

# Plasmonic-organic hybrid (POH) modulators for OOK and BPSK signaling at 40 Gbit/s

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**Abstract:** We report on plasmonic-organic hybrid(POH) phase modulator generating error free (BER<10<sup>-10</sup>) BPSK signals at 40Gbit/s. In addition, generation and direct detection of 40Gbit/s OOK signals are discussed using POH Mach-Zehnder modulators on the transmitter side.

**OCIS codes:** (250.5403) Plasmonics; (230.2090) Electro-optical devices; (250.4110) Modulators

## 1. Introduction

Compact, high-speed and efficient optical modulators are essential for future optical interconnects [1]. Compact modulators are commonly realized using resonant structures such as ring or disk resonators or photonic crystals [2-4]. However, the resonant nature of these devices limits their operating wavelength range, makes an active temperature control inevitable and often limits the RF bandwidth due to the finite photon life time in the resonator [2]. Compact non-resonant modulators can be realized by plasmonic integration [5-8]. Among all, the plasmonic-organic hybrid(POH) approach allows phase modulations at rates of up to 40 Gbit/s by combining the metal slot waveguide with the electro-optic (EO) organic cladding [5,6]. A compact POH-Mach-Zehnder modulator (MZM) generating binary phase-shift keying (BPSK) signals at data rates of up to 72 Gbit/s with a bit error ratio (BER) of  $3 \times 10^{-3}$  has been reported recently [7]. However, the application of plasmonic modulators in optical links calls for lower BERs to minimize the coding overhead for forward error correction (FEC) and the associated latency. Furthermore, on-off-keying (OOK) with direct detection remains the most promising method for short-reach links because of its technical simplicity and low implementation costs [9]. Thus, a plasmonic MZM that can reliably generate OOK signals is in the focus of interest.

Here, we report on highly efficient POH modulators that enable the lowest BER so far been achieved with plasmonic devices at technically relevant data rates. In particular, we demonstrate a 29  $\mu\text{m}$ -long BPSK modulator and show error-free (BER <  $1 \times 10^{-10}$ ) operation at up to 40 Gbit/s. The modulator's energy consumption amounts to 70 fJ/bit. Furthermore, we report on the generation and direct detection of 40 Gbit/s OOK signals using POH-MZMs at BER less than  $6 \times 10^{-4}$  which is below the threshold of hard-decision FEC codes. To the best of our knowledge, this is the first error-free generation of BPSK signals using POH phase modulators, and the first 40 Gbit/s OOK signaling with a POH-MZM.

## 2. Design and fabrication

The POH modulators are realized on a silicon-on-insulator (SOI) wafer and silicon nanowires are used as access waveguides to the modulators. The BPSK modulator is constructed from a single POH phase shifter (PS) operating as a phase modulator (PM), see Fig. 1(a) and (b) [5]. Light is coupled in and out of the silicon nanowire waveguide using silicon diffraction grating couplers. The phase of the optical signal is modulated in the plasmonic PM section with the length of 29  $\mu\text{m}$ , see Fig. 1(b). The gap surface plasmon polariton (SPP) mode is excited via metallic taper mode converters. The POH-MZM for OOK consists of PSs placed in each of the two arms of a Mach-Zehnder interferometer (MZI), see Fig. 1(c). The MZI is designed with unbalanced arms to enable adjustment of the operating point by wavelength tuning. Silicon multimode interference couplers act as optical power splitters/combiners.

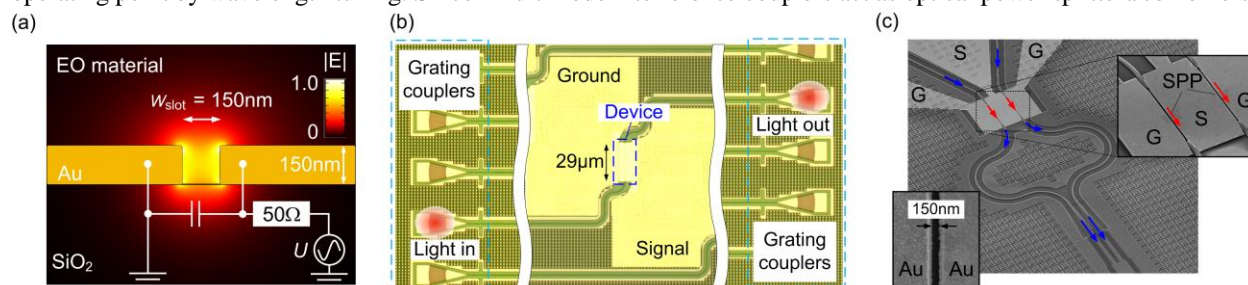


Fig. 1: Plasmonic-organic hybrid (POH) phase modulator (PM) and Mach-Zehnder modulator (MZM) realized on an SOI platform. (a) Gap-SPP mode profile in a metal slot filled with an electro-optic (EO) material. (b) Optical microscope image of the fabricated POH-PM. Grating couplers are used to couple light in and out of the chip. (d) Scanning electron microscope (SEM) picture of the POH-MZM. The modes of the Si waveguide are coupled to the POH-PS, where the SPP phase is modulated.

