50-Gb/s silicon optical modulator with travelingwave electrodes

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Abstract: We demonstrate silicon Mach-Zehnder Interferometer (MZI) optical modulator with 50.1-Gb/s data rate and 5.56 dB dynamic extinction ratios. The phase shifter is composed by a 4 mm-long reverse-biased p-n junction with a modulation efficiency (V_{π} ·L_{π}) of ~26.7 V·mm and phase shifter loss of ~1.04 dB/mm at $V_{\text{bias}} = -6$ V. The measured electro-optic bandwidth reaches 25.6 GHz at $V_{\text{bias}} = -5$ V. Compensation doping method and low loss traveling-wave electrodes are utilized to improve the modulator performance. Measurement result demonstrates that reasonable choosing of working point and doping profile of the silicon optical modulator is critical in order to match the performance requirement of the real application.

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1. Introduction

In the next generation core building blocks of fiber-optic network, the key points that industry focus on are higher bandwidth, high quality data communication, low insertion loss and low cost. Silicon photonics technology becomes the first choice considering from the point of low cost and mature Si CMOS fabrication process. As the indirect band structure of silicon material, DFB laser is flip-chip bonded on the photonics chip as the light source of the silicon photonics circuit. Currently, bandwidth limitation of the single channel data transmission lies on the silicon optical modulator and photo detector [1–4]. A 38 GHz optical-electrical bandwidth of Germanium photo detector has already been demonstrated which is good enough for the currently requirement of receiver [5]. Thereafter, silicon optical modulator is becoming the final bandwidth bottleneck of the transceiver. Recently, 10-Gb/s 80 km-optical transceiver has been widely used on the optical network between cities. In order to further increase of the data rate, people focus on enhancing the phase usage efficiency by Phase-Shifter Key [6,7] technology, the wavelength and polarity usage efficiency by multiplexing technology such as Wavelength-Division-Multiplexing (WDM) [8] and Polarization-Division-Multiplexing (PDM) [9]. Apparently, these approaches increase the complexity of the system and lots of affiliated technique issues have to be solved correspondingly. Increasing the bandwidth of single channel building block using the simplest on-off keying (OOK) format is still quite necessary.

The recently reported silicon ring optical modulator realizes 44-Gb/s data rate with 3.01 dB dynamic extinction ratio [10]. Silicon Mach-Zehnder optical modulators with OOK format and highest switching speed (50-Gb/s) are realized with a reverse-biased p-n junction lied near the centre of the waveguide [11,12]. However, their dynamic extinction ratio still needs improvement for practical application. In this paper, we demonstrate a single arm driver MZI silicon optical modulator with 50-Gb/s data rate and 5.56 dB dynamic extinction ratios. Both compensation doping method [13] and low loss traveling wave electrodes are utilized to improve the performance of the silicon modulator.

Light Output

2. Structure

Fig. 1 Schematic diagrams of the MZI silicon optical modulator.

The schematic diagram and doping profile of the asymmetric MZI silicon optical modulator is shown in Fig. 1. The SOI wafer had a 220 nm top silicon layer and 2 μ m buried oxide layer. Phase shifter was formed by a p-n junction in the centre of a 4mm-long, 500 nm-wide and 220 nm-high silicon waveguide with 100 nm slab thickness. After the ion implantation of the p-n junction and Ohm contact, a 250 Å TaN and 2 μ m Aluminum layer were deposited and patterned on the contact as the electrodes part. Compensated doping method was utilized to optimize the doping profile of PN junction for high speed and low phase shifter loss [13]. Electrical signal was uploaded onto the modulator through a traveling-wave electrode design. Deep trenches were etched near the edge of the nano-tips for fiber to waveguide coupling. All of the fabrication was compatible with standard 8 inches CMOS process.

3. Experimental results and discussion

3.1 DC measurement and working point chosen



Fig. 2. Output spectra of 4 mm-long phase shifter (a), phase shift of 4 mm long phase shifter (b), loss and efficiency $V_{\pi}L_{\pi}$ of the phase shifter under different applied voltage (c) and performance of phase shifter under different doping profile by fixing $V_{\text{bias}} = -6.0$ V and $V_{pp} = 3.0$ V (d).

The measured output spectra of the silicon modulator under different V_{bias} are shown in Fig. 2(a). The free spectrum range (FSR) of the asymmetric MZI is 5.75 nm corresponding to a group index $N_g = 4.18$. In Fig. 2(b), a π phase shift can be realized with 7.0 V bias for a 4mm-long phase shifter which corresponds to a modulation efficiency of $V_{\pi} \cdot L_{\pi} = 26.7 \text{ V} \cdot \text{mm}$ at $V_{\text{bias}} = -6 \text{ V}$. The measured phase shifter efficiency $V_{\pi} \cdot L_{\pi}$ and optical loss under different V_{bias} are shown in Fig. 2(c). As the increase of the applied reversed voltage V_{bias} , the free carriers in the p-n junction keeps depleting which reduced the absorption loss of the phase shifter. In the deep depletion region, as there are less and less free carrier left in the depletion region, the modulation efficiency becomes lower.

