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**Author(s):**
Eppenberger, Marco; Bitachon, Bertold Ian; Messner, Andreas; Heni, Wolfgang; Habegger, Patrick; Destraz, Marcel; De Leo, Eva; Meier, Norbert; Del Medico, Nino; Hoessbacher, Claudia; Bäuerle, Benedikt; Leuthold, Juerg

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# Plasmonic Racetrack Modulator Transmitting 220 Gbit/s OOK and 408 Gbit/s 8PAM

Marco Eppenberger (1), Bertold Ian Bitachon(1), Andreas Messner(1), Wolfgang Heni(2), Patrick Habegger(2), Marcel Destraz(2), Eva De Leo(2), Norbert Meier(2), Nino Del Medico(2), Claudia Hoessbacher(2), Benedikt Baeuerle(2), and Juerg Leuthold(1)

(1) ETH Zurich, Institute of Electromagnetic Fields (IEF), 8092 Zurich, Switzerland
(2) Polariton Technologies AG, 8803 Rüschlikon, Switzerland
Author e-mail addresses: marcoep@ethz.ch, benedikt@polariton.ch, leuthold@ethz.ch

**Abstract** OOK line rates of 220 Gbit/s and 408 Gbit/s 8PAM and transmission over 100 m are demonstrated with a resonant plasmonic racetrack modulator. The device requires low 0.6 $V_p$ driver voltages, offers a bandwidth >110 GHz and on-chip losses of 1.0 dB.

## Introduction

Optical intensity modulation/direct detection (IM/DD) systems play an important role in modern datacom systems. Currently, the demand for optical data transmission increases with 40% p.a.[1], and telecom standards foresee data rates of IM/DD systems to grow from 100 to ≥200 Gbit/s per dimension[2].

Electro-optic (EO) modulators serving these links should offer a compact footprint, low optical loss, and a low energy consumption[3]. Intensity modulators based on Mach-Zehnder interferometers meanwhile provide EO bandwidths in excess of 100 GHz[4] and symbol rates >200 GBaud[5]. However, resonant EO modulators[6, 7] can be advantageous for IM/DD, because of a more compact footprint, lower electrical energy consumption and an inherent wavelength-division-multiplexing capability enabled by their wavelength selective nature. Indeed, recent advances have been impressive: Symbol rates up to 120 GBd have enabled net data rates after forward-error correction (FEC) of nearly 200 Gbit/s[8-14], see Fig 1. However, a further increase of the line rate is hampered by the photon-lifetime-limited EO bandwidth of resonant devices, which has not yet reached 120 GHz in photonic resonant modulators.

In this work, we demonstrate a racetrack modulator based on a plasmonic-organic hybrid (POH) phase shifter fabricated on the silicon-on-insulator platform. Our device features a 1 dB on-chip device loss. The moderate quality factor of $Q \approx 730$ enables a 3-dB bandwidth exceeding 110 GHz and allows for 220 Gbit/s 2PAM and 400 Gbit/s 8PAM intensity modulation (IM) and is shown to enable rack-to-rack communication over 100 m and reception by direct detection (DD).

## Device Technology

Fig. 2(a) shows the schematic of the device. Silicon photonic waveguides and a directional coupler form a racetrack structure; grating

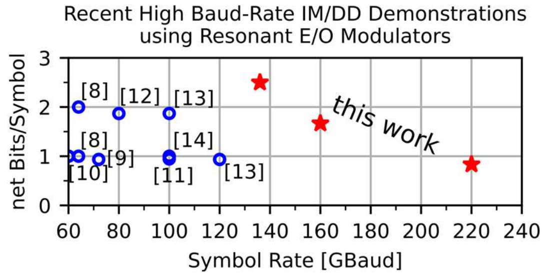


**Fig. 1:** Bits per symbol and symbol rate of recent high Baud-Rate IM/DD demonstrations.

couplers are used to couple light to and from the chip. The device obtains its active functionality from a high-speed POH phase shifter, which is integrated into the racetrack[11]. The plasmonic gold-insulator-gold slot waveguide is 7.5 µm long and 105 nm wide, and its metal electrodes serve both as waveguides and as pads for high-speed radio frequency (RF) probes. The plasmonic slot is functionalized using Lightwave Logic's Perkinamine™ chromophore series 3[15]. This organic material has been tested for reliability and has achieved a stable performance of less than 5% variance at 85°C for over 2000 hours[16]. The material features a glass transition temperature $T_g$ greater than 170°C. The bulk $r_{33}$ electro-optic coefficient at 50% APC loading has been measured to amount to 148 pm/V at 1550 nm. The chromophre has been deposited from an organic solvent onto the chip.

