Design of 100 GHz-class Mach-Zehnder modulators in a generic indium phosphide platform

A. Meighan, Y. Yao, M. J. Wale, and K.A. Williams
Institute of Photonic Integration, Eindhoven University of Technology, P.O.Box 513, 5600 MB Eindhoven, The Netherlands Author e-mail address: A.Meighan@tue.nl

***Abstract*—We propose a push-pull electrode design for a Mach-Zehnder modulator in a generic indium phosphide platform. We calculate the frequency response of the modulator for a range of mask design parameters. We propose the design parameters for a 50Ω, velocity matched MZM with 95GHz bandwidth.**

***Keywords*— High-speed modulator, Mach-Zehnder, traveling wave electrode**

I. Introduction

Mach-Zehnder modulators (MZM) are widely used in transmission systems due to their fast modulation speed and large optical extinction [1]. High-speed 100 GHz class MZMs which employ hybrid coplanar waveguide (HCPW) electrodes have been demonstrated in III-V material platforms before, but are based on specifically tailored epitaxial layers [2] and not embedded within a generic photonic circuit platform. For the latter, MZM components have been studied in the generic InP platform [3]. However, the bandwidth is constrained by high electrical loss in these HCPW electrode designs, and the line impedance is limited to 30Ω at high frequencies [4], leading to undesired electrical reflections. We propose in this work a new MZM design for generic InP platforms based on coplanar stripline (CPS) electrodes that can overcome these limitations.

CPS modulators have widely been modeled and studied in combination with horizontal p-i-n junctions for silicon photonics because it is a more straightforward design. It has also been used with vertical p-i-n junctions in GaAs modulators with a customized layer stack [5] but they place the two electrodes out of the plane at different heights on the chip. By placing those in-plane at the same height, on top of the two waveguides, the capacitance can be significantly reduced. This has been successfully used in CPS capacitively-loaded modulators and is one factor that leads to a speed increase [6, 1]. These however employ a combination of loaded and unloaded electrode sections, making the modulator longer than the sum of its active sections. In this work, by placing the two electrodes in-plane, connecting to the two optical waveguides from the sides, and by controlling the capacitance and inductance of the line utilizing narrow dimensions, we not only reduce the microwave loss in the HCPW-MZMs but also achieve velocity matching to the optical signal with a desirable impedance match without capacitive loading. We propose design parameters for a short 1 mm long velocity-matched 50Ω push-pull CPS-MZM with a 3dB EO-bandwidth of 95 GHz with the same $V_{\pi}L$ efficiency of 7 Vmm compared to the HCPW-MZMs reported previously for the InP generic platform [3].

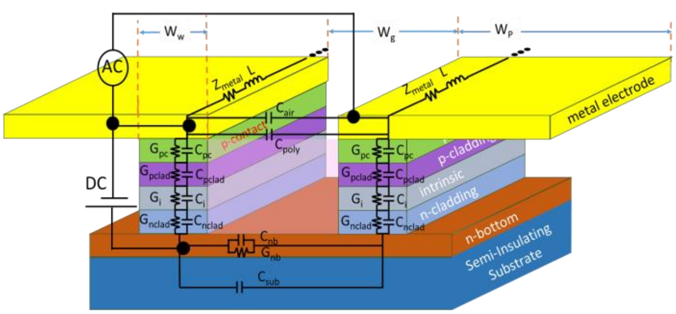

Fig. 1. a) Cross section of the CPS-MZM in the generic InP platform, perunit length circuit elements and electrical connections

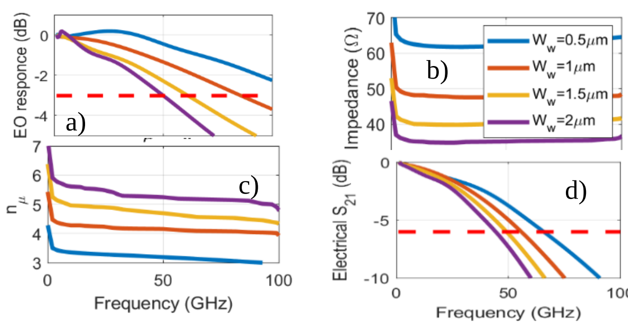

Fig. 2. a)- Effect of Ww on EO response of the CPS-MZM b) frequency dependent line impedance, c) microwave index and d) electrical S21

II. Methodology

Fig. 1. shows the cross-section of a 1 mm long push-pull CPS-MZM electrode in the generic InP platform and how it is connected to the DC and AC sources. The two metal electrodes on top of the optical waveguides are driven by an AC signal and terminated with a load. This figure also shows the cross-sectional equivalent circuit elements of the MZM, which have per unit length (PUL) values. This circuit has been implemented in the Advanced Design System (ADS), which facilitates its embedding within electrical interconnect, 50Ω load, and source networks. In this circuit, Z_{metal} is the metal-air impedance of the electrodes [7], L is the inductance of the CPS line [8], $C_{pc,i,ncald,pclad,nb}$, are the capacitances of the semiconductor layers below the metal lines under parallel plate approximation. C_{air} and C_{sub} are partial capacitances in the absence of all non-metal material and substrate, respectively [9]. $G_{pc,i,ncald,pclad,nb}$ are the conductance of each semiconductor material of the optical waveguide [7] . The layer stack and physical parameters are taken from the COBRA generic platform [3]. Assuming the small-signal approximation [10] the model is able to

yield the EO-frequency response of the modulator according to [4]. In ADS, we also performed time-domain large-signal simulations and obtained the optical eye diagram response of the modulator.

