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100 Gbit/s NRZ Data Modulation in Plasmonic Racetrack Modulators on the Silicon Photonic Platform

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Abstract Low power broadband plasmonic silicon-photonic racetrack modulators are introduced. 100 Gbit/s NRZ-OOK and 100 Gbit/s 4-PAM direct detection is demonstrated. The devices feature a bandwidth of 50 GHz, operate with 1.3 V_p and are of interest because of the low on-chip loss characteristics.

Introduction

Low-loss integrated electro-optic modulators with a high bandwidth and low power consumption are sought-after devices for optical communication links.

Recently, many concepts that address these challenges have evolved. Ring modulators feature both a low optical insertion loss and low energy consumption^[1-3]. However, their electro-optic bandwidth is often limited by a long photon cavity lifetime.

On the other hand, plasmonic-organic hybrid modulators feature a very large bandwidth,^[4] and a very low energy consumption,^[5] but at the expense of extra optical insertion loss that are inherent to the technology.

A solution to overcome inherent losses relies on exploiting resonant configurations. The incorporation of plasmonic modulators into ring structures is hence promising. And indeed, a device with a low insertion loss of 2.5 dB, operated at 72 Gbit/s and a bandwidth exceeding 110 GHz has already been demonstrated.^[6] However, the device's low Q-factor of ~30 inhibited efficient modulation so that voltage swings of 6.6 V_p were needed.

In this publication, we present introduce a siliconphotonic racetrack resonator with a built-in plasmonic modulator. 100 Gbit/s NRZ-OOK modulation has been achieved with an electrical signal of 1.3 Vp. This is enabled by optimizing the Q-factor to a value of 1250, which allows for without limiting efficient modulation. the bandwidth due to a long photonic lifetime. Measured on-chip losses of only 5 dB are not inherent to the platform and can be further reduced. It should be stressed that the electrical energy consumption of resonator-based devices is inherently loweras compared to Mach-Zehnder modulators.^[7]

Plasmonically activated modulator

Fig. 1 shows the electro-optic modulator employed for this experiment. Light is coupled to and from the chip with silicon photonic grating couplers. A 33-µm-long directional coupler maps a fraction of the guided waveguide mode from the bus waveguide into the resonator section. A plasmonic-organic hybrid (POH) phase modulator^[8] of 15 µm length and with a 100 nmwide slot is included in the resonator. The gold electrodes forming the plasmonic metalinsulator-metal slot waveguide also serve as the electric contact pads for a ground-signal pico probe. The chip is coated with the electro-optic organic (OEO) material composite HD-BB--OH/YLD12-4^[9].



Fig. 1 Microscope image of the silicon racetrack resonator with a 15-µm-long plasmonic active section.

Device Characterization

Fig. 2(a) shows the passive on-chip transmission spectrum of the racetrack modulator. The data has been compensated for the fiber-to-chip coupling losses, which have been determined by cut-back measurements. The transmission in the on-state peaks at \sim -5 dB at a wavelength of 1580 nm, and amounts to \sim -7 dB at 1550 nm, where the extinction ratio is 39 dB, an indication that the critical coupling condition has been met.



Fig. 2: Transmission spectrum around the operating point. The Q factor is approximately Q=1250, which corresponds to an electro-optical bandwidth of 50 GHz. The red line indicates the operating point. Slight thermal drift was observed upon switching on the laser.

We determined the Q-factor of the resonator by $Q = \lambda_{\rm res} / \Delta \lambda_{\rm FWHM}$ and find found a value of $Q \approx 1250^{[1]}$. From that, the cavity lifetime can also be deduced,

$$\tau_{\rm cav} = \lambda_{\rm res} \cdot \frac{Q}{2\pi c_0} \approx 1 \, {\rm fs},$$

where $\lambda_{\text{res}} = 1549.08 \text{ nm}$ is the wavelength of

the resonant dip.

Following the approach of Gheorma and Osgood^[10], the electrical 3-dB bandwidth can be determined to be

$$f_{3 \text{ dB}} = \frac{1}{2\pi\tau_{\text{f}}} \sqrt{\sqrt{2} - 1} \approx 50 \text{ GHz},$$

A DC voltage of 1 V leads to a shift of the resonance wavelength by 0.12 nm. As a phase shift of 2π corresponds to a spectral shift of one full free spectral range, the device's half-wave voltage is deduced to be $12 V_{DC}$. We approximate the device by a lumped element capacitor due to its dimensions of <(100x50) μ m². Therefore, the RF half-wave voltage is 6 V_{RF} due to voltage doubling.

