High bandwidth Silicon Mach-Zehnder modulator with 1 V · cm $V_{\pi}L$

Qingfeng Long, Wei Tan, Junlong Zhang, Huaxiang Yi, Tiantian Li, Zhiping Zhou* and Xingjun Wang*

State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing, 100871, China
*zjzhou@pku.edu.cn; xjwang@pku.edu.cn

Abstract: We demonstrated a carrier-depletion type silicon Mach-Zehnder modulator with 3dB bandwidth beyond 23 GHz, as well as with modulation efficiency $V_{\pi}L$ of ~1 V · cm. 30Gb/s modulation eye diagram was observed with S/N ~9.6 dB.

OCIS codes: (230.4110) Modulators; (060.4510) Optical communications

1. Introduction

The carrier-depletion type silicon Mach-Zehnder modulator (MZM) has vast potential applications in optical communication domain. A great deal of research [1-7] has been done to improve the performance of MZM. Both 3dB bandwidth and modulation efficiency play important roles in high speed modulation. Generally, MZM needs as short as possible phase shifter for less RF propagation loss and to achieve high bandwidth. Meanwhile the short phase shifter leads to the low modulation efficiency [3]. So there is a trade-off between bandwidth and modulation efficiency. In this paper, we demonstrated a MZM to achieve high bandwidth and high modulation efficiency at the same time. The $S_{21}$ 3dB bandwidth of the 2mm-long device is beyond 23 GHz and the modulation efficiency is ~1 V · cm. The MZM operates well at 30Gb/s modulation rate.

2. Design and fabrication

The Si MZMs described in this paper utilize multi-mode-interference (MMI) as the splitter and combiner. The silicon rib waveguides have a height of 220nm, a width of 600nm and a 100nm high slab. There is a 100μm length difference between two arms. The phase shifter in both arms is composed of reversed PN junction. The P region has a 100nm offset to enhance the modulation efficiency. The doping concentrations of P and N regions are about $5 \times 10^{17}/cm^3$ and $1 \times 10^{18}/cm^3$, respectively. The P++ and N++ regions with $1 \times 10^{20}/cm^3$ doping concentration are 500nm away from the waveguide, which can form a good ohmic contact with minimal optical absorption loss. A coplanar waveguide (CPW) is utilized to drive the phase shifter. The matched termination resistors are fabricated on chip to absorb the redundant microwave signal. We have fabricated a series of MZMs with different PN junctions and coplanar waveguides to obtain a high performance Si MZM.

3. Experiment result

Figure 1 shows the normalized optical response of specially designed MZMs with 2mm-long phase shifter. Firstly, the devices with different coplanar waveguides and the same PN junction, which means the devices had different signal line widths(W) and gaps(G), were measured at -3V bias voltage by a vector network analyzer. The intrinsic region width in PN junction is 50nm. The different coplanar waveguides are designed with (W, G) parameters
corresponding to (4μm, 6.5μm), (20μm, 7.5μm), (28μm, 7.5μm), (10μm, 6.4μm). A lumped electrode MZM was fabricated as well. As shown in Figure 1(a), the MZM with 28μm signal line width and 7.5μm gap achieved the highest 3dB bandwidth of ~23 GHz if we set the reference point as 1.5 GHz, which is consistent with the simulation results by the HFSS software. This CPW has the lowest microwave loss. Meanwhile the microwave speed is close to the speed of light.

In addition, we also analyzed the influence of different intrinsic region widths in PN junction. The MZMs were fabricated with intrinsic region width of 0nm, 50nm and 80nm and the (W, G) was (28μm, 7.5μm). Figure 1(b) shows the normalized response measured with no bias voltage. The MZM with 80nm intrinsic region width achieved the highest 3dB bandwidth of ~19.5 GHz under the 1.5 GHz reference point condition. Actually, the 3dB bandwidth can be higher than 23GHz when the MZM is applied with -3V bias voltage due to wider depletion width and smaller capacitance.

![Normalized S21 response of different coplanar waveguides with -3V bias voltage.](image1)

**Fig. 1.** (a) Normalized S21 response of different coplanar waveguides with -3V bias voltage. (b) Normalized S21 response of different PN junctions with no bias voltage.

![Normalized S21 response of different coplanar waveguides with -3V bias voltage.](image2)

**Fig. 2.** Spectra of the Si MZM with different DC voltages.

The highest bandwidth device was used to do the further research. The measured transmission spectra under various DC voltages are shown in Figure 2. The high modulation efficiency of ~1 V · cm and high on-off extinction
ratio (ER) of more than 30dB of the 2mm-long device can be demonstrated. As shown in Figure 3, the optical eye diagrams under 10Gb/s, 20Gb/s and 30Gb/s modulation rate were measured at 6V_{pp} and -3.3V bias. The corresponding extinction ratios are 11.6dB, 10.8dB and 6.5dB, respectively. All of the eye diagrams are in high quality and the high speed performance of the MZM can be approved. The eye diagram of higher speed is limited by instrument. According to the high 3dB bandwidth beyond 23 GHz, it is predicted the Si MZM can reach more than 40Gb/s.

![Eye Diagrams](image)

Fig. 3. Optical eye diagrams under different modulation rates (a) 10Gb/s, (b) 20Gb/s, (c) 30Gb/s.

4. Conclusion

In conclusion, we have demonstrated a high performance silicon Mach-Zehnder modulator with a 2mm-long phase shifter by optimizing the coplanar waveguide and PN junction. The S_{21} 3dB bandwidth, modulation efficiency and high speed modulation are presented to approve the high performance of the device.

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6. References