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Citation for published version (APA):
Meighan, A., Wale, M. J., & Williams, K. A. (2021). Waveguide width effect on increasing the Mach-Zehnder Modulators bandwidth. In *Proceedings of the 25th Annual Symposium of the IEEE Photonics Society Benelux Chapter, 25th-26th November 2021, University of Mons, Belgium* (pp. 1-4) https://photonics-benelux.org/wp-content/uploads/pb-files/proceedings/2021/Posters_odd/Poster_43.pdf

Document status and date:
Published: 25/11/2021

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Waveguide width effect on increasing the Mach-Zehnder Modulators bandwidth

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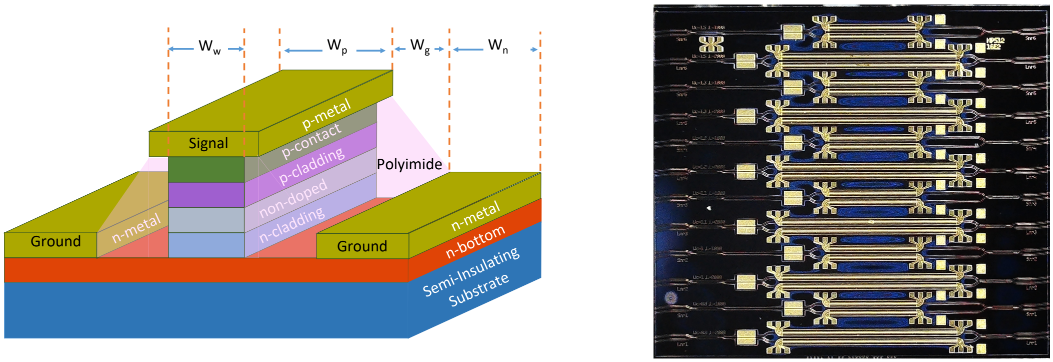
A systematic experimental study is presented on the waveguide width effect on the high-speed electrical and electro-optical (EO) response of the traveling wave co-planar waveguide Mach-Zehnder modulators (MZMs). Modulators with waveguide widths from 1 to 1.5 μm fabricated in a generic InP platform are measured. Electrical peak reflection of the 50 Ω terminated modulators shows that waveguide width reduction improves the impedance matching. Modulators with narrower waveguides also offer higher electrical bandwidth and velocity matching. Moreover, the electro-optical frequency response of the MZMs shows 47% bandwidth improvement from 36 GHz in a modulator with 1.5 μm waveguide width to 53 GHz with 1 μm width.

Introduction

To transfer information through optical fibers, electrical information has to be converted to light in optical communication systems. Optical transmitters generate optical carriers and modulate information from the electrical domain into the optical domain.

Traveling wave co-planar-waveguide Mach-Zehnder modulators with 1 mm length and 1.5 μm waveguide width have been modeled and assessed in a generic InP platform with semi-insulating substrate [1]. The 3 dB EO-bandwidth of this modulator was limited to 30 GHz by low electrical bandwidth of the CPW line and high electrical reflection from the 50 Ω termination to the modulator traveling wave electrode of 23-25 Ω. The vectorial method of lines (MoL) has been employed to model the effect of the waveguide width on reducing the electrical RF attenuation of the CPW-MZMs in a generic InP platform from 3.8 dB/mm in a modulator with 2 μm waveguide width to 2.6 dB/mm in a modulator with 1 μm waveguide width [2]. Moreover 3 dB bandwidth of over 60 GHz for a CPW-MZM with 2 mm length and 35 Ω characteristic impedance was calculated [3, 4]. However the high-electrode contact resistance resulted only in a measured 3-dB bandwidth of 17 GHz [4].