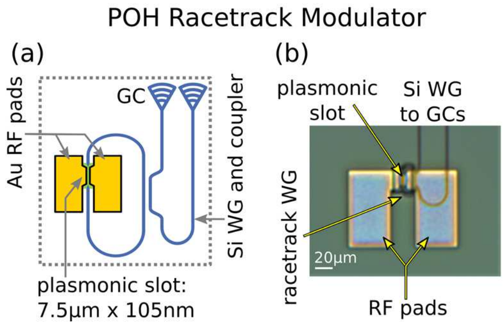


**Fig. 2:** a) Schematic of a POH racetrack modulator. The active plasmonic section is 7.5 µm long and 105 nm wide. b) Optical microscopy image of the reference device. GC is grating coupler, WG is waveguide.

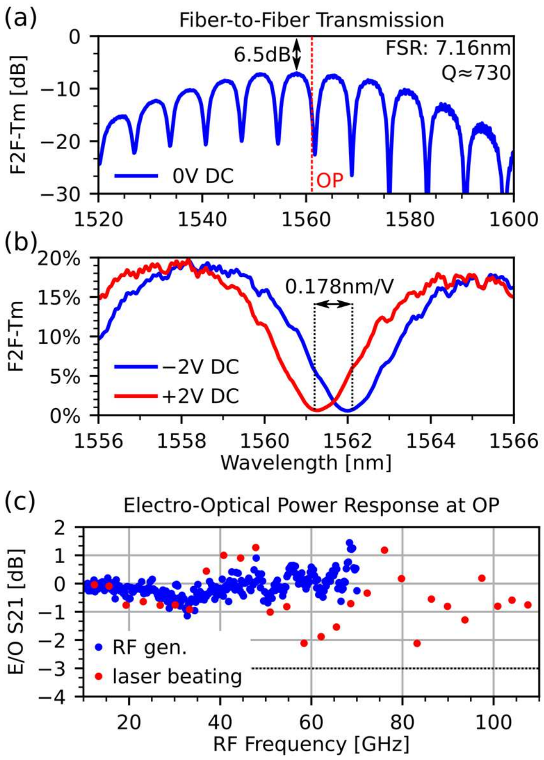


**Fig. 3:** a) F2F transmission spectrum in log scale. The F2F loss is 6.5dB including GCs and 1.0 dB device loss. b) F2F transmission spectrum at +-2$V_{DC}$. The device features a DC tunability of 0.178 nm/V c) Electro-optical power response with bandwidth exceeding 110GHz. F2F-Tm is fiber-to-fiber transmission.

Chromophores have been aligned by electric field poling near the material $T_g$. A microscope picture of the reference device is shown in Fig. 2(b).

By applying a voltage to the electrodes, the optical phase relation of the racetrack is modulated, effectively changing its resonance wavelength. This modulates the optical power transmitted through the device.

**Static and BW Characterization**

Fig. 3(a) shows the fiber-to-fiber insertion loss (IL) of the device. At 1550 nm, the total IL is only 6.5 dB. This value includes the on-chip plasmonic racetrack modulator losses in the order of 1.0 dB and the silicon photonic grating couplers losses contributing 2.75 dB/coupler. The racetrack cavity exhibits a free-spectral-range of 7.16 nm and a Q-factor of ~730. Fig. 3(b) shows the transmission spectra at -2 and +2 $V_{DC}$. We measure a modulation efficiency of 0.178 nm/V.

To measure the EO frequency response of the racetrack modulator, Fig. 3(c), the modulator was driven with a continuous-wave RF signal. The laser was tuned to the operating point (OP) at 3 dB into the right resonance. Up to 70 GHz, a signal generator was used to feed a signal of -10 dBm to the device (blue dots), whereas the beating of two laser lines on a 70-GHz photodetector (PD) was used to generate higher frequencies at a signal level of -16 dBm. Our device shows a flat frequency response up to the equipment limit of 110 GHz.

