A 100 GBaud co-planar stripline Mach-Zehnder modulator on Indium Phosphide platform

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Abstract*—*Electro-optic Mach-Zehnder modulators using a high-performance, co-planar-stripline design on an InP platform are studied. We demonstrate a 3 dB electro-optic bandwidth of 80 GHz alongside fully open eye diagrams at 100 Gbaud.

Keywords — *integrated photonics, indium phosphide, optical modulator, high-bandwidth modulation*

I. Introduction

The increasing demand for higher symbol rate data transmission has led to the development of high-bandwidth Mach-Zehnder modulators (MZMs) [1], [2]. In the design of such ≥ 100 GBd class-modulators, the half-wave voltage (V_π), optical insertion loss, and the electro-optic (EO) bandwidth, are the most crucial parameters to enable lower power consumption and faster operation of the modulator. Indium phosphide (InP) based modulators offer promising solutions for realizing high-bandwidth modulators beyond 100 GBd due to the superior electro-optic efficiency achievable with the quantum confined Stark effect, the low intrinsic carrier concentration in the optical waveguide layer, and the high thermal conductivity. In addition, the InP platform inherently allows for the integration of active and passive components on a single chip enables the development of more complex and integrated photonic circuits. Several $\geq$ 100 GBaud-class integrated modulators have been reported, but they each compromise one or more key areas [3]. Firstly, lithium niobate- and silicon-based modulators cannot be as-readily integrated with active components [4]. Capacitively loaded modulators on the InP platform compromise on device length and footprint [5]. Specialized layer stacks introduce incompatibilities with the generic foundry processes and/or can change the behavior of other integrated components [5].

To overcome these challenges, Meighan *et al.* recently proposed the adoption of high-performance, co-planar stripline (CPS) MZMs [6], [7]. The CPS-MZM design places the signal and ground electrodes in-plane, on top of the two deep waveguides, and connects them from the sides. The design allows for smaller device footprint than traditional co-planar waveguide (CPW) electrodes and significantly reduces microwave loss, all while maintaining a high bandwidth and close compatibility with the generic foundry process [8]. Vitally, the design achieves velocity matching to the optical signal with a desirable impedance match to around 50 Ω near the -3 dB bandwidth [6], [7]. These factors make CPS-MZMs highly promising candidates for future large-scale PICs and high-speed optical communications. Previous small-signal measurements of these devices could only confirm a 3 dB EO bandwidth of 30 GHz and > 67 GHz for CPS-MZMs on a n-doped and semi-insulating Si substrates, respectively [6], [9]. Here. In this work, we utilize 110 GHz class equipment to reveal a $\sim$80 GHz bandwidth for a 1 mm MZM and discuss the implications of the results. Finally, we study the large-signal performance for the impedance and velocity matched CPS-MZMs capable of error-free and fully open eye diagrams at ≤ 100 GBaud. To the best of our knowledge, these performance factors are amongst the current state of the art for InP-based modulators.

II. High-Speed InP Optical Modulator

Figure 1 presents a schematic illustration of the cross-section of the CPS-MZM design [7]. The CPS-MZM is created using the process design kit for the JePPIX [3] InP generic platform at SMART photonics, with a process adaptation for the multi-quantum well modulator layer stack where the active layer bandgap was 1.39 ± 0.02 µm.

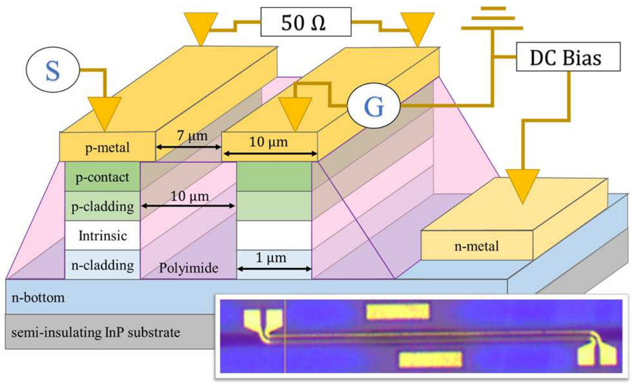

Fig. 1. Schematic illustration of the cross section for the co-planar stripline Mach-Zehnder modulator (CPS-MZM) in the generic indium phosphide platform indicating the electrical connections used for measurement. The inset shows a microscope image of a 1 mm CPS-MZM.

