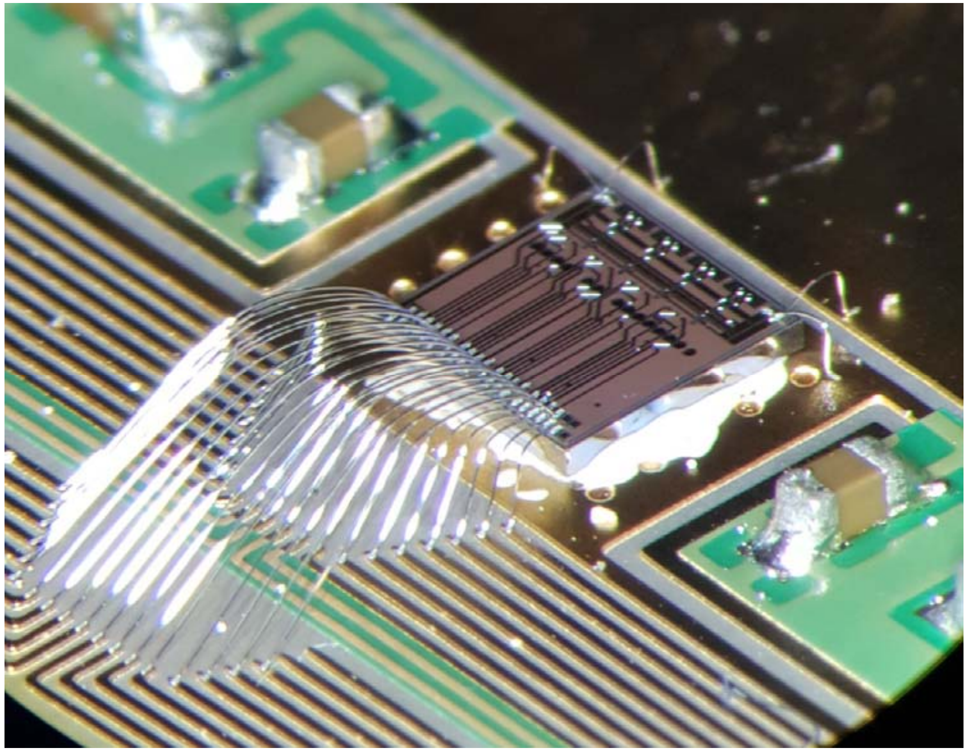


Group delay and phase shift of slices can be estimated from spectral overlap regions.

MZM-based Sampling → Frequency Interleaved





D. Fang *et al.*, "Optical Arbitrary Waveform Measurement (OAWM) Using Silicon Photonic Slicing Filters," in *Journal of Lightwave Technology*, vol. 40, no. 6, pp. 1705-1717, 15 March15, 2022

