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Electrically Packaged Silicon-Organic Hybrid Modulator for Communication and Microwave Photonic Applications

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Abstract: We demonstrate electrical packaging of a silicon-organic hybrid (SOH) modulator. Gold traces on an Al_2O_3 substrate define the electrical connections to an IQ-modulator having a π-voltage of 1.5 V. Signal generation up to 128 Gbit/s is demonstrated.

OCIS codes: (250.7360) Waveguide modulators; (230.2090) Electro-optical devices; (130.3120) Integrated optics devices;

1. Introduction

Efficient broadband electro optic (EO) modulators are key components in microwave photonics and optical communications. Silicon-organic hybrid (SOH) EO devices [1], in particular, have been shown to exhibit record performance with respect to efficiency [2,3], bandwidth [4] and achievable data rates [5–7]. The SOH integration concept combines silicon photonic (SiP) waveguides with organic EO cladding materials, thereby leveraging both the benefits of large-scale CMOS processing and the wealth of optical properties obtained by theory-guided molecular design of organic chromophores [1,8]. However, to leverage these fundamental advantages in technical applications, SOH devices need to be complemented by stable organic materials and reliable packaging technologies. With recent progress towards stable organic EO materials [9] and novel technologies for a hybrid photonic integration [10], broadband electrical packaging remains as one of the key challenges. In general, a good electrical package should provide good mechanical stability and protection, efficient thermal coupling to a heatsink, and efficient radio frequency (RF) transmission to external circuits. Moreover, when it comes to RF packaging of densely integrated SiP components, the underlying printed circuit board (PCB) must bridge the gap between microscopic on-chip transmission lines and macroscopic external RF components and connectors. This requires RF PCB that combine micrometer resolution with overall board dimensions on the centimeter scale.

In this paper, we demonstrate broadband electrical packaging of an SOH modulator using a PCB based on a ceramic substrate and a Au layer. The Au is patterned by direct laser writing (DLW) and wet etching, allowing scaling to large areas while enabling trace widths and spacings as small as 7 µm. The traces form transmission lines (TL), which support signals with bandwidths of more than 60 GHz. The PCB is wire-bonded to the SOH chip and populated with GPPO compatible end-launchers to interface with coaxial cables. The embedded modulator has a π-voltage of only 1.5 V and allows to generate on-off keying (OOK) signals with line rates of up to 40 Gbit/s and quadrature phase-shift keying (QPSK) signals with symbol rates (line rate) of 64 GBd (128 Gbit/s). To the best of our knowledge, this is among the highest symbol rates so far demonstrated with an electrically packaged SiP modulator.

2. Device Concept, Fabrication and Characterization

The concept of the SOH Mach-Zehnder Modulator (MZM) is shown in Fig. 1. The basic waveguide structure is fabricated on standard silicon-on-insulator (SOI) wafers using 248 nm deep-UV lithography. Each arm comprises a slot waveguide with Si rails. These rails are electrically connected to an aluminum (Al) coplanar ground-signal-ground (GSG) TL by thin, doped Si slabs and Al vias. In a post-processing step, the slots are filled with the organic

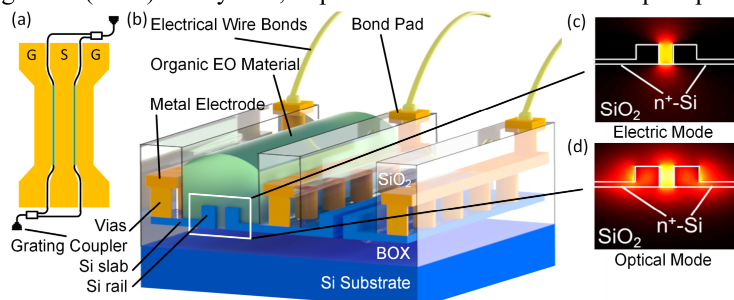

Fig. 1. SOH device concept. **(a)** Schematic of Mach-Zehnder modulator (MZM) with ground-signal-ground transmission line electrodes. **(b)** Artist's view of MZM; the organic EO cladding (green) is shown in one arm only. Aluminum vias connect the doped thin Si slabs with the travelling-wave electrodes and the top metal layer with bond pads. **(c)** RF electric field. **(d)** Optical electric field, showing strong overlap with the RF mode field, leading to efficient modulation.

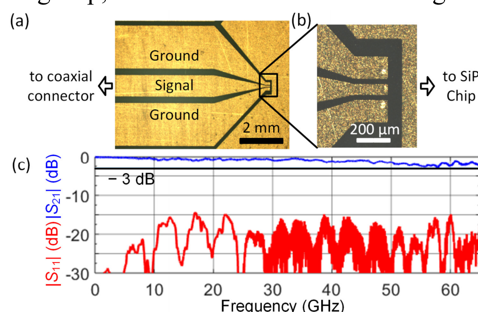

Fig. 2. PCB. **(a)** Tapered TL structure interfacing macroscopic RF components to microscopic on-chip bond pads. **(b)** Traces matching the size scales of on-chip pads. **(c)** Reflection ($|S_{11}|$) and transmission factor ($|S_{21}|$) of a 14 mm long Au trace comprising two of the tapers shown in (b).