**Rack-to-Rack Data-Transmission Experiment**

The device has been tested for its performance in a short-reach scenario with transmission up to 600 m over a standard single-mode fibers.

The experimental setup is shown in Fig. 4(a). A C-band tunable laser source (TLS) is used to couple light into the device with a fiber-array (FA). As an electrical data source, we used a 256GSa/s, 70GHz arbitrary waveform generator (AWG). We use it to differentially drive[17] the device with a 0.6 $V_p$ amplitude (single-ended, measured into 50Ω). The driving voltage over the plasmonic slot is doubled due to the signal reflection at an almost purely capacitive load. The resonant nature of the device helps in reducing the required driving voltage. After the device, there is a variable length of SMF28 fiber (0 to 600 m). The signal is then received in a preamplified direct-detection receiver. The receiver consists of an EDFA, an attenuator to 9 dBm and a 145 GHz PD. The PAM signal has been sampled using a 256 GSa/s, 113 GHz real-time oscilloscope (DSO), followed by offline digital signal processing (DSP).

In a first experiment, we transmit three different signals through 100 m of fiber: a 220 GBaud 2PAM signal with a 0.15-roll-off square-root-raised-cosine pulse-shape (SRRC), a 160 GBaud 4PAM signal (0.6 SRRC), and a 136 GBaud 8PAM signal (0.85 SRRC). All signals are generated using random binary data. In Fig. 4(b), the optical spectra taken directly after the device at ① are shown for each of the symbol rates. The spectra have been recorded with a