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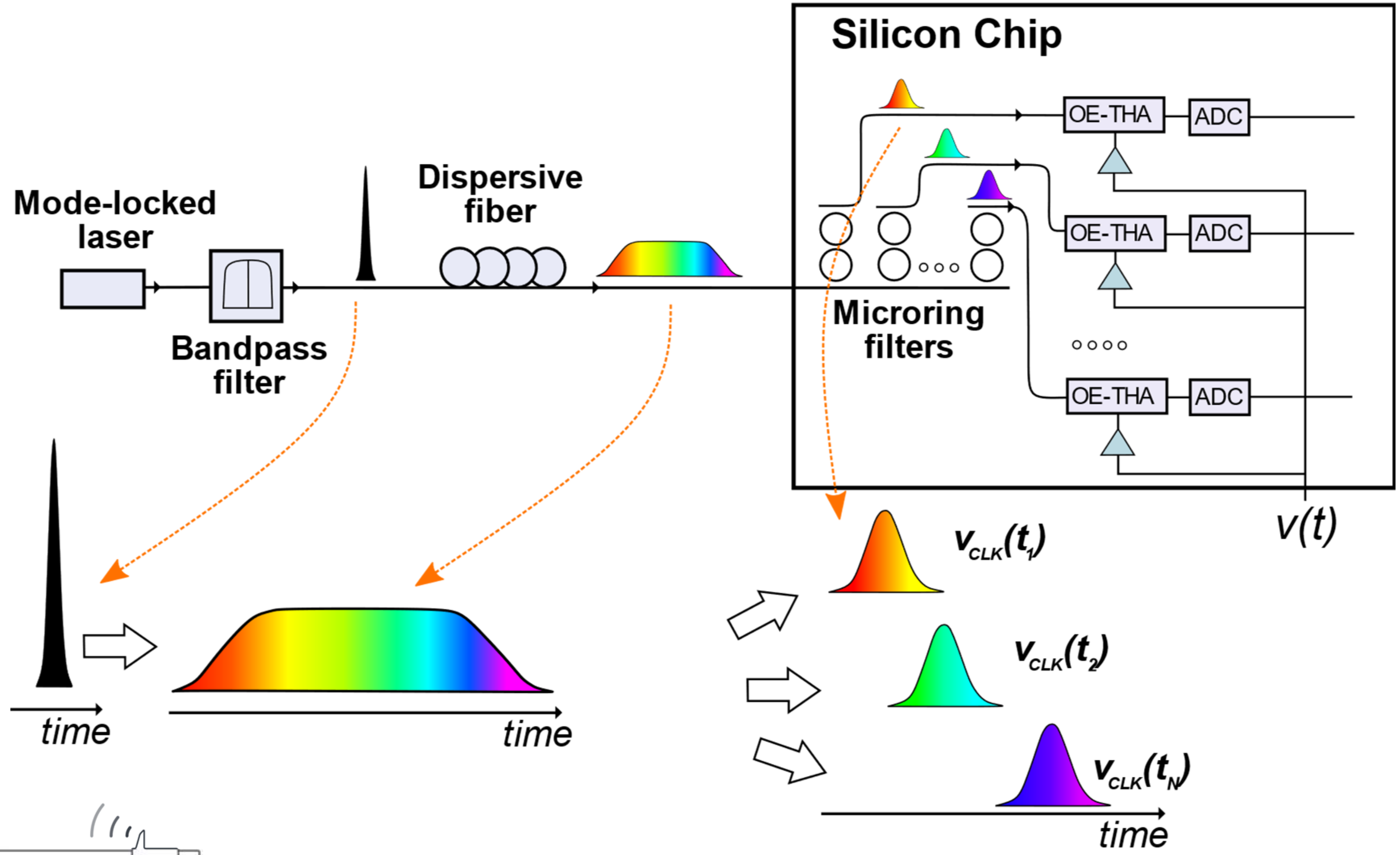
Optically Clocked Electronic Sampling



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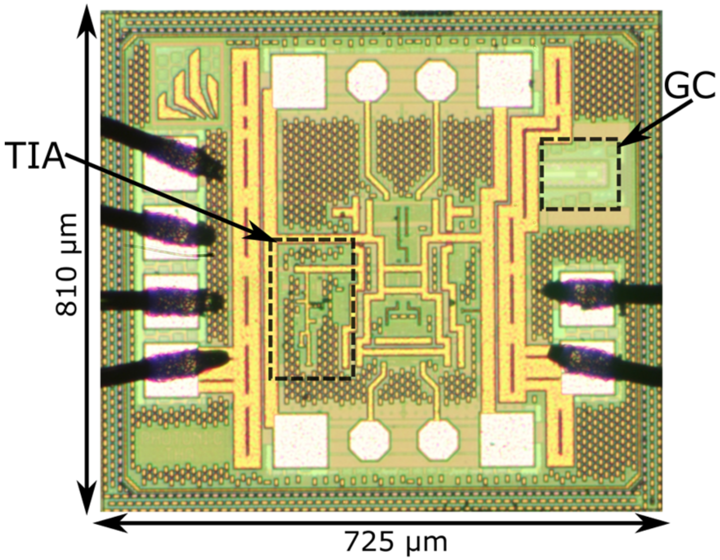

