Low-Power Data Center Transponders Enabled by Micrometer-scale Plasmonic Modulators

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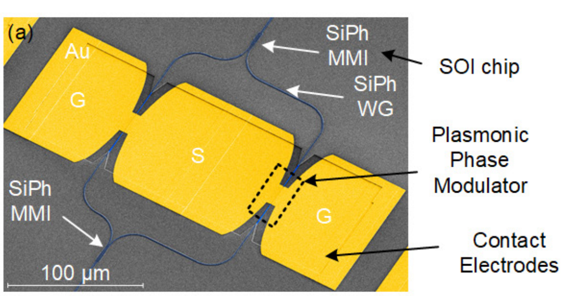
Abstract: Plasmonic modulators allow for high-speed data modulation beyond 200GBd at the micrometer-scale and low driving voltages below 700mV. The compact footprint enables dense integration and makes plasmonic modulators a promising solution for next-generation optical interconnects.

1. Introduction

Electro-optic (EO) modulators, that convert electrical into optical signals with low power consumption and high bandwidth, are a key element in transceivers for data center applications. The EO data conversion is the bridging element between the electronic world of information processing and the photonic world of information transport. However, the ever-increasing amount of generated information leads to a disparity between data generation and the EO conversion of this data, resulting in an interconnect bottleneck [1, 2]. The increasing bandwidth demands in all kind of networking applications, from high-performance computing and data center inter/intra connections to the optical backbone network, require scaling through spectral and spatial parallelism [1] under the constraint of low power consumption [3]. Realizing scaling through parallelism requires the dense integration of transceiver arrays on smallest footprints, preferably down to the micrometer scale to meet requirements of for example a 300 µm lane pitch, enabling an optical interface for switch-ASICs [4]. Besides compactness, a large EO bandwidth of up to 100 GHz is needed to realize simple and cost-efficient NRZ coding as well as to avoid inverse multiplexing [5]. Most important for the realization of such densely integrated high bandwidth EO interfaces is cost-efficiency in terms of power consumption and manufacturability. Power consumption can be reduced by avoiding power-hungry electronic amplifiers as well as by optimizing the interface between electronic circuitry and optical components in by means of close co-integration and the realization of non-50 Ω terminated electrical interfaces [1, 6]. Manufacturing costs can be reduced with help of scalable technologies such as silicon photonics [7], that allow for integration of several components and systems on a chip while relying on mature wafer fabrication techniques from the electronics industry



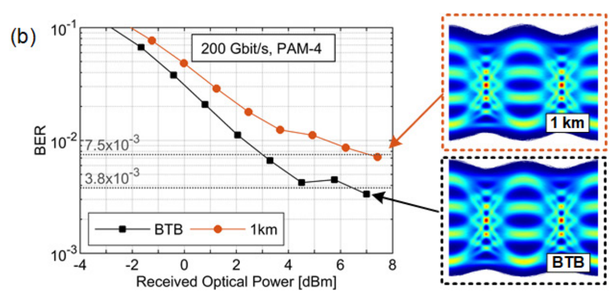


Fig. 1. (a) Colorized SEM picture of a plasmonic organic-hybrid Mach-Zehnder modulator on the silicon on insulator (SOI) platform including silicon photonics (SiPh) multimode interference (MMI) coupler and waveguides (WG). (b) 200 Gbit/s PAM-4 IM/DD transmission: BER as a function of received optical power in a IM/DD transmission distance of up to 1 km and data modulation of 200 GBit/s PAM-4 enabled by an plasmonic Mach-Zehnder modulator. [37]

[4, 8]. Furthermore, monolithic [9, 10] or hybrid [11] integration of electronics and optics on the same wafer improves high-speed performance by lessening bandwidth limiting parasitics and can help reducing manufacturing costs.

Power- and cost-efficient EO interfaces predominantly find their application in simple and cost-effective intensity modulated (IM) and direction detection (DD) systems for short-reach interconnects, deployed for distances from a few meters up to a few kilometers within or in-between datacenters [12]. The EO conversions can be realized as a directly modulated (DML) laser, or with an externally modulated laser (EML) in terms of electro-absorption modulators (EAMs) or Mach-Zehnder modulators (MZMs). Demonstration of DMLs can be found either as VCSELs [13] or as DFB laser diodes [14, 15]. The EAM concept has been demonstrated mainly on two platforms, Indium Phosphide [16, 17] and Germanium Silicon [18, 19]. The MZM concept has been demonstrated on different technology platforms including Lithium Niobate [20, 21], silicon photonics [22, 23], silicon-organic hybrid [24], Indium Phosphide [25, 26], and polymer photonics [27].

Recently, the plasmonic-organic hybrid (POH) technology has demonstrated high modulation speeds (200 Gbit/s direct detection), small footprint (10s of µm), and power efficient operation (V_{pp} < 200 mV), making it a promising solution for data center transponder applications. This paper reviews the recent progress in plasmonics as a solution for optical interconnects.