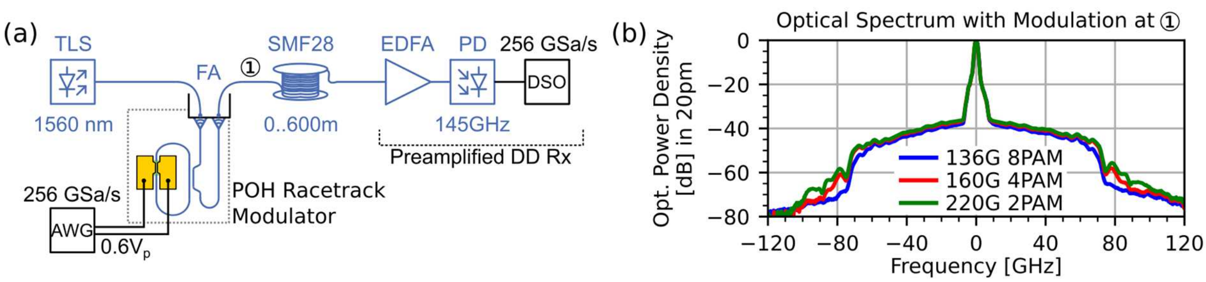


**Fig. 4:** a) Experimental setup for the IM/DD transmission. b) Optical spectrum measured after chip.

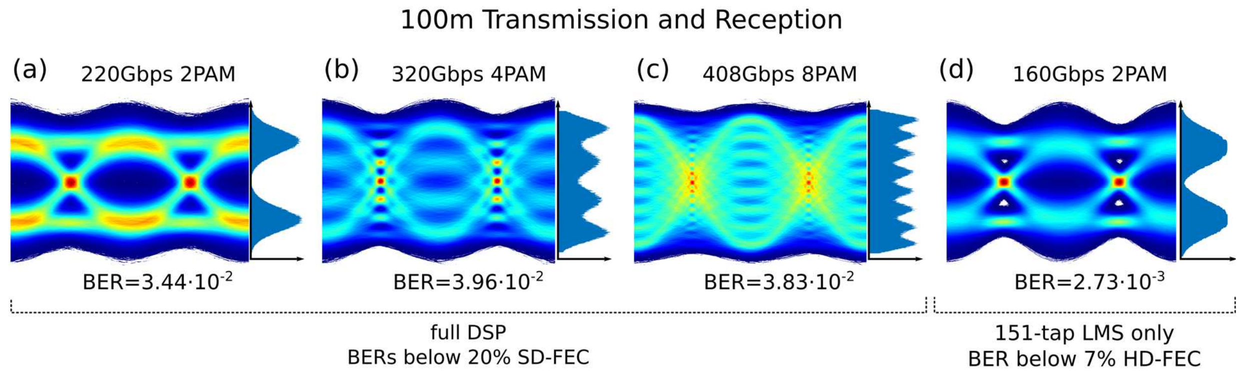


**Fig. 5:** Eye-diagrams and level histograms after 100 m fiber transmission and reception followed by DSP. a) 220 GBaud 2PAM 0.15 SRRC full DSP, b) 160 GBaud 4PAM 0.6 SRRC full DSP, c) 136 GBaud 8PAM 0.85 SRRC full DSP. d) 160 GBaud 2PAM 0.2 SRRC 151-tap linear equalization (LMS) only.

chip input optical power of 0 dBm. In the optical spectra, the 70 GHz limitation of the AWG is clearly visible.

We subject the received signals to offline DSP. For the 2PAM signal this consists of timing recovery, T/2-spaced linear equalization (LMS) with 151 taps, nonlinear pattern mapping with pattern length of 7, and an additional T-spaced linear equalization with 555 taps. For both 4PAM and 8PAM signaling, we use timing recovery, 3rd order Volterra equalizer (255 taps, 55 taps and 13 taps for each order respectively), and the T-spaced LMS. The Volterra equalizer helps to linearize the transfer function of the racetrack modulator for higher order modulation formats. In the future, there is room for improvement of the linearity by applying a static pre-distortion in the transmitter[18].

Fig. 5(a) to (c) shows the eye diagrams of the received signals at 10 dBm chip optical input power. Their BERs (220 Gbps 2PAM: $3.44 \cdot 10^{-2}$, 320 Gbps 4PAM: $3.96 \cdot 10^{-2}$, 408 Gbps 8PAM: $3.83 \cdot 10^{-2}$) are below the 20% overhead SD-FEC limit[19] of $4 \cdot 10^{-2}$. The achieved net data-rates are 183 Gbps (2PAM), 266 Gbps (4PAM), and 340 Gbps (8PAM).

When reducing the 2PAM symbol rate to 160 Gbaud and operating at 0 dBm chip optical input power, a BER of $2.73 \cdot 10^{-3}$ below HD-FEC is reached with a 151-tap LMS filter only.

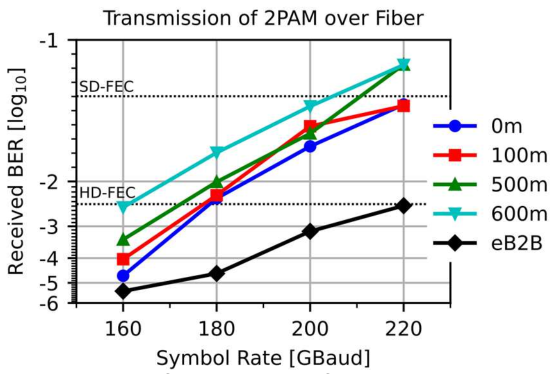


**Fig. 6:** BER of 2PAM signals after transmission over various fiber lengths after full DSP w/o Volterra Eq. Electrical back-to-back (eB2B) is included for reference.

In a second experiment, we evaluated the BER of the 2PAM signals (0.2 SRRC, 220 GBaud: 0.15 SRRC) at 0 dBm chip input power after transmission over distances 0 to 600 m fiber, see Fig. 6. The 200 GBaud 2PAM signal was successfully received below the SD-FEC limit for distances up to 600 m. However, the 220 GBaud 2PAM signal degraded after transmission over 500 m, due to dispersive effects in the SMF28 at 1550 nm. As no other subdivisions of fiber length have been available we report a successful transmission over 100 m.

## Summary and Outlook

We have demonstrated a high-speed plasmonic racetrack modulator with 1.0 dB on-chip device losses. It features a bandwidth exceeding 110GHz. The resonant nature of the device enables highest-speed operation with low 0.6 $V_p$ driver voltages. The device has been successfully tested transmission over 100 m of fiber with a 220 Gbps 2PAM, a 320 Gbps 4PAM and a 408 Gbps 8PAM signal. All BERs have shown to operate below the SD-FEC limits. Future devices operating also in the O-band and featuring a heater controlling the resonance wavelength may be viable, compact and low-loss alternatives to more traditional non-resonant devices.