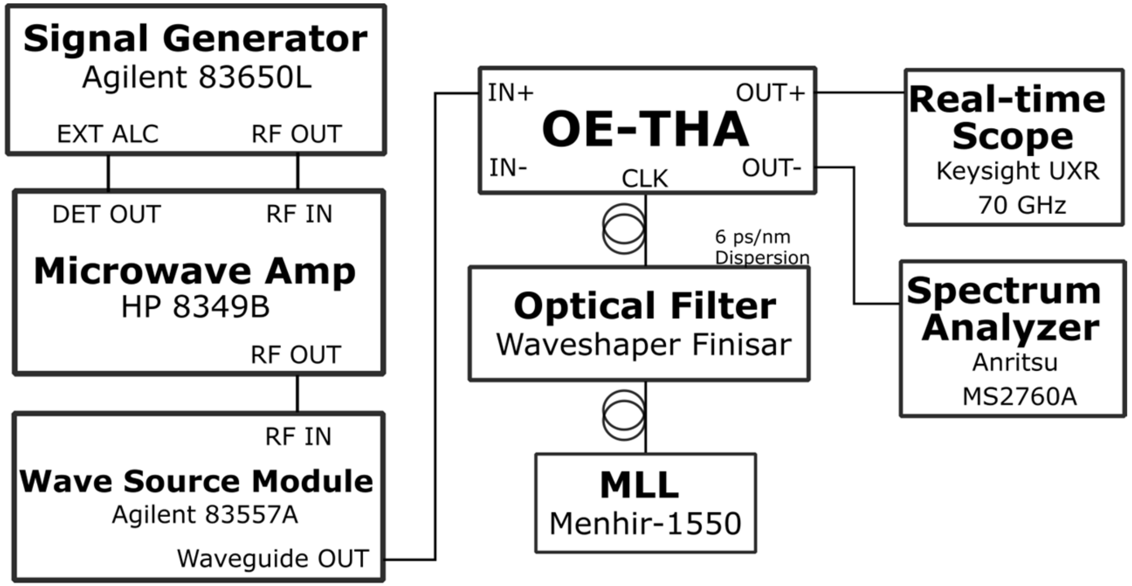

Maxim Weizel, J. Christoph Scheytt, Franz X. Kärtner, and Jeremy Witzens, "Optically clocked switched-emitter-follower THA in a photonic SiGe BiCMOS technology," Opt. Express **29**, 16312-16322 (2021)

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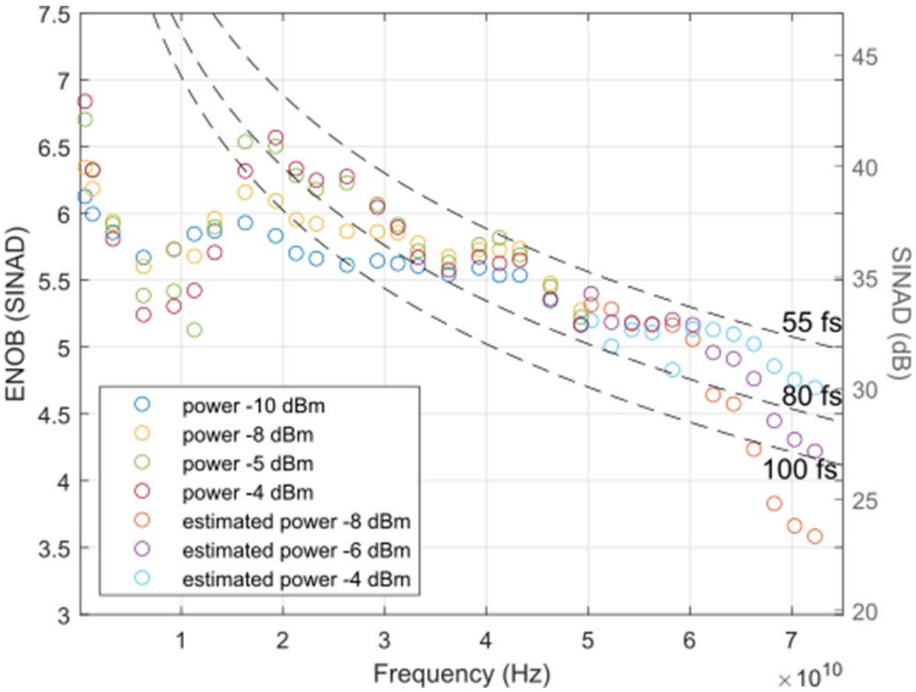