An appropriate choosing of working point is important for the real application of silicon optical modulator. For a fixed doping profile, working point denotes the applied reversed voltage V_{bias} that the modulator working under. Considering from the V_{bias} as shown in Fig. 2(c), if low power consumption is the main concern, for a fixed length of phase shifter, the modulator has to be with high modulation efficiency, which means a lower V_{bias} is better. But the modulator has to stand a 0.2 dB/mm loss penalty compared with that of high V_{bias} case. Meanwhile, as the pn junction is only partially depleted, the depletion width of the p-n junction is still quite small. As a result, the high junction capacitance of the phase shifter will degrade speed of the modulator. On the other hand, if the speed performance is the main concern, larger V_{bias} is preferred because of the low junction capacitance under deep depletion region. The phase shifter loss of unit length is also small under large V_{bias} region. The penalty is a high $V_{\pi} \cdot L_{\pi}$ value, which means that in order to realize π phase shift, a longer phase shifter or a larger V_{pp} is also difficult to be realized in electrical integration circuit design.

Another important parameter is the doping profile of the phase shifter. Figure 2(d) shows the phase shifter performance with 4 different doping profile on the cross section under V_{bias} = -6 V and V_{pp} = 3 V. The performance of the doping profile shown in Fig. 1 is noted by the

points with $V_{\pi} \cdot L_{\pi} = 26.7 \text{ V} \cdot \text{mm}$. Basically we increase both of the background doping level and also the compensated doping level on the cross section of the phase shifter. As the increase of the doping concentration near the p-n junction, the modulation efficiency is improved from $V_{\pi} \cdot L_{\pi} = 26.7 \text{ V} \cdot \text{mm}$ to $V_{\pi} \cdot L_{\pi} = 19.5 \text{ V} \cdot \text{mm}$. In order to realized π phase shifter with $V_{pp} = 3 \text{ V}$, the phase shifter length is reduced from 8.9 mm to 6.5 mm. Shorter length of the phase shifter means lower microwave loss coming from the electrodes. It will give a better speed performance of the modulator. However, the total optical loss of the phase shifter with shorter length is (6.5 mm × 1.48 dB/mm = 9.62 dB) which is worse than that of longer length (8.9 mm × 1.04 dB/mm = 9.26 dB). Regarding the doping profile with $V_{\pi} \cdot L_{\pi} =$ 22.0 V·mm, the length is 7.35 mm and total phase shifter loss is only 6.91 dB. This low loss of point $V_{\pi} \cdot L_{\pi} = 22.0 \text{ V} \cdot \text{mm}$ comes from the doping compensation method which reduces the absorption loss of the phase shift while keeping the phase shifter efficiency at a high level. Without the compensation doping, the phase shifter loss will increased along with the increase of the background doping level and phase shifter efficiency.

For the real application, reasonable choosing of the doping profile and working point of modulator must be carefully considered depending on if the requirement of modulator performance is high speed or low power consumption. Doping compensation method offers a good approach for fine tuning of the working point of the silicon modulator.

3.2 AC measurement of the microwave in the traveling-wave electrodes

Small signal performance of the microwave traveling in the electrodes is measured through Agilent N4373C Lightwave Component Analyzer. The 2-port S-parameters measurements are went through after probes calibration using standard short-open-load-through method with Cascade impedance standard substrate. Classical transmission line model is utilized to achieve the characteristic parameters of the electrodes [14]. The S-parameter responses of a lossy unmatched transmission line are:

$$[S] = \frac{1}{D_s} \begin{bmatrix} (Z^2 - Z_0^2) \sin h \, \gamma L & 2ZZ_0 \\ 2ZZ_0 & (Z^2 - Z_0^2) \sin h \, \gamma L \end{bmatrix}$$
(1)

In which

$$D_s = 2ZZ_0 \cosh \gamma L + (Z^2 + Z_0^2) \sinh \gamma L \tag{2}$$

In the equation, L is the length of the electrodes. Z_0 is matching impedance which is 50 Ω in our measurement system. Z and γ denotes the characteristic impedance and propagation constant of the transmission line which can be denotes by:

$$Z^{2} = Z_{0}^{2} \frac{(1+S_{11})^{2} - S_{21}^{2}}{(1-S_{11})^{2} - S_{21}^{2}}$$
(3)

$$e^{\gamma L} = e^{(\alpha + j\beta)L} = \frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}} \pm \frac{\left[(1 + S_{11}^2 - S_{21}^2)^2 - 4S_{11}^2\right]^{1/2}}{2S_{21}}$$
(4)

The measured S-parameters of 4 mm-long phase shifter and corresponding parameters achieved under different applied bias voltage are shown in Fig. 3. Along with the increase of the depletion region of the p-n junction under reversed bias voltage, the depletion capacitance is reduced and the corresponding 6.0 dB bandwidth of microwave transmission in the electrodes increases from 8.9 GHz at $V_{\text{bias}} = 0$ V to 13.9 GHz at $V_{\text{bias}} = -5.0$ V as shown in Fig. 3(a). The increase of the microwave traveling speed results in a larger phase shift according to the time. Thereafter, the phase shifter at a given frequency is smaller when the reverse bias is increased as shown in Fig. 3(b).



