Plasmonic Modulators: Bringing a New Light to Silicon

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Abstract *Plasmonic modulators provide high speed and convenient integration on SiPh platforms. To confirm their commercial viability, we discuss process integration and show reliability data under operation achieving a stability within ±2.5% of V_π in both low oxygen and air atmospheric conditions.*

Introduction

Advanced manufacturing processes have enabled the silicon photonic (SiPh) platform to become a key player in high-density photonic integration. In this context, a promising approach is hybrid and heterogeneous integration, which merges different materials and functionalities. For instance, to build a transceiver for optical communications, photonic integrated circuits (PICs) benefit from electronic ICs for driving the modulator, amplifying the signal from the photodetector, and performing additional digital signal processing. Further, manufacturing a laser in silicon is not feasible due to the indirect bandgap of the material. For this reason, most PICs today use disaggregated lasers. Incorporating modulators in the SiPh platform presents a further obstacle, as they have traditionally relied on free-carrier dispersion which exhibits relatively low modulation efficiency and limited bandwidth, due to high junction capacitances. Consequently, Pockels-type materials have been introduced to enable high-efficiency and high-bandwidth modulators. Determining how to integrate the different functions required to construct a system in the SiPh platform depends not only on performance but also on process integration and reliability considerations.

In this paper we will discuss the integration of plasmonic modulators into the SiPh platform. Our approach combines Pockels materials with plasmonic waveguiding. This enables ultra-fast modulation at a small scale (µm lengths), with speeds up to 500 GHz. Following an introduction to plasmonic modulators, the paper focuses on process integration and the reliability of commercial devices.

Plasmonic Modulators

A plasmonic phase modulator consists of a metal-insulator-metal slot waveguide that is filled with a Pockels material, see Fig. 1 [1]. This configuration is particularly suited for high-speed modulation since the metallic rails serve as both, plasmonic waveguide and electrical contacts of low resistance and capacitance. Application of a voltage across the contacts causes the refractive index of the Pockels material in the slot to alter, which results in a change in the phase of the guided light. When integrated into a Mach-Zehnder interferometer, this phase modulation is translated into an amplitude modulation (Mach-Zehnder modulator, MZM)

Several Pockels materials are available as thin films, including lithium niobate [2-4], barium titanate [5-7], and organic electro-optic (OEO) materials [8]. For plasmonic applications, we specifically opted to use OEO materials. Although the stability of OEO materials can be challenging, they offer high nonlinearity and large intrinsic bandwidths. Importantly, OEO materials are easy to process as their solubility allows for coating or printing onto various platforms at a large scale.

Process Integration

Plasmonic devices benefit from their small footprint allowing to make most efficient use of the costly wafer area, which is a primary commercial concern. However, the effective yield can be affected by process integration challenges. Firstly, plasmonic components currently rely on materials that are not compatible with CMOS foundries. Secondly, the minimum feature size required by plasmonics is at the limit of processes available in photonic foundries.

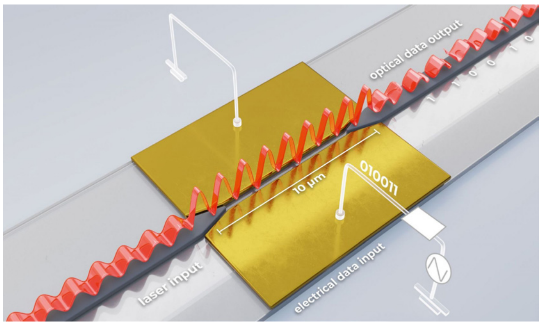

Fig. 1 Plasmonic phase modulator consisting of a metal-insulator-metal waveguide and a Pockels material.

One possible solution to these challenges is to post-process plasmonic components as a final step in the back-end-of-line to avoid impacting the standard process flow of the foundry. For example, plasmonic modulators have been integrated monolithically with SiGe driving electronics on the same chip in a post-processing step in [9].