Data Modulation Experiments

The schematic of the data modulation setup is shown in Fig. 3. A sequence of 2^{17} random bits is loaded onto a digital-to-analog converter (DAC) with 100 GSa/s, an analog 3dB bandwidth of 35 GHz, and an output voltage swing V_p between 0.1 and 0.25 V_p. The output signal is amplified to peak voltages between 0.9 and 2.25 V_p. The bias tee enables the optional tuning of the modulator's operating point by applying a DC signal.

Light from a tunable laser is fed to the chip via a grating coupler. The optical power fed to the modulator is \sim 3 dBm. The modulated output signal is amplified in an erbium-doped fiber amplifier, attenuated to a power level of 8-10 dBm and fed to a high-speed pin photodiode.



Fig. 2: Schematic of the data modulation experiment. Insets show the received eye diagrams either after TR or LMS equalization. The BERs of all measurements are below the 7% HD-FEC threshold, those of 50 and 100 Gbit/s NRZ-OOK are compliant with the Ethernet standard KP4-FEC.

A bias tee with a terminated DC port acts as a DC block between the photodiode and a realtime oscilloscope (63 GHz bandwidth, 160 GSa/s), which records the signal. The offline DSP includes timing recovery, an optional T/2-spaced feed forward equalization, a hard symbol decision and counting of the bit errors.

Tab. 1 and 2 show a detailed summary of the data measurements. Bit error ratios (BER) are always below the hard-decision forward error correction (HD-FEC) threshold of $3.8 \cdot 10^{-3}$. For data rates below 50 Gbit/s (25 GBd and 50 GBd OOK, 25 GBd 4PAM) only timing recovery without any further equalization was applied. 25 Gbit/s and 50 Gbit/s OOK signals are even compliant with the Ethernet-standard KP4-FEC limit of $2 \cdot 10^{-4}$. For 100 Gbit/s (50 GBd 4-PAM and 100 GBd OOK), a T/2-spaced feedforward equalizing (FFE) step was employed after the timing recovery. The FFE is trained with a dataaided least mean square (LMS) update over the first 30% of the received symbols and is afterwards applied statically.

Tab. 1 Summary of the NRZ-OOK data modulation experiments. TR: only timing recovery performed, LMS: timing recovery and linear equalization performed.

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Data Rate [Gbit/s]	25	50	10	0
V _p @ 50 Ω [V]	0.9	0.9	1.3	2.25
DSP	TR	TR	LMS	LMS
BER	0	$7.5 \cdot 10^{-5}$	$1.8 \cdot 10^{-3}$	$3 \cdot 10^{-5}$

Tab. 2 Summary of the 4-PAM data modulation

experiments.				
Data Rate [Gbit/s]	50	100		
V _p @ 50 Ω [V]	1.1	2.25		
DSP	LMS	LMS		
BER	$7.75 \cdot 10^{-4}$	$2.57 \cdot 10^{-3}$		

The on-chip losses of 5 dB are by no means a fundamental limit. The plasmonic losses can be reduced by further reduced by 2-3 dB by means of an electronic codesign of the modulator drivers.^[11]

Conclusions

We have demonstrated plasmonic siliconphotonic racetrack modulators. A Q-factor of 1250 and the resulting 3-dB cutoff frequency of 50 GHz have been engineered to provide high modulation efficiency and sufficient bandwidth for 100 Gbit/s NRZ-OOK modulation with a drive voltage peak of only 1.3 V_p. The on-chip device losses of 5 dB do not represent an inherent limit of the technology as they can be further reduced.

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References

- W. Bogaerts *et al.*, "Silicon microring resonators," *Laser & Photonics Reviews*, vol. 6, no. 1, pp. 47-73, 2012
- [2] E. Timurdogan *et al.*, "An ultralow power athermal silicon modulator," *Nature communications*, vol. 5, pp. 4008-4008, 2014
- [3] D. A. B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications," J. Light. Technol., 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., "Plasmonic IQ modulators with attojoule per bit electrical energy consumption," *Nature Communications*, vol. 10, no. 1, p. 1694, 2019
- [6] C. Haffner et al., "Low-loss plasmon-assisted electro-optic modulator," Nature, vol. 556, no. 7702, pp. 483-486, 2018
- [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] A. Melikyan et al., "High-speed plasmonic phase modulators," Nat. Photonics, Article vol. 8, no. 3, pp. 229-233, 2014
- [9] D. L. Elder *et al.*, "Effect of Rigid Bridge-Protection Units, Quadrupolar Interactions, and Blending in Organic Electro-Optic Chromophores," *Chemistry of Materials*, vol. 29, no. 15, pp. 6457-6471, 2017
- [10] I. Gheorma *et al.*, "Fundamental limitations of optical resonator based high-speed EO modulators," *IEEE Photonics Technology Letters*, vol. 14, no. 6, pp. 795-797, 2002
- [11] 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," Optics express, vol. 27, no. 12, pp. 16823-16832, 2019