In this work we assess the effect of the waveguide width on the high-speed electrical and electro-optical response of traveling wave co-planar-waveguide Mach-Zehnder modulators. Reducing the waveguide width reduces both the electrical loss and the frequency-dependent capacitance of the traveling wave electrode. This is expected to increase electrical bandwidth, match the characteristic impedance to the electronics and improved electro-optic efficiency through matching of the electrical and optical microwave index. First we assess the effect of the waveguide width on the electrical characteristics of the MZMs fabricated in a generic InP platform with a semi-insulating substrate. We show that



(a) Cross-section

(b) Microscope image of the chip

Figure 1: Plots of a) cross-section of the phase shifter of the Mach-Zehnder modulators and b) microscope image of a 4.6 mm x 4.0 mm cell containing 12 Mach-Zehnder modulators

reducing the waveguide width from 1.5 μm to 1 μm increases the electrical bandwidth of the modulator. Then we measure the electrical reflection of the modulator terminated to a 50 Ω load, and we show that reducing the waveguide width improves the impedance matching of the MZM. Moreover, we show that reducing the waveguide width reduces the frequency-dependent microwave index of the traveling wave electrode and improves the velocity matching between the electrical and optical signals. Finally we assess the effect of the waveguide width on the electro-optical frequency response of the modulator.

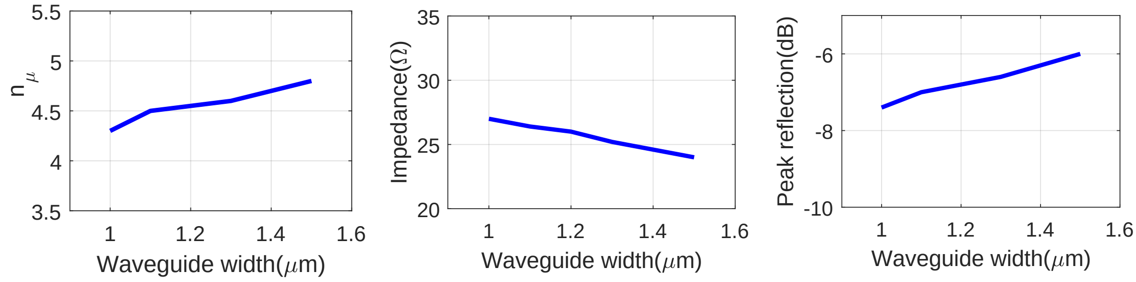
Modulator design

Figure 1 shows a) cross-section of the phase shifter of the Mach-Zehnder modulators and b) microscope image of a 4.6 mm x 4.0 mm cell containing 12 modulators fabricated in a generic InP platform. To show all the critical layers and electrodes, Figure 1a is not in scale. Since this platform's ground and signal electrodes are in two different planes above and below the p-i-n junction, we use the term hybrid co-planar waveguide (HCPW) instead of co-planar waveguide. The optical waveguide of the HCPW-MZM includes an intrinsic core layer with n-cladding and p-cladding layers above and below it, respectively. A highly doped InGaAs ternary-layer (p-contact) is between the p-metal and p-cladding to minimize the contact resistance. The signal p-metal line is located on the optical waveguide, and the two n-metal ground lines are next to the waveguide on the n-bottom layer. Cross-sectional parameters are listed in reference [1]. The width of the signal and ground (W_p, W_n) and the gap between them (W_g) are 10 μm and the waveguide width is varied from 1.5-1.0 μm.

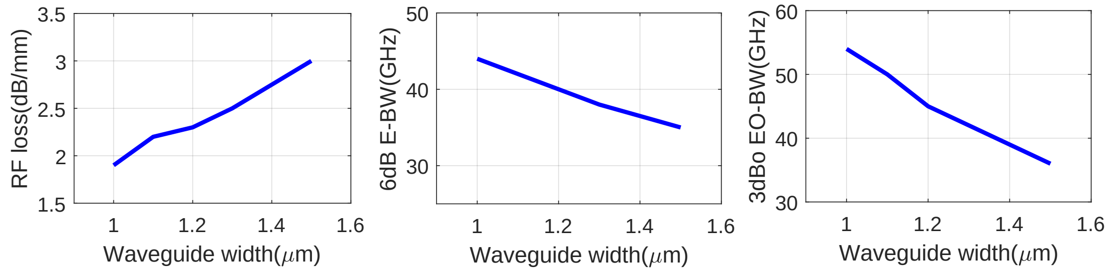
Electrical and electro-optical response

The RF electrical design is first analyzed at zero DC bias using a vector network analyzer. The calibration procedure is done by probing an on-wafer calibration kit. The electrical attenuation, impedance, and microwave index are determined by de-embedding the measured electrical scattering parameters of the modulators with two different length designs. The S11 reflections are determined with the second port terminated to 50 Ω.

