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Optimization of a 64Gbps O-band thin-rib PN junction Mach-Zehnder Modulator fabricated on a 200mm silicon photonics platform.

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Abstract

The fabrication of a thin-rib PN junction Mach-Zehnder modulator is presented. Design and process optimization have led to a modulation efficiency of 1.7Vcm $V\pi L\pi$ with insertion losses in the range of 1dB/mm and an electrical bandwidth larger than 26GHz. NRZ modulation up to 64Gbps is demonstrated.

1. Introduction

Modulators are key components in photonic transceivers for datacenter interconnects and telecommunications applications. In the O-band, the free carrier dispersion effect is the most practical way of achieving high-speed phase shifters for modulators in silicon. This effect can be obtained with either a capacitive structure, a carrier-injection or carrier-depletion device [1]. Among these structures, carrier-depletion-type phase shifters in Mach-Zehnder configuration are generally used for high-speed silicon modulators.

In this paper, we report the integration of a thin-rib PN junction modulator. Extensive characterization of the device, from DC parameters to modulation tests, is presented.

2. Device design and process Optimization

A PN junction depletion mode phase shifter is integrated in CEA-LETI's 200mm silicon photonic platform. This technology has already been described in [2]. The cross-section of a standard half-etched-rib phase shifter, designed for O-band applications, is shown in Fig1. Such structures have been extensively studied, generally achieving 25Gbps NRZ modulation. Fig2 presents the static response of this device in a 2mm-long Mach-Zehnder modulator (MZM) configuration fabricated using our platform. Modulation efficiency is 2V.cm for a reverse bias voltage of -2V, whereas losses are 1.2dB/mm. A thin slab, in the range of 65nm is also available in the technology. This feature was originally introduced to define small radius ring modulators. Recently, it has been shown that a thin rib can improve the static performance of a linear phase shifter due to better light confinement within the waveguide [3-4]. This has proved to be the case using our platform (Table 1): modulation efficiency is improved with a reduction of the slab thickness, optical losses are unchanged whereas the electrical frequency bandwidth is reduced due to an increase of the access resistance. In order to improve the bandwidth of the thin-rib based device, additional slab implantation steps were introduced (see Fig3). Optimization of the doping conditions and design rules were carried out. Various doping conditions were evaluated as well as the distance between the doped slab and the waveguide. TCAD simulation results are presented in figure 4, illustrating these design and process variations. It is worth noting that in the case of a slab doping distance of 0nm, the hard mask remaining on top of the waveguide acts as an implantation mask leading to self-alignment of the implantations. In this particular case, the device is insensitive to the misalignment of the lithography steps used for the slab implantations.

3. Characterization

Wafer level electro-optical characterizations have been performed in order to identify the best device as a function design (i.e. Slab implantation location) and process (i.e. implantation dose). All the other parameters, in particular the P and N type implantations defining the junction remained unchanged compared to the standard process. Modulation efficiency, insertion losses and electrical bandwidth are presented in figures 5, 6 and 7, respectively. Efficiency is improved by increasing the slab doping density and reducing the distance with the waveguide. On the other hand, insertion losses increase only in the case of the self-aligned implantation and are worse when the doping level is higher. These efficiency/loss variations show that the slab doping affects the modulator junction when the distance is at its minimum. As expected, the frequency bandwidth increases when the slab doping area is at its maximum tested value, reaching 27 GHz for the lowest doping level. Meanwhile, in the case of higher doping levels, the bandwidth remains limited, probably due to the increase of the junction capacitance related the proximity of the slab doping.

Modulation tests have been done on the best performing device (self- aligned slab doping with condition A). Eye diagrams for various NRZ modulation data rates and extracted parameters are presented in Fig 8 and Fig.9. 64 Gbps NRZ modulation is demonstrated with an extinction ratio (ER) of 4.6dB and signal noise ratio (SNR) larger than 7. Finally, 28GB PAM4 is also demonstrated (Fig.10). All modulation tests have been carried out in a push-pull configuration using an SGS probe and a pair of phase matched modulator drivers. For NRZ modulation, we used the maximum available drive amplitude (6.0Vpp) as measured at the driver output. However, the RF probe loss is significant at frequencies above 30GHz leading to a strong decrease in the drive amplitude seen by the modulator, especially for the 56Gbps and 64Gbps signals. This reflects in the Extinction Ratio of the output optical eye diagrams.

4. Conclusions

The fabrication of a thin-rib PN junction Mach-Zehnder modulator is presented. From the design and process optimization, a self-aligned doped slab is introduced in order to improve the dynamic behavior of the device. Modulation efficiency of 1.7Vcm, insertion losses in the range of 1dB/mm, electrical bandwidth larger than 26GHz and modulation up to 64Gpps were demonstrated.

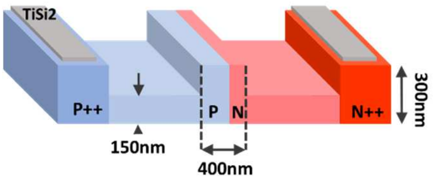

Fig.1: Standard half-etched-rib phase shifter cross-section. For O-band, the waveguide width is 400nm and its height is 300nm.

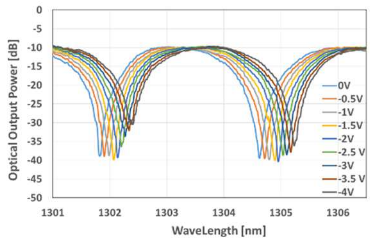

Fig.2: Static Response spectra of a 2mm-long half-etched rib MZM at different voltages.

