Plasmonic-Organic Hybrid (POH) Modulators

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Abstract: *An overview of high-speed plasmonic-organic hybrid (POH) modulators for BPSK and OOK signaling is presented. The optimum length of POH modulators resulting in maximum optical modulation amplitudes (OMA) are discussed.*
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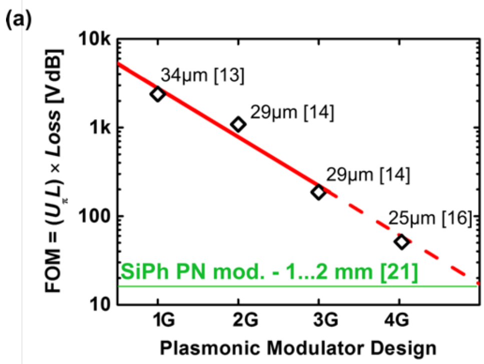
I. INTRODUCTION

Electro-optic modulators are key components in optical communications links [1]. They are required for electrical-to-optical signal conversions on the transmitters side of the optical link. To meet the future demands of large capacity optical links, the modulators should allow scaling in both number of parallel channels and the symbol rates [2]. Silicon photonics has been envisaged as the technology that fulfills both these requirements at reasonably low cost [3]. Most of the high-speed silicon photonic modulators use the plasma dispersion effect in silicon PN-junction and provide data rates up to 40 Gbit/s [1]. To generate sufficient modulation amplitudes, these devices are typically several millimeters long, which limits the integration density and imposes practical challenges associated with the group velocity matching and with the electrical/optical losses [4]. A more efficient phase modulation is reported for silicon-organic hybrid (SOH) modulators [5]. The high-speed operation of SOH modulators, however, is challenging because of the large RC-time constant of the devices [5]. To achieve modulation bandwidths in excess of 100 GHz, a vast amount of research has been long directed towards discovering novel and non-traditional solutions using metal optics – the so called plasmonics [6]. Plasmonic high-speed modulator designs, fundamentally relying either upon the Pockels [7] or the carrier dispersion [8-12] effects, have been subsequently reported.



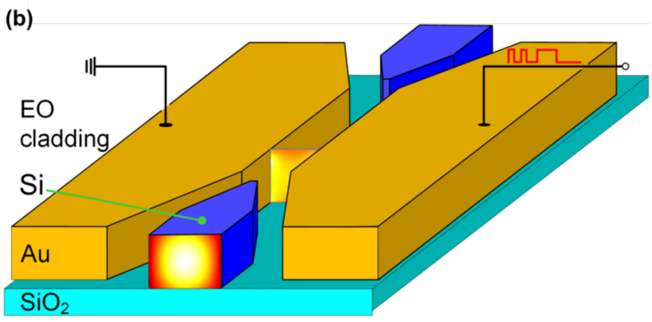


Fig. 1. Plasmonic-organic hybrid technology and an overview of the figure-of-merits (FOM) reported previously. (a) Performance improvement reported for POH modulators over the last several years. In the calculation of the FOMs, only the optical losses in the plasmonic section are only considered. (b) The schematic of the POH phase modulator comprising two metallic taper mode converters and metallic slot waveguide.

In 2014, a plasmonic-organic hybrid (POH) was demonstrated for the first time. It provides an electro-optic bandwidth of 64 GHz for the sub-50 µm long phase shifters [13, 14]. Moreover, recent developments in this area demonstrate the unequalled compactness of POH modulators, with footprints of only a few square micrometers [15]. The POH modulators have also the potential to outperform most of the conventional solutions in terms of the modulation bandwidths and the required drive voltages [13-20]. Fig. 1(a) summarizes the evolution of the POH modulators in terms of a figure of merit (FOM) defined as a product of $U_\pi \times L$ and optical loss [21, 24], where $U_\pi \times L$ is the voltage-length product that results in a phase modulation of π for a modulator of length L. Typical FOMs reported for state-of-the-art silicon modulators are given in a green solid line [21]. For given optical and electrical input powers, POH modulators might soon be able to provide the same optical modulation amplitudes at much higher speeds and with significantly smaller footprints. Provided that some of the technical challenges of POH modulators are solved in the future, the scaling in the symbol rates and in the numbers of parallel spatial and/or wavelength channels will become practical with POH modulators for a broader application range in optical communications. A step further is taken in Ref. [18, 19], by demonstrating the first POH modulator array for optical interconnect applications.

In this paper, we provide an overview of some of these latest advances in the field of plasmonic-organic hybrid (POH) integration [13-20]. The POH technology is first introduced followed by the discussion of the performance of POH modulators in direct detection and coherent systems [13,14]. First, we discuss error-free binary phase shift keying (BPSK) signaling with a single POH phase modulator for data rates up to 40 Gbit/s [14]. For low-cost direct detection applications, on-off keying (OOK) at the data rates of 40 Gbit/s is reported by incorporating two POH phase modulators in a silicon photonic Mach-Zehnder (MZ) interferometer [14]. As a fundamental limitation, the influence of the optical losses on the performance of a POH MZ modulator is discussed. The optimum POH phase shifter length resulting in a maximum optical modulation amplitude (OMA) is discussed.