Fig. 3. Transmission coefficient S21EE amplitude (a), phase of the microwave (b), group refractive index of the microwave (c), Reflection coefficient S11EE amplitude (d), real part of impedance (e), image part of impedance (f), absorption loss (g) of microwave in the 4 mm long traveling wave electrodes under different applied voltage and normalized loss (h) under $V_{\text{bias}} = -5 \text{ V}$.

Main reason of using a transmission lines electrode is to transfer RF power along the electrodes synchronously with low loss. Synchronization means the microwave and optical wave must travels in the waveguide with a same speed v or group index n. Any velocity mismatching between them will reduce the accumulated interaction between electrical microwave and optical wave along the electrode. Under $V_{bias} = -5.0$ V, the group refractive index of microwave shown in Fig. 3(c) is around $N_{eff_{Microwave}} = 4.2$ near 26.0 GHz which means a good matching with the optical mode ($N_{group_optical} = 4.18$) traveling in the silicon waveguide. The return loss in a transmission line system, which is denotes by S11, means the reflectivity coefficient of the microwave coming from the impendence mismatch between the transmission line electrodes Z and terminal load Z_0 . In our transmission line electrodes, the return loss S11 shown in Fig. 3(d) are all below -10 dB which means a quite small microwave reflection under all of the frequency. On Fig. 3(d), the return loss under $V_{bias} = -5.0$ V.

-5.0 V reaches about -35 dB under 12.3 GHz and 26.0 GHz, which denotes a perfect impedance matching $Z = Z_0 = 50 + 0j$ as shown in Fig. 3(e) and Fig. 3(f) and also the π shift point in Fig. 3(b).

Except the return loss, another part of the loss comes from the absorption of the microwave in the electrodes. The measured absorption loss of the microwave is shown in Fig. 3(g), which has a similar (reversed) profile compared with that of transmission coefficient S21 shown in Fig. 3(a). Higher value of bias voltage results in larger depletion region of the p-n junction and lower absorption loss of the microwave. Figure 3(h) carries a comparison between the return loss and the absorption loss under $V_{\text{bias}} = -5.0$ V which shows that the absorption loss plays a main part in the total loss. Further optimization of the electrodes lies on reducing the absorption loss while keeping the return loss at low level. Possible approaches include increasing the width and thickness of the metal layer and reduce the resistance of the handle wafers.

3.3 AC measurement of the silicon optical modulator



Fig. 4. The AC measurement system of the silicon MZI optical modulator.



Fig. 5. The electro-optic bandwidth of silicon modulator with doping profile under $V_{\pi}L_{\pi} = 26.7$ V·mm (a), eye diagram of the silicon modulator with the doping profile under $V_{\pi}L_{\pi} = 26.7$ V·mm (b) and eye diagram of the modulator with doping profile under $V_{\pi}L_{\pi} = 22.0$ V·mm (c).

The speed performance measurement setup is shown in Fig. 4. The high speed electrical signal coming from 50/56-Gbit/s Anritsu Pattern Generator MP1822A was firstly amplified through a 67 G high speed driver. It was applied to the modulator through a 60 G DC bias tee and a 67 G probe. A 50 Ohmic termination load was added on the other end of the travelling wave electrodes for impedance matching. A continuous-wave light coming from the tunable laser was firstly amplified through an EDFA, after that it was modulated by adding a non-return-zero pseudorandom binary sequence (PRBS) 2^{31} -1 signal under V_{bias} = -5.0 V with V_{pp}

= 7.0 V. The output optical signal was amplified again and collected by an Agilent DCA after optical filter. The measured electro-optics bandwidth reaches 25.6 GHz under $V_{bias} = -5.0$ V and the data rate of the eye diagram reaches 50-Gb/s with an extinction ratio of 5.56 dB as shown in Fig. 5(a) and Fig. 5(b). The measurement eye diagram comes from the silicon modulator with doping profile show in the Fig. 1 which has a phase shifter efficiency of $V_{\pi} \cdot L_{\pi} = 26.7$ V mm. Higher dynamic extinction ratio at 50-Gb/s is achieved with the doping level under $V_{\pi} \cdot L_{\pi} = 22.0$ V mm as shown in Fig. 5(c).

4. Conclusion

We demonstrate high speed silicon MZI modulator with 50.1-Gb/s data rate and 5.56 dB extinction ratio. The measured phase shifter optical loss is 1.04 dB/mm with a modulation efficiency ($V_{\pi} \cdot L_{\pi}$) of ~26.7 V·mm at $V_{\text{bias}} = -6.0$ V. The modulation efficiency, phase shifter loss and switching speed have a close relation with each other. V_{bias} and doping profile of the phase shifter has to be reasonably chosen in order to achieve the ideal performance of the silicon optical modulator depending on different requirement. Compensation doping method and traveling-wave electrodes will be the mainly two approaches in order to further optimizing the loss and switching speed of the reversed PN junction MZI silicon optical modulator.