Reliability

Although organic light-emitting diodes (OLEDs) have been successfully implemented in various consumer electronics such as cell phones and digital cameras, the hybrid integration of organic materials with PICs is still in the early stages of development. However, significant progress has been made in the recent past to develop stable and high-performance OEO materials for integrated modulators. In [10], the long-term shelf storage of the OEO material HLD was examined and proved to be stable at 85 °C under inert conditions. Similarly, [11] showed the storage at 85 °C of modulators containing Perkamine 3 and 5 without degradation. Further, continuous modulation in a plasmonic modulator was shown at 85 °C and 100 GBd NRZ for 330 min with the Perkamine 3 material [6]. While the results of these studies are promising, longer in-device reliability testing during operation is needed to meet desirable standards. Hereafter we present reliability data for plasmonic MZMs containing the OEO material HLD over weeks and months.

In a first experiment, long-term operation of a packaged plasmonic MZM was evaluated by operating in a controlled low-oxygen atmosphere environment at room temperature. The device was operated at 1524 nm wavelength, 0 dBm optical input power and without RF power. A bias voltage was applied to the DC electrodes to compensate for a possible drift and an automatic bias-control circuit locked the device operating point. The voltage V_π required to switch the modulator from the on- to the off-state was determined by overmodulating the device using a triangular 100 kHz drive signal [12]. The voltage V_π, the insertion loss IL, and the bias voltage V_bias were recorded every 10 min for >4500 h (>6 months). All parameters were normalized to the first data point. As shown in Fig. 2, the variation of V_π remained within ±2.5% over 4500 h, the IL stayed within 0.3 dB and the V_bias within 15%. The outliers in the IL curve are attributed to instability of the measurement setup.

In a second experiment, an unpackaged and wafer-level encapsulated plasmonic MZM was operated in air atmosphere and at room temperature for several weeks. In this case, the device was operated at 6 dBm optical input power. The operating point was set via adjusting the signal wavelength in an imbalanced Mach-Zehnder interferometer configuration. The initial $V_{\pi,\mathrm{eq}}$ (at 50 Ohm) of 3.7 V stayed within ±2.5% over >400 h, see Fig 2. The step variations are not related to changes in the performance of the device, but rather to the measurement system.

These promising initial results suggest that plasmonic modulators utilizing OEO materials have the potential to meet reliability standards, and further data could solidify their viability in practical applications.

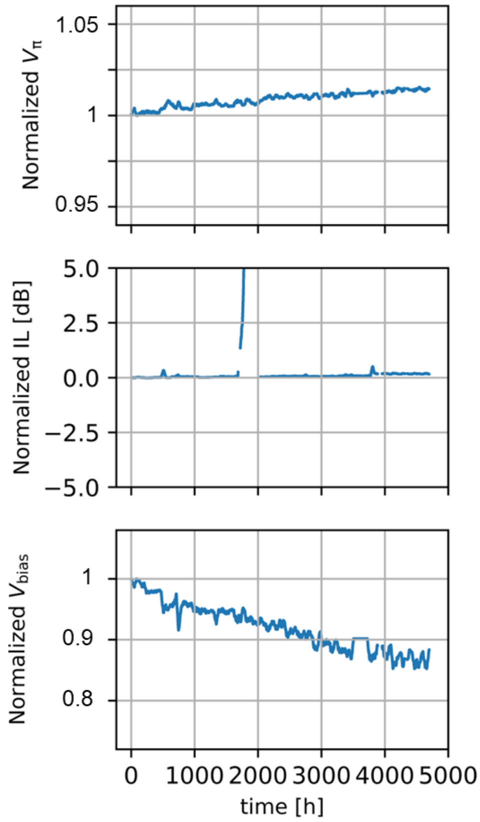

Fig. 2 Long-term stability of an MZM operated in low-oxygen atmosphere at 0 dBm optical input power for >6 months.

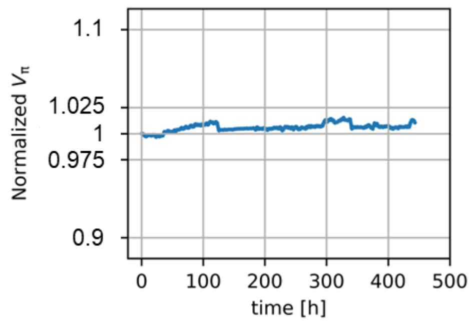

Fig. 3 Stability of an MZM operated in air at 6 dBm optical input power for several weeks.

Conclusions

To conclude, advancements in performance, manufacturing processes, and reliability of Plasmonic modulators integrated in the SiPh platforms are expected to continue, enabling the use of complex photonic integrated circuits (PICs) in an increasing number of applications.

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