# High-Density Coplanar Strip-Line Mach-Zehnder Modulators in a InP Generic Platform

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**Abstract** *A high-density, 27µm wide, Mach-Zehnder modulator with a new coplanar strip-line electrode enables velocity and impedance matching, increasing the 3dB electro-optical bandwidth to 27.3 GHz, 3.6 times higher than a more conventional coplanar waveguide design with similar length, waveguide parameters, and n-doped substrate.*

## Introduction

Mach-Zehnder modulators (MZM) are widely used in high-speed transceivers, but they take considerable chip area. The phase-shifting section of the MZM requires traveling wave electrodes to carry the electrical signal along with the optical signal, leading to complex electrode designs for maximum efficiency and speed [1].

Coplanar waveguide (CPW) lines exhibit a constrained bandwidth due to high-frequency electrical electrode losses. Additionally, the line impedance of high-speed CPW MZMs is commonly limited to 25Ω[2], leading to bandwidth-limiting electrical reflections. The high capacitance of the active layer p-i-n junction also leads to velocity mismatch for optical and electrical signals reducing efficiency.

Capacitively loaded electrode designs ensure both velocity and impedance matching of the MZMs[1]. However, having an additional transmission line next to the segmented electrodes increases the width of the MZM, limiting the achievable densities. The unloaded sections also lead to longer phase modulators.

The coplanar strip-line (CPS) electrode design has been used for silicon photonics push-pull modulators[3] where lateral fields apply across the active region, but it has not been considered for indium phosphide so far, where the field is vertically applied. The CPS can be used in a push-pull configuration when the two p-electrodes of the phase modulators are used as ground and signal lines. Additionally, the electrodes are in-plane, allowing a route to reduced separation and inductance.

In this work, we present a design for high-density, high-speed MZM with a new electrode design in the InP platform with an n-doped substrate. We directly compare the ultra-narrow CPS electrode design with the more conventional CPW approach. We study the impedance and velocity matching before addressing radio-frequency (RF) electrical losses, experimental performance, and the route to extending the bandwidth.


**Fig. 1:** Photonic integrated circuit cell including 22 modulators under electro-optical measurement

## Coplanar strip-line (CPS) modulator

Fig. 1 shows the photonic integrated circuit (PIC) cell assessed in this work. The cell has dimensions of $4 \times 4.6mm^2$; and is produced on a multi-project wafer with the JePPIX[4] InP generic platform by Smart Photonics. An n-doped substrate is used, enabling direct comparison with a previously produced CPW design[5]. Because of the electrical loss, the use of an n-doped substrate will limit the bandwidth, but the design is portable to a higher speed in a semi-insulating platform. The cell includes twenty-two CPS modulators: half have 1mm length phase modulators, and the other half have 2mm length. The width of the CPS modulator is 27µm. This compares to a width of 110µm for the CPW modulator design.

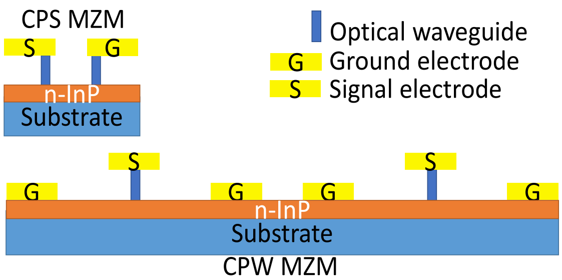


**Fig. 2:** Cross section of the traveling wave electrodes for the phase modulators sections in the CPS and CPW designs. DC biassing not shown.

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The difference in cross-sections for the CPW and CPS designs is shown in Fig. 2. Waveguide width and other waveguide parameters are the same as for the previous CPW design. The width of all ground and signal electrodes is 10µm, and the gap between the ground and signal is 10µm and 7µm in the CPW and CPS, respectively. In the CPS modulator, two signal electrodes are in-plane and placed on the optical waveguides. In the CPW modulator, there are six traveling wave traces: both the signal electrodes on the optical waveguides and pairs of ground electrodes on the top of the n-doped layer. There are three times as many electrodes for the CPW design. There is also an additional gap of 10µm between the two CPW traveling wave electrodes. By reducing the number of electrodes and the gap between them in the CPW MZM, the width of the design is reduced from 110 µm to 27 µm.

**Impedance matching**

The difference in cross-section is expected to directly impact the electrical impedance and, therefore, the impedance matching to the 50 Ω measurement equipment. The modulators are probed on-chip and measured with a 67 GHz bandwidth vector network analyzer.