We fabricated devices with lengths along the propagation direction of 1 mm and 2 mm, a waveguide width of 1 µm, electrode width of 10 µm, and a waveguide/signal-ground gap of 7 µm. Note that these parameters are differ slightly from those previously shown to result in optimal performance [7]. These dimensions were chosen to ensure device functionality, using safe margins above the technological limits of the foundry process.

III. Small-signal performance

To experimentally verify the predicted, beyond-67 GHz, state-of-art performance of the CPS modulator design [7], we conducted small-signal measurements of the electrical-electrical (EE) transmission ($S_{21,EE}$) using a Keysight PNA-X Series Microwave Network Analyzer. A swept RF signal with a power of −5.0 dBm was applied over the frequency range of 0.5 − 110 GHz, and the RF electrical signal from the 50 Ω network analyser system was applied at the input of the modulator electrode using a ground-signal (GS) RF probe (6 dB electrical bandwidth of ~110 GHz). The output connection was made via an identical RF probe and a coaxial cable back to the network analyzer. The RF probes were de-embedded using short-open-load-through measurements on a calibration substrate. Figure 2 presents the $S_{21,EE}$ as a function of the RF frequency for the 2 mm (black line) and 1 mm (red line) devices.

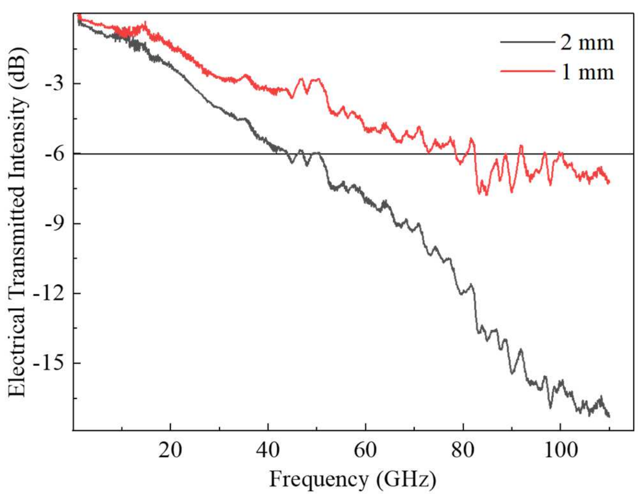

Fig. 2. (a) Electrical-electrical (EE) transmitted intensity (S_{21}) of a 2 mm (black line) and 1 mm (red line) long co-planar stripline Mach-Zehnder modulators (CPS-MZMs) up to 110 GHz.

For the 1 mm device, however, it should be noted that the frequency response plateaus after 80 GHz. Herby, $S_{21,EE}$ does not drop below −8 dB for frequencies up to 110 GHz (the largest measurable frequency). The achieved bandwidth for a 1 mm long MZM is comparable to state-of-art for InP [5], and, to the best of our knowledge, represents a significant improvement over previously reported values for MZMs fabricated using the generic foundry process [10].

IV. Large-signal performance

Determination of $V_\pi L$ for both devices was performed by sweeping reverse bias voltage from 0 − 10 V in steps of 0.2 V. We used a 1550 nm laser source with an output power of 15 dBm, providing a peak optical intensity at chip output of 3.5 ± 0.1 dBm. A polarization controller was used to ensure transverse-electric mode input by maximizing the modulation depth. The quadrature points for the 1 mm and 2 mm devices were determined to be −5.7 ± 0.4 V and −3.9 ± 0.2 V, respectively. The corresponding values of V_π were 9.1 ± 0.4 V and 4.5 ± 0.1 V, resulting in a $V_\pi L$ of 0.91 ± 0.03 Vcm. Finally, the insertion losses for the full device were estimated to be 8.6 − 9.1 dB, assuming no losses during fiber-fiber butt-coupling. The on-chip power was thus estimated to be 12.1 ± 0.3 dBm and the extinction ratio was determined to be 19.3 dB.

To measure large-signal electro-optic modulation, we utilized the Keysight M8199A 256 GSa/s arbitrary waveform generator (AWG) to generate a 100 GBd pseudo-random bit sequence of 2^{16} bits using on-off keying (OOK) with a peak-peak drive voltage, V_{pp}, of 0.2 V at 100 GBd. The signal was pre-distorted, for bandwidth limitations of the experimental setup, and ran through a raised-cosine filter with a roll-off of 1. The pseudo-random bit sequence was amplified by an in-built Keysight M8158 AWG Remote Head pre-amplifier up to 0.45 V at 100 GBaud. An SHF 807c amplifier with a nominal gain of 23 dB provided a V_{pp} up to ~5 V. Note that this voltage is still considerably smaller than V_π for the higher bandwidth 1 mm device (9.1 V). Therefore, we limited eye-measurements to the 2 mm device. The signal was transmitted through a 1.85 mm diameter coaxial cable and fed into the modulator by a ~110 GHz-rated GS probes. the transmission line was terminated using a 50 Ω load (avoiding back-reflected signals) and an SHF DCB110R-A DC block. It should be noted that due to the use of the GS probe configuration, it was necessary to discard the inverse signal, $\overline{S}$.