The passive silicon photonic circuit is fabricated using standard processes such as 193 nm DUV lithography and Si dry etching in the framework of ePIXfab. The PM is fabricated with a ground-signal configuration as described in Ref. [5], see Fig. 1(b). For the MZM, two high-speed PS with a common signal electrode are fabricated as given in

Fig. 1(c). The metallic slots having widths of 150 nm are fabricated with e-beam lithography and a lift-off process. The slot of the POH-PMs is filled with an EO material YLD124/PSLD41(25:75 wt.%) mixture which has been shown to provide a record EO coefficient of  $r_{33} = 230 \text{ pm/V}$  [10]. For the POH-MZM, we employ the EO material SEO100 (Soluxra, LLC) because of its good thermal stability up to 85°C, which is an important requirement for use in real-world communication systems. The Pockels effect in the EO materials is activated via a poling procedure.

### 3. Data modulations

In the BPSK modulation experiments, light with a wavelength of 1550 nm and with a power of +10 dBm is launched into the chip. The phase of the SPP is encoded with a  $2^{31} - 1$  long pseudo-random bit sequence (PRBS) at a voltage swing of  $U_{pp} = 3.8 \dots 4.2 \text{ V}$ , measured across a  $50 \Omega$  resistor. Constellation diagrams of the optical signal with the corresponding error vector magnitudes (EVM) are depicted in Fig. 2(a), (b). The BER corresponding to the measured EVMs are below  $10^{-10}$ , which is a record value for POH devices [11]. We calculate an energy consumption of  $(2U_{pp})^2 \times C_{\text{device}}/4 \approx 70 \text{ fJ/bit}$  for 40 Gbit/s operation, where the device capacitance  $C_{\text{device}} = 4.5 \text{ fF}$ .

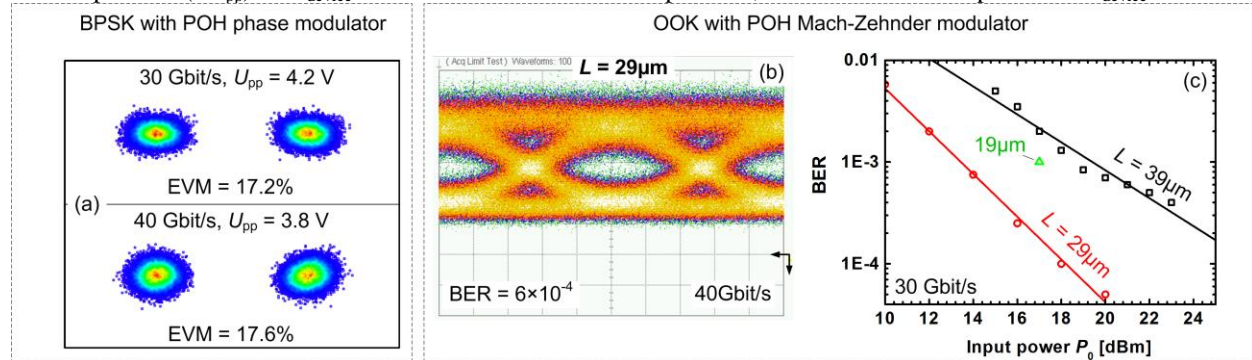


Fig. 2 Experimental results of BPSK and OOK data modulations. (a) BPSK constellation diagrams generated with the POH-PM at the bit rates of 30 Gbit/s and 40 Gbit/s. Measured EVMs are  $\sim 18 \%$  corresponding to BERs less than  $10^{-10}$  [11]. (b) An eye diagram of the 40 Gbit/s OOK signal after the POH-MZM with  $29 \mu\text{m}$  long phase shifters and received with a standard pre-amplified direct receiver. Corresponding BER is in the range of  $6 \times 10^{-4}$ . (c) BERs measured for the POH-MZMs with PSs having lengths of  $19 \mu\text{m}$  (one measurement point, the device deteriorated),  $29 \mu\text{m}$  and  $39 \mu\text{m}$  for various modulator input powers. A compromise between the optical loss and the modulation index can be achieved by using a MZM with a PM length of  $29 \mu\text{m}$ .

In the OOK modulation experiments, an electrical NRZ signal with PRBS pattern length of  $2^{31} - 1$  and with a voltage swing of 5V (measured across a  $50 \Omega$ ) is fed to the modulator via a ground-signal-ground (GSG) RF probe. Intensity modulated signal is received with a standard pre-amplified direct receiver. The eye diagram measured after the MZM with  $29 \mu\text{m}$  long PM sections for bit rate of 40 Gbit/s (BER =  $6 \times 10^{-4}$ ) is given in Fig. 2(b). The measured BER is below the threshold of  $4.5 \times 10^{-3}$  for hard-decision FEC codes with 7% overhead [12]. In order to find the optimum length of the PSs, we measured the BERs for MZMs with three different lengths of PSs and for various modulator input powers while operating the EDFA in a constant output power mode (gain/current controlled). The optimum length of the PS is defined by a compromise between insertion loss and modulation index — making the device too short results in a small optical modulation amplitude, while too long a phase modulator section decreases the receiver's input power. We find that in our case ( $U_{pp} = 5 \text{ V}$ , SPP propagation losses of  $\sim 0.4 \text{ dB}/\mu\text{m}$ ,  $r_{33} = 70 \text{ pm/V}$ ) the optimum performance can be achieved with  $29 \mu\text{m}$  long phase modulators, see Fig. 2(c).

### 4. Summary

We report on error-free generation and detection of 40 Gbit/s BPSK signals using a  $29 \mu\text{m}$  POH phase modulator with an energy consumption of 70 fJ/bit. Furthermore, we report on OOK signaling with POH Mach-Zehnder modulators (MZM) at rates of up to 40 Gbit/s. The measured BERs represent the lowest values that so far been shown with plasmonic modulators at technically relevant data rates.

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