2. Plasmonic-Organic Hybrid Modulators Concept

The plasmonic-organic hybrid (POH) modulator technology [28] takes advantage of the silicon photonics platform and enhances it by high-speed and compact active plasmonic structures (see Fig. 1(a)). On the one side, the silicon photonics platform allows for the dense integration of mature passive components with high fabrication yield, low-cost fabrication, and still acceptable small footprints [29]. On the other side, plasmonic technology enables micrometer-small and terahertz [30] fast active devices. The plasmonic Mach-Zehnder modulator consists of two plasmonic phase modulators embedded in a silicon photonic Mach Zehnder interferometer. The phase modulators form the active sections of the MZM. They are combining the advantages of plasmonic sub-wavelength light confinement [31, 32] and efficient organic electro-optic materials [33]. This way they enable MZMs featuring voltage-length products of down to 50 Vµm [34] with active lengths of typically 10 µm to 20 µm, mitigating plasmonic propagation losses. Further, the micrometer-scale characteristic of the plasmonic modulator technology allows for an ultra-broad electro-optical bandwidth beyond 500 GHz [35]. It originates from the quasi-instantaneous Pockels effect and the extremely small RC time constant of the electrode structure. In fact, the plasmonic phase modulators feature capacitances down to 3fF, and, due to the compact size, can be considered as a lumped element up to >100 GHz that do not require a 50 Ω far-end termination. This way, plasmonic modulators avoid travelling-wave electrode designs of MZMs and the dominant power dissipation in the termination resistance required for impedance matching. Furthermore, the POH technology has shown improved performance in terms of modulation efficiency at a wavelength of 1310 nm [36] that is typically used for transmission distances below 10 km. This makes the plasmonic MZM a suitable solution for optical interconnects that was demonstrated for 200 Gbit/s PAM-4 over 1 km of SSMF with IM/DD (see Fig. 1(b)) [37].

3. Low driving voltage operation

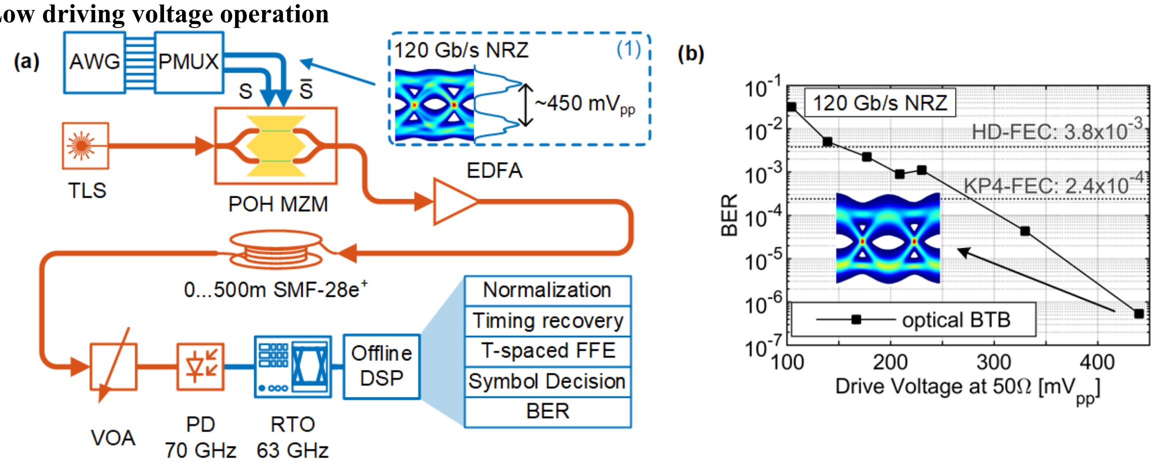


Fig. 2. (a) Experimental setup of a short-reach interconnect with intensity modulation and direct detection and a differentially driven plasmonic-organic hybrid MZM operated at 120 GBd NRZ. (b) BER as a function of reduced peak-to-peak driving voltages for 120 Gbit/s NRZ data modulation [38]

To allow for low-voltage electrical drivers, the plasmonic modulator can be implemented in a balanced differential driving configuration ($\overline{S}S\overline{S}$) [38]. Enabled by the compact size of the modulator and it's lumped capacitive impedance characteristic this implementation allows for a four times stronger voltage drop at the modulator compared to a conventional dual electrode GSG$\overline{S}$G driving scheme with 50 Ω termination. Thus, requirements on the electrical driver can be drastically reduced. The differentially driven MZM has been demonstrated to operate at 120 Gbit/s NRZ-OOK with a peak-to-peak drive voltage of only 178 mVpp measured at 50 Ω (see Fig. 2). This corresponds to a potential electrical energy consumption of only 862 aJ/bit dissipated in the modulator. Recently, this implementation was connected via ribbon bonds with a driver-amplifier-less high-speed multiplexer enabled a 222 GBd NRZ-OOK data modulation [39].

4. Dense integration of plasmonic modulators

The compact footprint of the plasmonic modulator allows for a dense integration of several parallel transmitters [40], resulting in an 0.8 Tbit/s data modulation on an area of only 90 μm × 5.5 μm [41]. The possibility for dense integration allows not only for parallelization but also for more complex devices like most compact IQ-MZMs [42, 43] that have been demonstrated to operate at 100 GBd without electrical driving amplifier or electronic equalization [44]. Ultimately, it has been demonstrated that plasmonic modulators can be integrated on almost any substrate [45]. This resulted in the demonstration of a monolithic transmitter on a BiCMOS-plasmonic platform with data modulation beyond 100 GBd [46].

5. Summary

The recent progress in the plasmonic modulator technology demonstrates plasmonics to be a viable solution for optical interconnects in datacenters offering high speed, low driving voltages, and compact form factors. Further, plasmonic modulators enable dense integration and parallelization as well as the direct integration on an electronic chip. We show that plasmonic modulators overcome limitations in size, speed and drive voltages of conventional modulators, enabling power-efficient and highly parallelized interconnects for 1.6 Tbit/s and beyond.

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