II. Plasmonic-organic hybrid (POH) modulators

The plasmonic section of a POH modulator is a metallic slot waveguide (MSW) comprising two metal electrodes separated by a sub-200 nm gap which is filled with an electro-optic organic cladding, see Fig. 1(b). Adiabatic metallic tapers convert the photonic mode to a plasmonic mode and vice versa [22]. Alternatively, an MSW can be constructed by stacking two metal electrodes separated by a horizontal slot filled with an electro-optic material. In this case, a directional coupler can be used for efficient photonic-to-plasmonic mode conversion [20]. In MSWs, both the optical and the RF fields are confined to the slot, resulting in a strong interaction between the two [6]. The modulating RF field changes the refractive index of the EO material inside the slot through the Pockels effect [23]. The refractive index change then produces a phase modulation of the optical signal propagating in the device.

A. Plasmonic-organic hybrid (POH) phase modulators

Fig. 2(a) shows the schematic of the POH phase modulator fabricated on silicon photonic circuit [13, 14]. Low-loss silicon waveguides are used for on-chip light routing. Light from a single mode fiber is launched to and collected from silicon waveguides with grating couplers (GC) having a coupling loss of 4…5 dB.

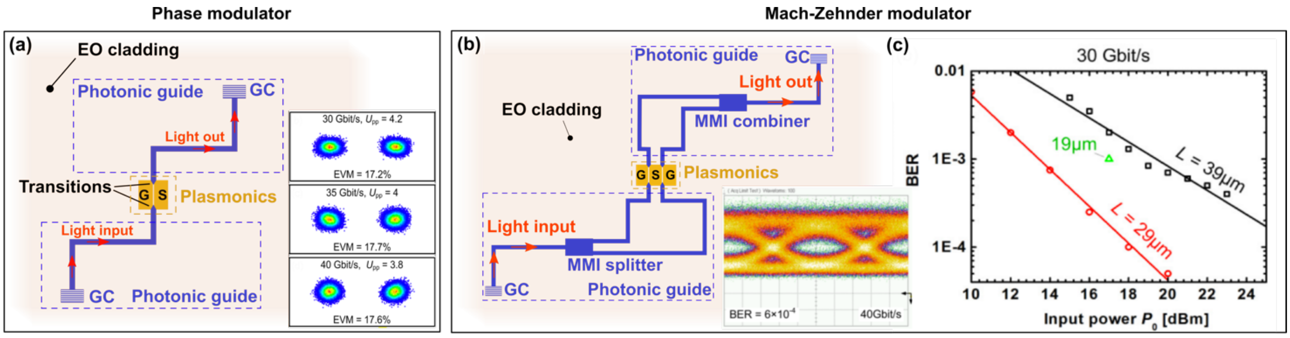


Fig. 2 Plasmonic organic hybrid (POH) phase and Mach-Zehnder modulators. (a) Schematic of the POH phase modulator. Grating couplers(GC) are used to couple light to the silicon waveguide (blue). The photonic-to-plasmonic conversion is performed by metallic tapers. Error-free BPSK constellation diagrams up to 40 Gbit/s generated with a coherent receiver are given as insets. (b) POH Mach-Zehnder (MZ) modulators. Two POH phase modulators with the length of $L = 29$ µm are incorporated in the arms of a silicon photonic MZ interferometer. The MZ interferometer comprises two 1×2 multimode interference couplers and nanowire waveguides. The footprint of the active part of the modulator is 21×29 µm^2. A 40 Gbit/s OOK NRZ eye diagram measured with a standard pre-amplified direct detection receiver is given as inset. (c) Performance dependence on the phase shifter length. For given optical and RF input powers, a POH phase shifter with the optimum length generates in a maximum optical modulation amplitude [14].

Binary phase shift keying (BPSK) modulation is reported with POH technology using a single phase modulator [6-7]. For a drive voltage swing of 3.8…4.2 V_{pp} and an input optical power of +10 dBm, error free BPSK reception with a bit error ratio of 10^{-10} are reported for 30 Gbit/s, 35 Gbit/s and 40 Gbit/s with absolutely no dependence on the data rate, see Fig. 2(a) [14].

B. Plasmonic-organic hybrid Mach-Zehnder modulators

The intensity modulation in a Mach-Zehnder (MZ) interferometric configuration has been reported by incorporating two plasmonic phase shifters inside a MZ interferometer, see Fig. 2(b) [14]. The OOK signals after the POH MZM have been received with a standard pre-amplified direct detection receiver. The 40 Gbit/s optical OOK eye diagram is given as an inset in Fig. 2(b) with the measured bit error ratio (BER) of 6×10^{-4}, which is below the threshold of the hard-decision forward error correction codes. We further study the influence of the length of the POH phase shifters on the optical signal quality [14]. A modulator with the optimum length realizes the best compromise between modulation depth and optical loss, and therefore leads to maximum optical modulation amplitudes, see Fig. 2(c).

III. Conclusions

We gave an overview of high-speed plasmonic-organic hybrid (POH) modulators for BPSK and OOK signaling for both direct detection and for coherent systems at data rates up to 40 Gbit/s. We also investigated the optimum length of the phase shifter sections inside the POH Mach-Zehnder modulator resulting in a maximum optical modulation amplitude and a minimum bit error ratio.

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