During electro-optical eye diagram measurements, the optical signal as output from the chip was amplified by an Erbium-doped Fiber amplifier (EDFA), as we did not use a trans-impedance amplifier (TIA) at the receiver, and a Finisar Waveshaper 1000A was used as a band-pass filter to decrease the amplifier noise. Finally, the optical signal was converted into an electronic signal using a Finisar XPDV3120R photodetector (70 GHz) and measured by a Keysight UXR1102A Real-Time Oscilloscope (70 GHz, 256 GSa/s, 10-bit). Figure 3 presents the resulting (a) EE and (b) EO eye diagrams for the 2 mm MZM and 100 GBd on-off keying. The eye diagrams for 100 Gbps data rates displayed clear open eye patterns, with a signal-noise ratios (SNRs) calculated to be 18.3 dB and 16.7 dB for EE and EO transmission, respectively. This agrees with previous simulations that also predicted open eyes at > 200 Gbaud for the 1 mm device [6], provided a sufficient V_{pp} is provided.

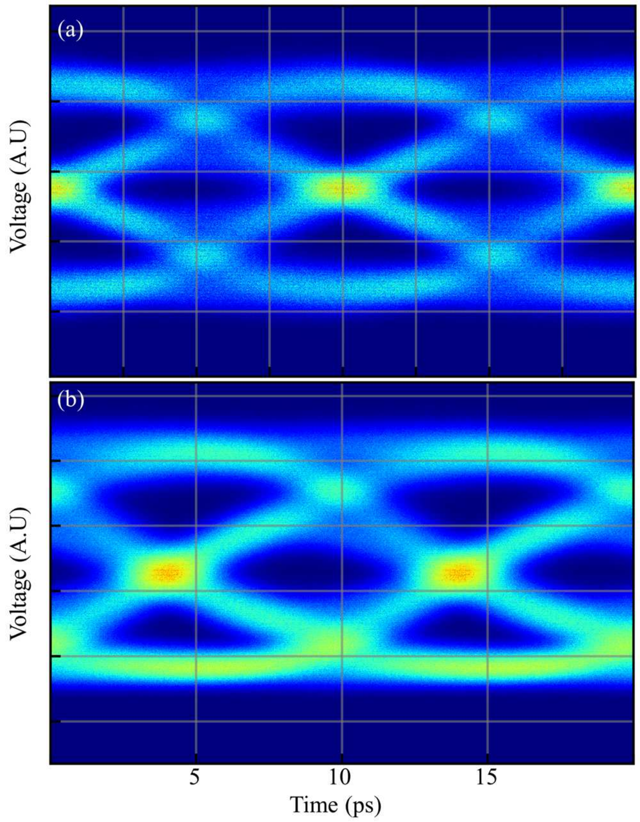

Fig. 3. (a) Electrical and (b) optical eye diagrams for a 2 mm co-planar stripline Mach-Zehnder modulator (CPS-MZM) at 100 GBd on-off keying.

After equalization [11], we observe error-free operations at 100 Gbd (i.e., bit-error-rate of $\leq 1.5 \times 10^{-5}$), which is far below the threshold for soft-decision forward error correction.

V. Conclusions

In this work, we experimentally verified the high-speed performance of a $50\,\Omega$ characteristic impedance, and velocity-matched CPS-MZM design, using the InP generic foundry process. For a 1 mm-long device, we demonstrated an EE bandwidth of approximately 80 GHz, which is amongst the state of the art for InP modulators, and a $V_{\pi}L$ of 0.91 ± 0.04 Vcm. For a 2 mm long device, we also demonstrated a high-quality optical eye diagram at 100 Gbps, with a bit error rate of $< 1.5 \times 10^{-5}$, for the 2 mm device. It is noteworthy that this high performance is due primarily to changes in the mask-level design choices rather than novel layer stack modifications. Furthermore, the design is compatible with the InP generic foundry platform, requiring only an additional passive regrowth to provide "off the shelf" availability to the wider industry.

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