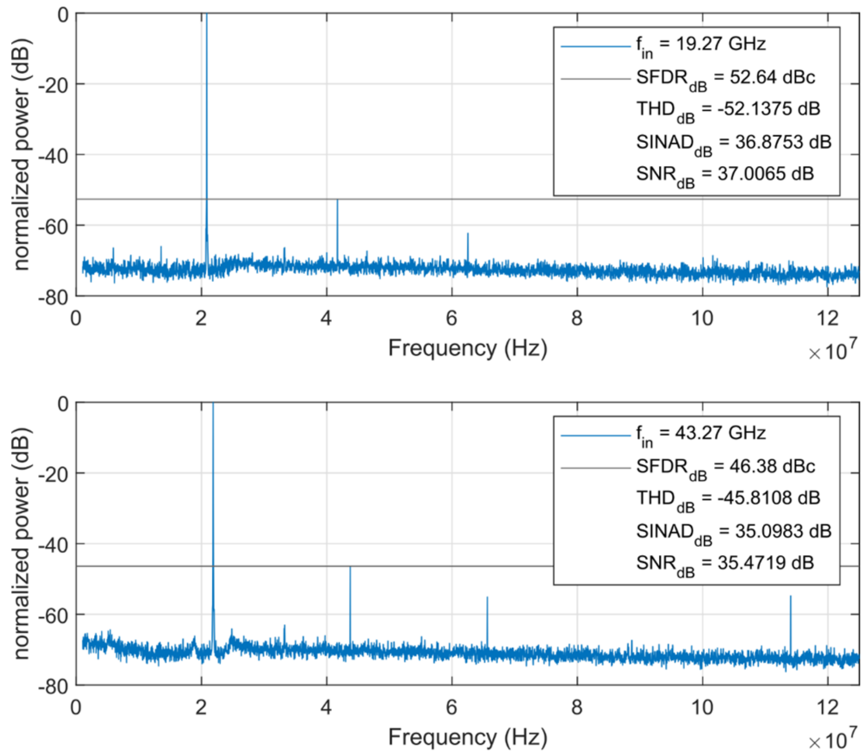

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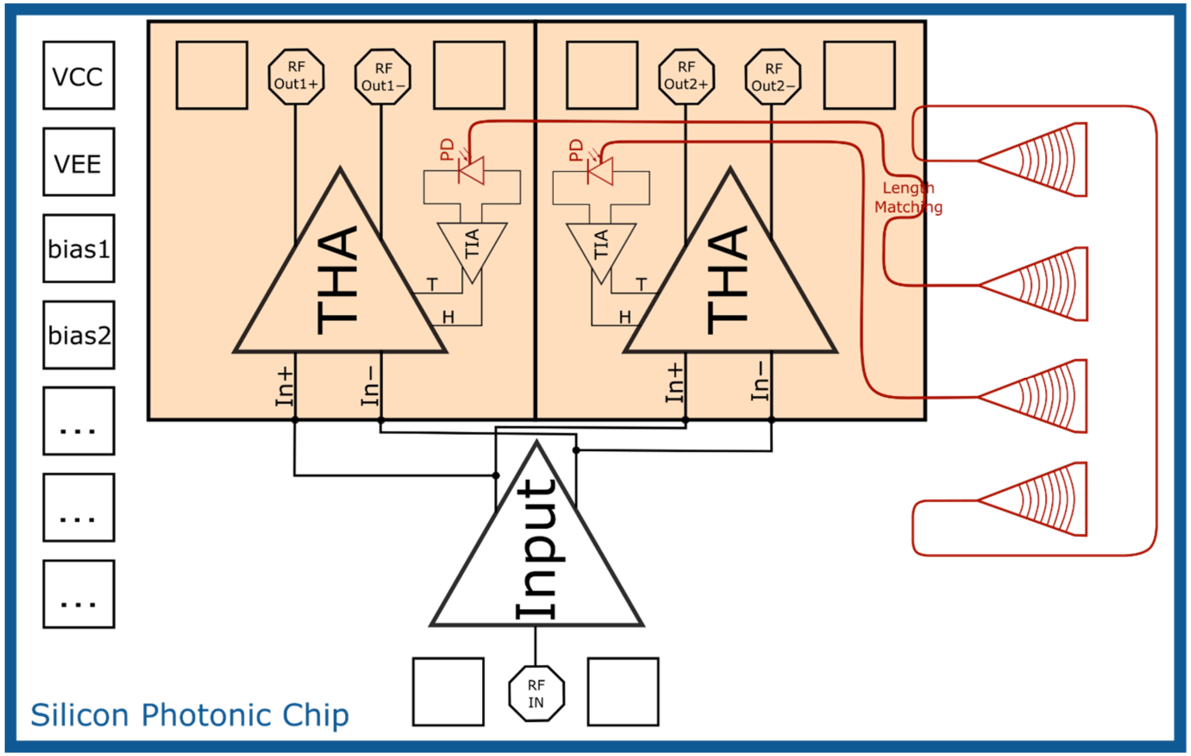
Optically Clocked Electronic Sampling – Our Recent Activities

2 x Time-Interleaved Track and Hold

- 70 GHz 3dB bandwidth
- 120 GS/s operation
  - 35 GHz TIA + Frequency Multiplier