Figure 2 shows the electrical and electro-optical characteristics of the HCPW when the



(a) Microwave index (b) Impedance (c) Peak E-reflection

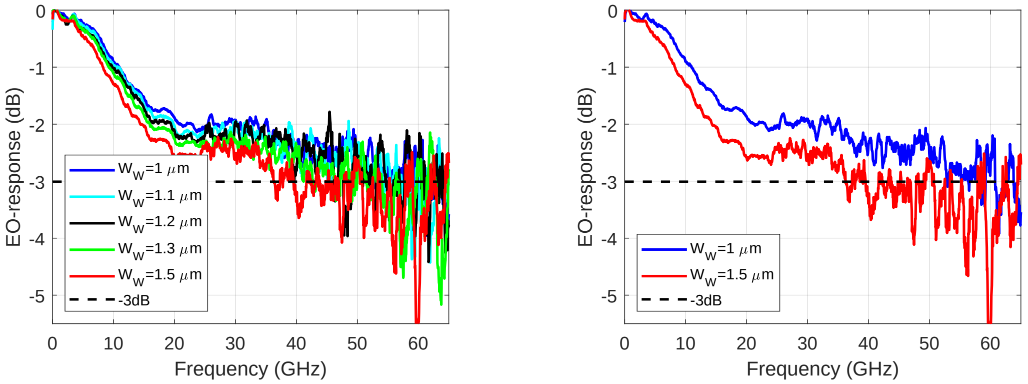


(d) Attenuation constant (e) 6 dB E-bandwidth (f) 3 dB EO-bandwidth

Figure 2: Plots of a) microwave index (n_μ) at 20 GHz, b) characteristic impedance at 20 GHz, c) peak electrical reflection, d) attenuation constant at 20 GHz, e) 6 dB electrical bandwidth and f) 3 dB electro-optical bandwidth of the HCPW-MZM when the waveguide width is changed from 1-1.5 μm

waveguide width is changed from 1-1.5 μm. In figure 2a the microwave index of the modulator reduces from 4.8 to 4.3 when the waveguide width reduces from 1.5 to 1.0 μm. Since the optical index is 3.7, the narrower waveguide has better velocity matching between the electrical and optical signals. Reducing the waveguide width also increases the modulator's impedance. In figure 2b reducing the waveguide width from 1.5 to 1 μm increases the impedance from 24 to 27 Ω at 20 GHz. This results in reducing the peak electrical reflection of the modulator to the 50 Ω system from -6 dB to -7.5 dB, which is depicted in figure 2c. Moreover, since narrower waveguide width leads to less RF loss (figure 2d), reducing waveguide width offers higher 6 dB electrical bandwidth, which is shown in figure 2e. The DC electro-optic modulation response is analyzed at the wavelength 1550 nm. $V\pi L$ of the modulators is 7.5 Vmm and the extinction ratio is measured to be above 27 dB. The optical insertion losses excluding the fiber coupling losses for the five measured MZMs are 8-9 dB. The electro-optic modulation response is measured with Agilent's lightwave component analyzer model N4373C. An optical amplifier and an optical bandpass filter have been used in the S21 measurements.

Figure 3a shows the electro-optical frequency response of the HCPW-MZM as a function of waveguide width. The second plot (figure 3b) just shows two values (1.0 and 1.5 μm width) for clarity. The transition from slope to plateau at 20GHz is attributed to an electrical reflection between the electrodes and the 50 Ω electrical network. In figure 2f the 3 dB bandwidth improvement from 36 GHz in a modulator with 1.5 μm waveguide width to 53 GHz with 1 μm width is achieved.



(a) W_W= 1.0-1.5 μm

(b) W_W= 1.0 and W_W=1.5 μm

Figure 3: EO-frequency response of the modulators when a) waveguide width (W_W) is 1.0-1.5 μm, b) W_W= 1.0 and W_W=1.5 μm

Conclusions

We experimentally measure and confirm that narrower waveguide width is beneficial in terms of velocity and impedance matching and reduces also the RF losses of the modulator. Therefore, by reducing the waveguide width from 1.5 μm to 1 μm, we improved the electro-optical bandwidth of the modulator from 36 to 53 GHz.

Acknowledgments

We acknowledge the Dutch NWO HTSM Photronics project, no. 13906, for their support and SMART Photonics for chip fabrication.

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