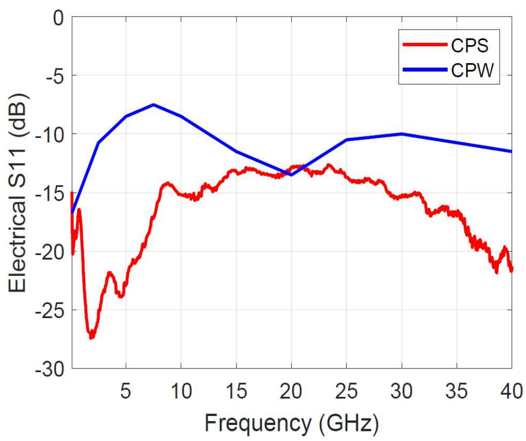


**Fig. 3:** Electrical reflection (S11)

Fig 3. shows the electrical reflection at the input port (S11) of the 1mm CPS and 1.25mm CPW[5] modulators at -3.8V DC. The peak reflection for the CPW is -7.5dB, while the CPS design has a reflection peak of less than -13dB. The 5.5dB reduction of the electrical reflection in the CPS modulators is attributed to the improved impedance matching. The extracted impedance values at 0 VDC and 40 GHz are 41.5 Ω and 17.5 Ω for the CPS and CPW designs, respectively.

**Reducing the radio-frequency loss**

The smaller width of the CPS MZM in this work has the advantage of including fewer n-InP and n-substrate regions in the cross-section of the MZM. Since there is reduced overlap between metal traces and lossy semiconductor regions, the CPS electrode of this work is expected to have a much lower electrical loss than CPW. The radio-frequency attenuation constant, defined as the real part of the electrical propagation constant, is calculated by de-embedding the measured electrical scattering parameters of the CPW and CPS electrode designs with two different length designs at 0V DC.

In Fig. 4, we compare the RF electrical

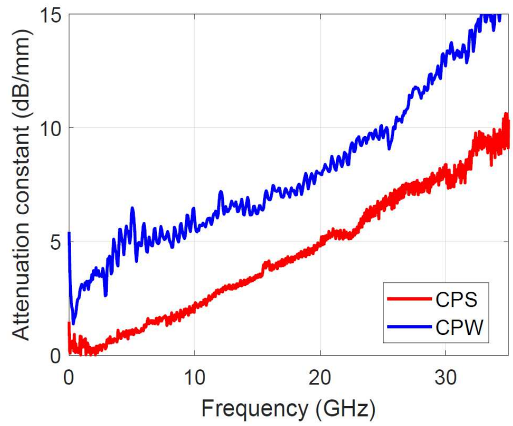


**Fig. 4:** RF electrical attenuation constant of the CPS and CPW electrodes

attenuation constant of the CPS and CPW electrodes. We see that the CPS electrode has a much lower electrical attenuation constant in the whole range of the depicted frequency.

**Velocity matching**

The CPS design enables the matching of optical and microwave impedances for improved electro-optic bandwidth. The electrical refractive index (also known as the microwave index) of both CPW and CPS modulators is determined by de-embedding the measured electrical scattering parameters of the CPW and CPS electrodes with two different length designs when 0V DC voltage is applied. The group index of the optical

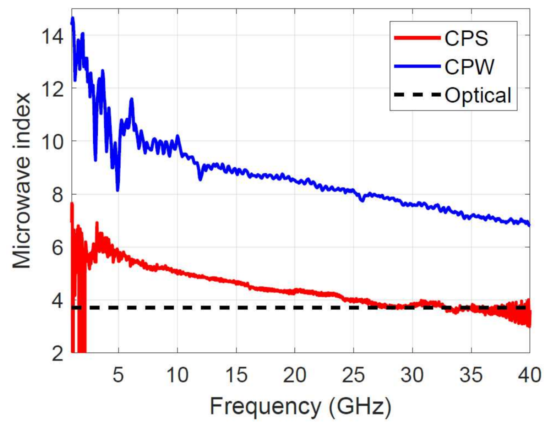


**Fig. 5:** Frequency-dependent microwave index

waveguide is 3.7.

Fig. 5. compares the frequency-dependent microwave index of the modulators. This figure shows that the microwave index of the CPS modulator is much smaller than the CPW modulator. We also see that at the higher frequency ranges, when the electrical signal is shorter and velocity matching is more important, the microwave index of the new CPS modulator design is in very close agreement with the optical index. This means that the new design is velocity matched at the higher frequencies.