- IHP SG25H5 EPIC technology
  - f_t/f_{max} of 220GHz/280GHz
- Currently in fabrication



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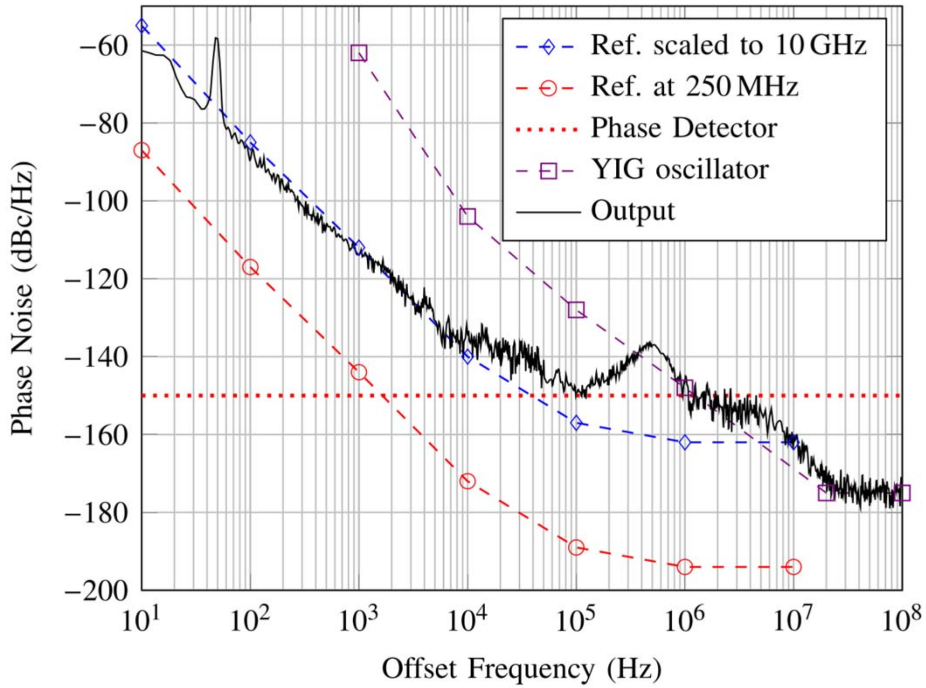
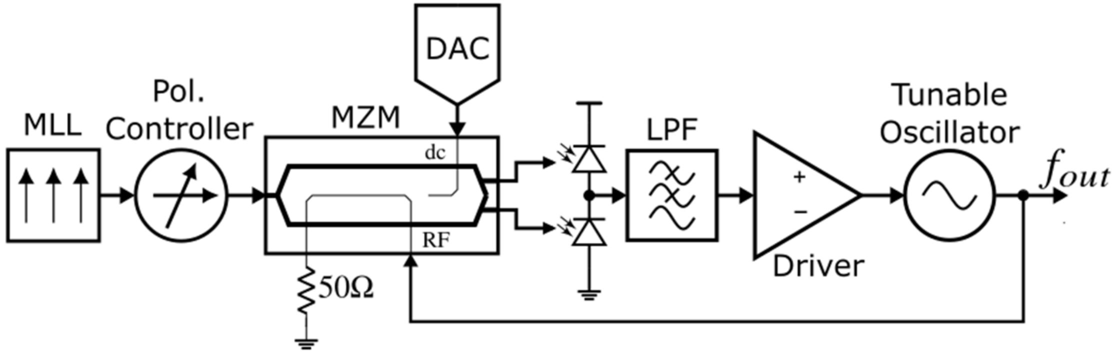
Photonically Referenced Oscillator / Optoelectronic PLL (OE-PLL)