III. Simulations

Using the cross-sectional circuit in ADS, the impact of the waveguide width W_w, on the EO response of the CPS-MZM is studied. We also studied the gap and widths of the electrodes, but the focus is on the optical guide here as it has the strongest impact. By reducing the waveguide width (W_w) and keeping the electrode gap and width at 10μm, the cross-sectional electrical loss of the semiconductor reduces significantly, and therefore, as shown in Fig.2 d), the electrical S_{21} is higher for narrower waveguides. Also, in Fig 2.b,c) we see that the narrower width causes desirable higher impedance and lower microwave index, which is due to the reduction of the line capacitance.

Narrower gap (W_g) results in a lower electrical loss in the n-bottom semiconductor layer, which contributes to a higher EO bandwidth, but its impact is lower compared to the W_w. Decreasing the gap from 20 μm to 5 μm when W_w=1.5 μm and W_p=10 μm increases the EO-bandwidth from 55GHz to 70GHz. Also, the frequency-dependent line impedance and microwave indexes at 100 GHz reduce from 48 Ω to 34Ω and from 5 to 3.8, respectively, because a larger gap provides larger line inductance. Increasing the width of the electrode (W_p) makes the metal losses lower, which is not significant comparing to the semiconductor losses in the MZMs cross-section. It only increases the EO bandwidth by about 10 GHz when W_g=10 μm, W_w=1.5 μm, and W_p increases from 5μm to 20μm. Increasing the W_p also increases the capacitance, and by that line, impedance reduces from 45 to 38 Ω, and the microwave index increases from 4 to 5 at 100 GHz.

With the obtained insight, we propose a parameter set for a high-speed 100GHz, 50-Ω, velocity matched CPS-MZM. We chose the waveguide width of W_w=1 μm, an electrode width of W_p=8 μm, and a gap of 5 μm. In figure 3. We see the EO-frequency response of the modulator with a bandwidth of 95 GHz. The microwave index at 100 GHz is 3.65, which is close to the optical group index of 3.7, while the impedance is in the range of 45 to 60 over the 100GHz frequency range. The optical eye diagram has been calculated for a non-return-to-zero (NRZ) data sequence of 2^8 bits at 150 Gbps, showing a quality factor of 12.5. The extinction ratio at this bitrate is predicted to be 10 dB.

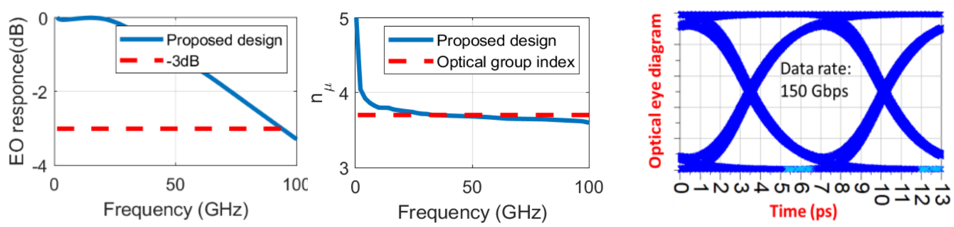

Fig. 3. Shows the EO-frequency response, microwave index and NRZ optical eye diagram of the proposed design for the 150 Gbps data rate.

IV. Conclusion

In this work, we propose a new electrode design of high-speed MZMs for a generic InP platform. We study the effect of the electrode design parameters on the frequency response of the MZM using a circuit model. The new CPS electrode design with 1 mm length is suitable to a 50-Ω environment, velocity matched, and can yield 150 Gbps NRZ operation, making it a promising candidate for 100 GHz class modulators.

References

[1] R. G. Walker, et al., "High-speed III-V semiconductor intensity modulators," *IEEE Journal of Quantum Electronics,* vol. 20, no. 3, p. 654 –660, 1991.

[2] Y. Shibata, et al., "Demonstration of 112-Gbit/s DP-QPSK modulation using InP n-p-i-n Mach-Zehnder modulators," in *ECOC*, Torino,Italy, 2010.

[3] M. Smit, et al., "An introduction to InP-based generic integration technology," *Semiconductor Science and Technology,* vol. 29, no. 8, pp. 1-41, 2014.

[4] W. Yao, et al., "Equivalent Circuit Modelling of Integrated TravelingWave Optical Modulator in InP Foundry Platform," in *European Conference On Integrated Optics*, Warsaw, Poland, 2016.

[5] S. Y. Wang, et al.,"GaAs traveling-wave polarization electro-optic waveguide modulator with bandwidth in excess of 20 GHz at 1.3 μm," *Appl. Phys. Lett,* vol. 51, pp. 83-85, 1987.

[6] S. Lange, et al., "100 GBd Intensity Modulation and Direct Detection With an InP-Based Monolithic DFB Laser Mach–Zehnder Modulator," *J. Lightwave Technol.,* vol. 36, no. 1, pp. 97-102, 2018.

[7] K. Giboney, et al.,"Traveling-wave photodetector design and measurements," *Journal of Selected Topics in Quantum Electronics,* vol. 2, no. 3, pp. 622 - 629, 1996.

[8] C. R. Paul, Inductance: Loop and Partial, Wiley-IEEE Press, 2010.

[9] E. Chen and S. Chou, "Characteristics of coplanar transmission lines on multilayer substrates: modeling and experiments," *IEEE Transactions on Microwave Theory and Techniques,* vol. 45, no. 6, pp. 939 - 945, 1997.

[10] G. Ghione, Semiconductor Devices for High-Speed Optoelectronics, Cambridge, UK: Cambridge University Press, 2009.

This research was carried out within the Dutch NWO HTSM Photronics project.