## Electro-optical performance

The electro-optic performance is measured by connecting a 1550 nm, +14 dBm optical signal to a single-mode optical fiber which couples light to the facet of the chip. The output fiber transfers light passed through the MZM to the optical amplifier, optical bandpass filter, and then the optical port of the lightwave component analyzer. An electrical probe is used for applying the high-speed electrical signal from the lightwave component analyzer to the CPS traveling wave electrode. The electrical output of the traveling wave electrodes is connected to 50 Ω termination by a second electrical probe. A DC voltage referenced to the ground of the RF signal generator is applied to the n-substrate to ensure appropriate biasing across each phase modulator for single-ended modulation.

Fig. 6 shows the normalized EO-frequency response of the 1mm CPS modulator and the CPW modulator with 1.25mm length[5]. The 3dB

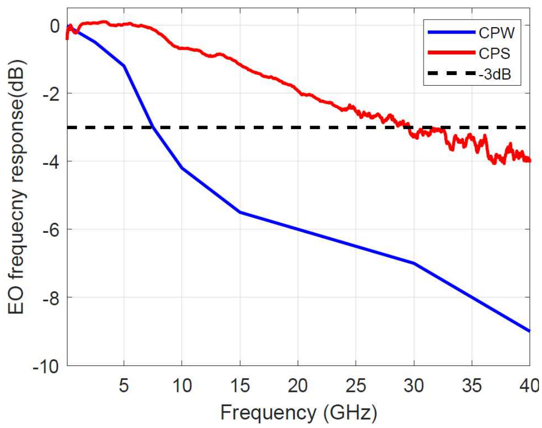


**Fig. 6:** Comparison between the normalized EO-frequency responses

EO bandwidth of the CPS modulator for 1mm length is 30 GHz, and the CPW is 7.5 GHz. DC bias of both modulators is -3.8V. The longer length of the CPW design will lead to a small bandwidth reduction. The bandwidth of the 2mm CPS modulator is 18GHz. From the de-embedding of the 1 and 2mm CPS modulators, the 3dB EO bandwidth of a 1.25mm CPS modulator is estimated to be 27.3 GHz. This is 3.6 times the bandwidth of the CPW modulator of the same length.

$V\pi.L$ of the CPS modulator is 0.8 Vcm, and optical insertion loss of the Mach-Zehnder modulator is estimated to be 9.8 dB, which is similar to the CPW design with an insertion loss of around 10 dB[5]. Further bandwidth enhancements may be anticipated when porting the design to a semi-insulating substrate with lower electrical loss compared to the n-InP substrate.

## Conclusions

A new CPS electrode design for the high-density, high-speed InP Mach-Zehnder modulator is presented. This is realized in an open-access generic InP platform. The design allows a width reduction from 110 µm in the CPW electrode to 27 µm in the CPS electrode, allowing a fourfold increase in density. A length-normalized bandwidth increase of 19.8 GHz is also observed, providing a path to order of magnitude bandwidth density improvements.

## Acknowledgments


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## References


[1] R. G. Walker, "High-speed III-V semiconductor intensity modulators," IEEE Journal of Quantum Electronics, vol. 27, no. 3, pp. 654-667, 1991.

[2] W. Yao, "Design and simulation of a series push-pull Mach-Zehnder modulator in a generic photonic integration platform," in Proceedings of the 19th Annual Symposium of the IEEE Photonics Benelux Chapter, 3-4 November 2014, Enschede, The Netherlands, Universiteit Twente, 2014.

[3] H. Zhu, "Single-drive push-pull silicon Mach-Zehnder modulator for OOK and BPSK modulation," in 2014 OptoElectronics and Communication Conference and Australian Conference on Optical Fibre Technology, Melbourne, VIC, Australia, 2014.

[4] JePPIX, 2021. [Online]. Available: https://www.jeppix.eu/.

[5] W. Yao, Towards a high-capacity multi-channel transmitter in generic photonic integration technology, Ph.D. dissertation, Eindhoven, The Netherlands: Eindhoven University of Technology, 2016, p. 45.

[6] W. Yao, G. Gilardi, M. K. Smit, and M. J. Wale, "Equivalent Circuit Modelling of Integrated TravelingWave Optical Modulator in InP Foundry Platform," in European Conference On Integrated Optics, Warsaw, Poland, 2016.