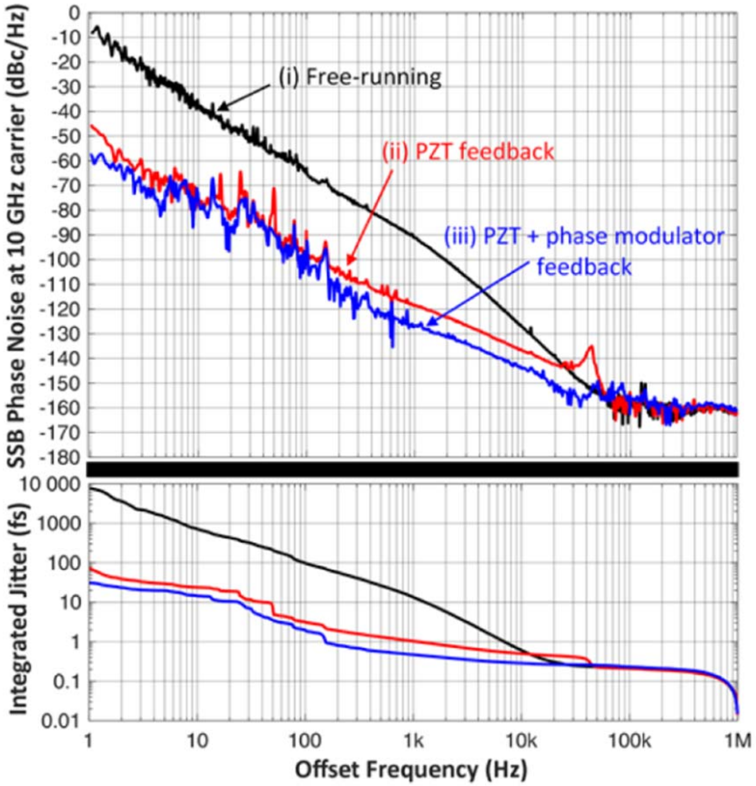




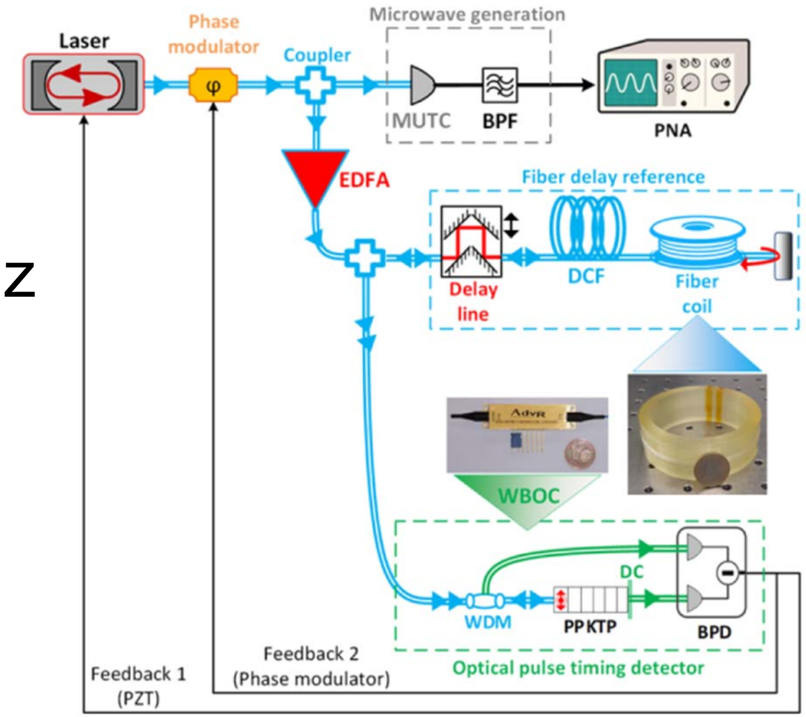
- 2.8 fs rms @ 10GHz [1 kHz-100MHz]

M. Bahmanian and J. C. Scheytt, "A 2–20-GHz Ultralow Phase Noise Signal Source Using a Microwave Oscillator Locked to a Mode-Locked Laser," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1635-1645, March 2021, doi: 10.1109/TMTT.2020.3047647.

Photonically Referenced Oscillator / Optoelectronic PLL (OE-PLL)



- 2 fs rms @ 10GHz [100 Hz-1MHz]