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## References

[1] P. J. Winzer *et al.*, "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade," *Journal of Lightwave Technology,* vol. 35, no. 5, pp. 1099-1115, 2017

[2] C. Minkenberg *et al.*, "Co-packaged datacenter optics: Opportunities and challenges," *IET Optoelectronics,* vol. 15, no. 2, pp. 77-91, 2021

[3] D. A. B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications," *Journal of Lightwave Technology,* vol. 35, no. 3, pp. 346-396, 2017

[4] M. Burla *et al.*, "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics," *APL Photonics,* vol. 4, no. 5, p. 056106, 2019

[5] W. Heni *et al.*, "Ultra-High-Speed 2:1 Digital Selector and Plasmonic Modulator IM/DD Transmitter Operating at 222 GBaud for Intra-Datacenter Applications," *Journal of Lightwave Technology,* vol. 38, no. 9, pp. 2734-2739, 2020

[6] Q. Xu *et al.*, "Micrometre-scale silicon electro-optic modulator," *Nature,* vol. 435, no. 7040, pp. 325-327, 2005

[7] Q. Li *et al.*, "Si racetrack modulator with III-V/Si hybrid MOS optical phase shifter," in *45th European Conference on Optical Communication (ECOC 2019)*, 2019, pp. 1-3

[8] J. Sun *et al.*, "A 128 Gb/s PAM4 Silicon Microring Modulator With Integrated Thermo-Optic Resonance Tuning," *Journal of Lightwave Technology,* vol. 37, no. 1, pp. 110-115, 2019

[9] C. Haffner *et al.*, "Low-loss plasmon-assisted electro-optic modulator," *Nature,* vol. 556, no. 7702, pp. 483-486, 2018

[10] Y. Ban *et al.*, "Low-Voltage 60Gb/s NRZ and 100Gb/s PAM4 O-Band Silicon Ring Modulator," in *2019 IEEE Optical Interconnects Conference (OI)*, 2019, pp. 1-2

[11] A. Messner *et al.*, "100 Gbit/s NRZ Data Modulation in Plasmonic Racetrack Modulators on the Silicon Photonic Platform," in *2020 European Conference on Optical Communications (ECOC)*, 2020, pp. 1-3

[12] Y. Tong *et al.*, "An Experimental Demonstration of 160-Gbit/s PAM-4 Using a Silicon Micro-Ring Modulator," *IEEE Photonics Technology Letters,* vol. 32, no. 2, pp. 125-128, 2020

[13] Y. Zhang *et al.*, "200 Gbit/s Optical PAM4 Modulation Based on Silicon Microring Modulator," in *2020 European Conference on Optical Communications (ECOC)*, 2020, pp. 1-4

[14] D. Pohl *et al.*, "100-GBd Waveguide Bragg Grating Modulator in Thin-Film Lithium Niobate," *IEEE Photonics Technology Letters,* vol. 33, no. 2, pp. 85-88, 2021

[15] "Perkinamine 3 is a trade marked proprietary chromophore electoral-optic organic material developed at Lightwave Logic Inc.,"

[16] M. Lebby, "Polymer modulators with >50GHz performance for power consumption reduction at 400, 800, and 1600 Gbaud aggregated datarates," in *2019 European Conference on Optical Communications (ECOC)*, 2019,

[17] B. Baeuerle *et al.*, "120 GBd plasmonic Mach-Zehnder modulator with a novel differential electrode design operated at a peak-to-peak drive voltage of 178 mV," *Opt. Express,* vol. 27, no. 12, pp. 16823-16832, 2019

[18] H. Li *et al.*, "A 112 Gb/s PAM4 Silicon Photonics Transmitter With Microring Modulator and CMOS Driver," *Journal of Lightwave Technology,* vol. 38, no. 1, pp. 131-138, 2020

[19] K. Schuh *et al.*, "Single carrier 1.2 Tbit/s transmission over 300 km with PM-64 QAM at 100 GBaud," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, 2017, pp. 1-3