Parameters	Units	Mid-rib	Thin-rib
$V\pi L\pi$ @ -2V	V.cm	2.01	1.75
Losses	dB/mm	1.2	1.15
BW @ -6dB (V=2V)	GHz	21.5	19

Table1: 2mm-long half-etched-rib and thin-rib MZM parameter comparison. Device are measured on the same wafer. Static performanes are improved with reducing the rib thickness. On the other hand, electrical bandwidth is reduced due to higher access resistance penalty.

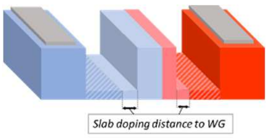

Fig.3: Thin-rib phase shifter cross-section with additional slab doping. Optimization parameter if the doping distance to the edge of the WG

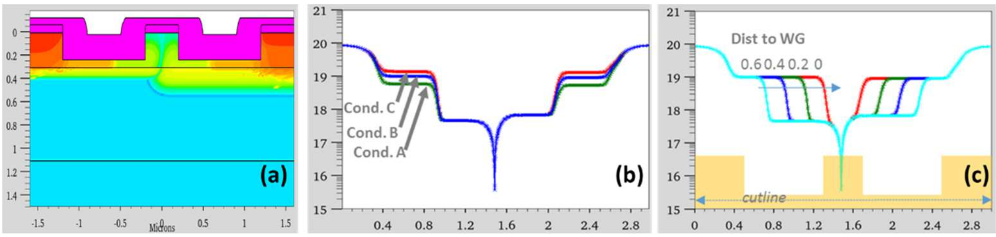

Fig.4: Thin-rib phase shifter TCAD simulations with Silvaco's Athena. Device cross-section (4a), doping level along the structure obtained with 3 implantation conditions (4b) and doping profile with various slab doping distance to wave guide (4c).

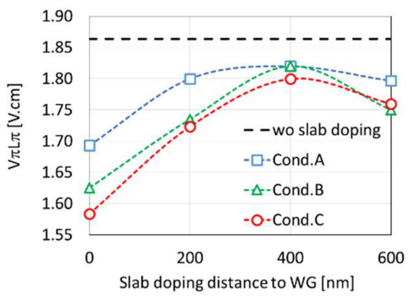

Fig.5: Modulation efficiency variations vs. the slab doping distance to the waveguide for various doping conditions.

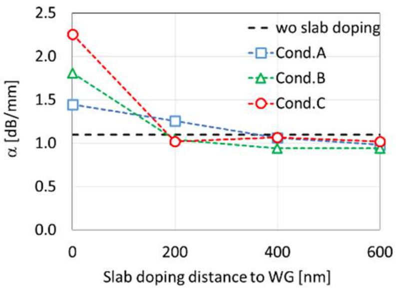

Fig.6: Optical losses vs. the slab doping distance to the waveguide for various doping conditions.

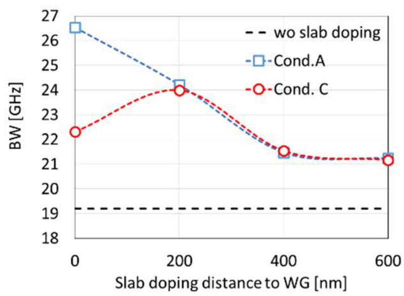

Fig.7: Electrical bandwidth vs. the slab doping distance to the waveguide for various doping conditions.

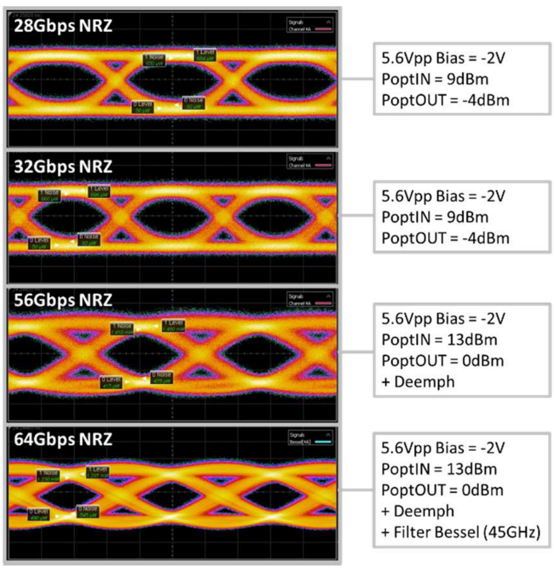

Fig. 8: Eye diagrams for different data rates in push-pull configuration.

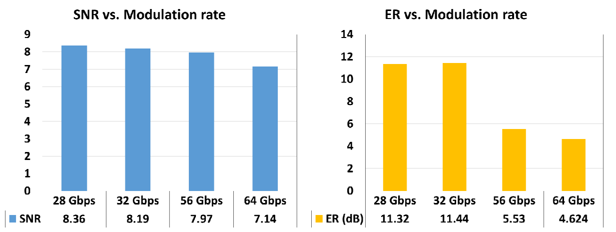

Fig. 9: Signal noise ratio and Extinction ratio measured on the eye diagrams of figure 8.

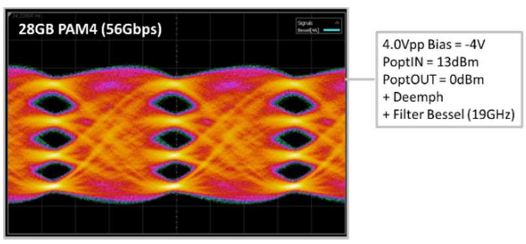

Fig. 10: 28GB PAM4 modulation eye diagram

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