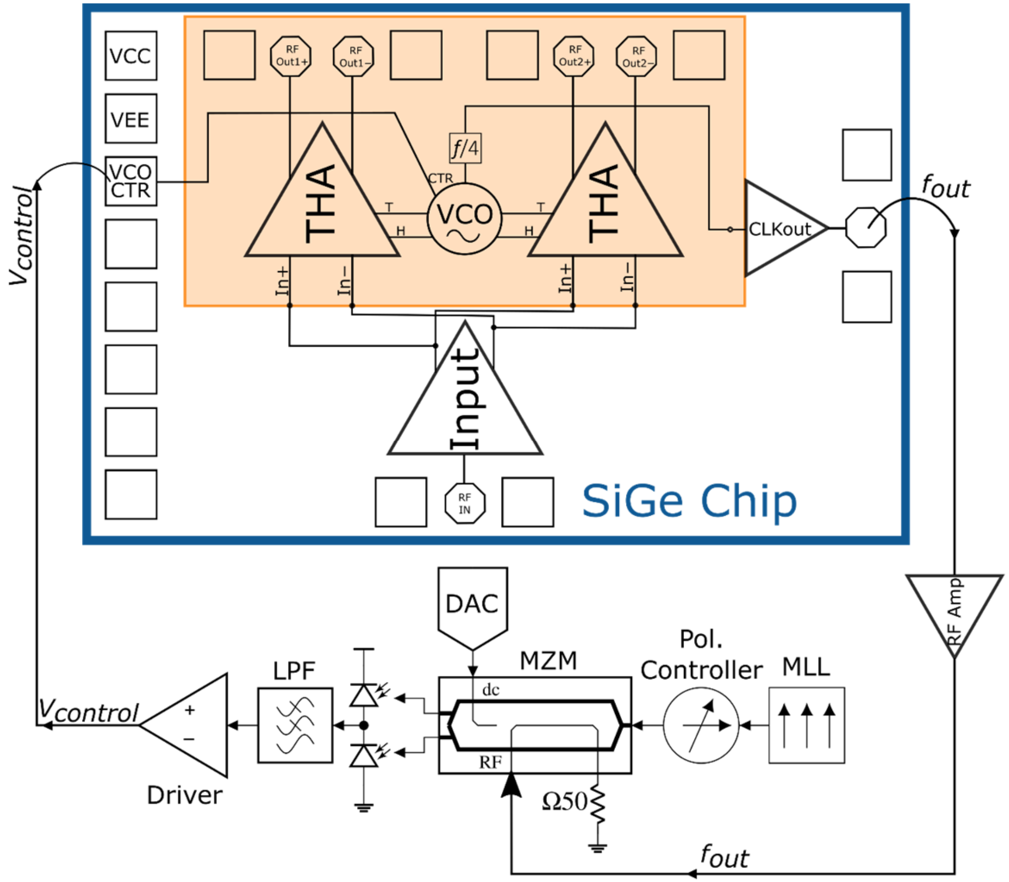


Kemal Şafak, Erwin Cano Vargas, Anan Dai, Marvin Edelmann, Florian Emaury, Karolis Balskus, Benjamin Rudin, Philip Battle, Tony D. Roberts, Bradley Slezak, Todd Hawthorne, and Franz X. Kärtner, "Photonically referenced extremely stable oscillator," Opt. Lett. **49**, 977-980 (2024)

Photonically Referenced Oscillator / Optoelectronic PLL (OE-PLL)

2 x Time-Interleaved Track and Hold

- 120 GHz 3dB bandwidth
- 120 GS/s operation
  - 60 GHz on Chip VCO
  - f/4 frequency divider
- IHP SG13G3Cu technology
  - f_t/f_{max} of 470GHz/650GHz
- Currently in fabrication



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  - Further Literature
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Further Literature

- Photonically Assisted Sampling overview:
  - George C. Valley, "Photonic analog-to-digital converters," Opt. Express 15, 1955-1982 (2007)
  - Krune, Edgar. “Performance analysis of low jitter high-speed photonic analog-to-digital converters in silicon photonics,” Technischen Universität Berlin, (2017)
  - Krune, Edgar et al. “Comparison of the Jitter Performance of different Photonic Sampling Techniques.” Journal of Lightwave Technology 34 (2016): 1360-1367.
- Optically Clocked Electronic Samplers:
  - B. Krueger *et al*., "A monolithically integrated, optically clocked 10 GS/s sampler with a bandwidth of >30 GHz and a jitter of <30 fs in photonic SiGe BiCMOS technology," *2017 IEEE Custom Integrated Circuits Conference (CICC)*, Austin, TX, USA, 2017, pp. 1-4