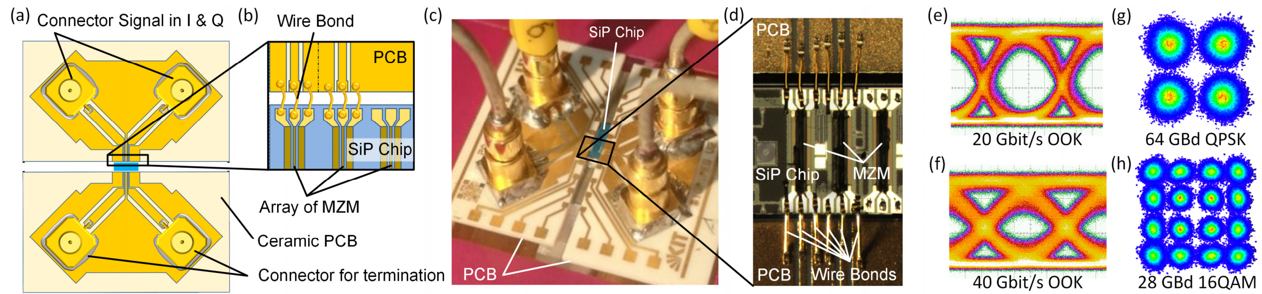

Fig 3. Electrical packaging. **(a)** Schematic of PCB layout connecting two MZM with surface-mounted end-launchers. **(b)** Two MZM are connected with wire bonds. **(c)** Image of the module. (d) Image of MZM array schematically depicted in subfigure (b). **(e, f)** OOK modulation. eye diagrams at 20 Gbit/s and 40 Gbit/s. **(g, h)** Constellation diagrams for 64 GBd QPSK and 28 GBd 16QAM.

EO material SEO250. Both, the optical and the RF field are highly confined in the slot leading to an efficient EO modulation after an appropriate poling step [1].

The PCB traces are realized as 50 Ω coplanar ground-signal-ground TL. To realize short wire bonds and to enable dense integration of a modulator array, the dimensions of the traces need to match the dimensions of the bond pads on the silicon chip, which are kept small to save chip area. For flexible low-cost fabrication of PCB with small feature sizes, centimeter-scale overall dimensions, and excellent RF properties, we developed a DLW-based fabrication process. An Al_2O_3 substrate with a 3 µm thick electroplated Au layer is coated with a photoresist which is patterned with a Nd:YAG laser. After development, the Au layer is wet-etched and the resist mask is removed. Figure 2(a) shows a micrograph of a fabricated coplanar TL. Figure 2(c) demonstrates the high transmission and reflection quality of the taper which interfaces the microscopic on-chip TL pads (80 µm), Fig. 2(b), to the larger structures, Fig. 2(a), that matches with solder parts such as end launchers and SMD components.

The schematic of the assembled module is shown in Fig. 3(a, b). The travelling-wave electrodes of the modulator are connected to PCB traces at both ends. Surface-mounted GPPO-compatible mini-SMP end-launchers and coaxial cables are used to connect to the signal source and to terminating resistors. The module contains two MZM that can be used individually for amplitude or intensity modulation, or can be operated, by using different optical inputs and outputs, as two nested MZM which form an IQ-modulator. Figure 3(c) shows an image of the module, and Fig. 3(d) displays a micrograph of the bonded chip. Light is coupled to the chip from single mode fibers using on-chip grating couplers. To demonstrate the module's functionality, we generate high-speed data signals. In a first experiment, the drive signals from the output of a 40 Gbit/s multiplexer are connected to one of the MZM. Eye-diagrams shown in Fig. 3(e, f) were recorded using a sampling oscilloscope. In a second experiment, IQ-modulation is demonstrated using an arbitrary waveform generator for electrical signal generation. A coherent receiver detects the signal, and a real-time oscilloscope takes appropriate recordings. We compensate the frequency response of the system by digital post-equalization. We receive a 64 GBd QPSK (28 GBd 16QAM) signal corresponding to a line rate of 128 Gbit/s (112 Gbit/s). To the best of our knowledge, this is among the highest symbol rates so far demonstrated with an electrically packaged silicon photonic modulator.

3. Summary

We demonstrate an electrically packaged SOH IQ-modulator with a U_π of 1.5 V and show signal generation up to 64 GBd QSPK (128 Gbit/s). The interface between standardized coaxial connectors and the silicon chip is realized using wire bonds and a ceramic PCB manufactured with direct laser writing.

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