  - Krune, Edgar et al. “Jitter Analysis of Optical Clock Distribution Networks in Silicon Photonics.” Journal of Lightwave Technology 32 (2014): 4378-4385.
- MZM-based Samplers:
  - F. Coppinger, A. S. Bhushan and B. Jalali, "Photonic time stretch and its application to analog-to-digital conversion," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 7, pp. 1309-1314, July 1999
  - Mahjoubfar, A., Churkin, D., Barland, S. *et al.* Time stretch and its applications. *Nature Photon* **11**, 341–351 (2017).
- Frequency Interleaved Samplers:
  - Zazzi , Andrea et al. "Fundamental limitations of spectrally-sliced optically enabled data converters arising from MLL timing jitter," Opt. Express **28**, 18790-18813 (2020)
  - D. Drayss *et al*., "Slice-Less Optical Arbitrary Waveform Measurement (OAWM) in a Bandwidth of More Than 600 GHz," *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2022, pp. 1-3.

Conclusion

- High-Speed ADCs are crucial for various applications
  - Telecom, Radar, Metrology
- Traditional electr. ADCs face limitations in achieving high-speed and high resolution simultaneously
- Photonically Assisted Sampling Outperforms Electronic Sampling at high analog input bandwidths
  - Best application region: >10 GHz and >5 Bit resolution

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Photonically Assisted ADCs have the potential to shift the performance limits of data converters towards yet unprecedented accuracies

Thank you very much for your Attention

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