Low-voltage, high extinction ratio carrier-depletion Mach-Zehnder silicon optical modulator

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ABSTRACT

As a result of the low modulation efficiency of carrier-depletion Mach-Zehnder silicon optical modulator, it always needs a high voltage around 6 V, which is very difficult to supply in an integrated high-speed CMOS chip. We demonstrate a carrier-depletion Mach-Zehnder silicon optical modulator which works at a low voltage. Its coplanar waveguide electrode is carefully designed to make sure the electrical wave loss along the device is low. The device operates well at a data rate of 12.5 Gb/s, whose phase-shifter length is 2 mm. Voltages with the swinging amplitudes being 1 V and 2 V are applied to the device with the reverse bias voltages of 0.5 V and 0.8 V. The extinction ratios are 7.67 and 12.79 dB respectively.

Keywords: low voltage swing, high extinction ratio, depletion, silicon, Mach-Zehnder Interferometer.

1. INTRODUCTION

Silicon-based optical modulator is a crucial device for integrated silicon photonics, which behaves as the interface from electronic domain to its optical counterpart. Since Liu et al. [1] demonstrated a high-speed carrier-depletion Mach-Zehnder Interferometer (MZI) silicon optical modulator, a lot of works [2-4] have been done to simplify the fabricating process and improve its extinction ratio. But the driving voltage is still around 5 V, which is not compatible with the microelectronic integrated circuits. It is a critical requirement for the CMOS chips to supply such a voltage in very high frequency. In order to reduce the driving voltage, we have designed a low transmission loss waveguide electrode. Our simulation result indicates that the loaded electrode containing a 2-mm-long phase-shifter has a transmission loss of less than 3 dB when the frequency is less than 16 GHz. 12.5 Gb/s data transmission measurement is performed. An extinct ratio of about 13 dB is achieved when the applied voltage swing is 2 V. The voltage swing can be even reduced to 1 V, while the device still has an extinction ratio of 7.67 dB.

2. DEVICE DESIGN AND FABRICATION

The optical structure of the device is based on a MZI design. There is a built-in arm length difference of 120 μm. A multimode interference structure is used as the optical splitter and combiner. The silicon ridge waveguide is 600 nm in width, 220 nm in height and 70 nm in slab thickness. Both arms of the device are doped to balance the transmission loss.
Figure 1 illustrates the schematic cross section of the modulation region. The p-doping concentration is $1 \times 10^{18} / \text{cm}^3$, and the n-doping concentration is $8 \times 10^{17} / \text{cm}^3$. The p-n junction locates 100 nm right of the middle of the ridge, because the hole is more efficient to change the refractive index than the electron. The P++ and N++ doping regions are 1 $\mu$m away from the side of the ridge. In order to reduce the capacitance of the diode, a 40 nm-wide gap between p and n doping regions is adopted. [5]

Figure 2 is the optical microscope image of the device. A CPW electrode is used as the electrical transmission line. A probe with GSG pattern is used to couple the radio-frequency (RF) wave into the device. A termination resistor is integrated in the chip, which is made of TiN. It is designed to absorb the electrical wave at the other end of the electrode, avoiding the reflection which can deteriorate the performance. The resistance of the terminator is 33 ohm.

3. SIMULATION AND EXPERIMENT RESULT

We use a commercial software package HFSS to simulate its electrical performance. The result indicates that the loaded transmission line with a reverse bias voltage ~1 V has a lower transmission loss. The 2-mm-long phase-shifter has a 3-dB bandwidth of 16 GHz, and its roll-off is not fast. It has only a 6 dB loss when the frequency is 40 GHz. This will make it possible to work at a high frequency.
Figure 4. Simulation result of the transmission loss of the loaded CPW electrode where 2-mm-long phase-shifter is below.

Figure 5 shows the normalized spectrum of the device under different applied voltages. The image shows that the spectrum has shifted obviously under a relatively low voltage of 2 V. The static extinction ratio is about 25 dB. This indicates that the loss balance of the two arms is well done.

Fig. 5. Response of 2-mm-long phase-shifter device with the applied voltage

Fig. 4. Simulation result of the transmission loss of the loaded CPW electrode where 2-mm-long phase-shifter is below.
The data transmission experiment is performed. An Anritsu MP1800A is used to provide a 12.5 Gb/s data stream. The electrical wave is directly coupled into the device by a probe. In order to meet the power requirement of the photodetector, the output light was amplified by an EDFA and then passes through an optical filter. The modulated optical signal is measured by an Agilent 86100A digital communication analyser with a 20 GHz optical head. The device is reversely biased at 0.8 V. When the input voltage swing is 2 V, the device exhibits an extinction ratio of 12.79 dB. There is even an extinction ratio of 7.67 dB while the voltage swing is 1 V and the reverse bias voltage is 0.5 V. The maximum power consumptions of the modulator are 98 mW and 30 mW when the voltage swings are 2 V and 1 V respectively. However, most of the power is not used to do the modulation, because the termination resistor has consumed a large part of power, if there is a DC current. When a DC termination resistor is adopted, most of the energy is used to charge and discharge the depletion capacitor which are indeed the modulation parts. The device’s power consumption will dramatically decrease to 20 mW and 5 mW, if a DC block termination is used. [6] Then the energy efficiency could be reduced to 400 fJ/bit.
4. CONCLUSION

We have successfully reduced the driving voltage to 1 V for the carrier-depletion Mach-Zehnder silicon optical modulator. As a result of the low electrical transmission loss of a 2-mm-long phase-shifter, 2 V voltage swing leads to an extinction ratio of about 13 dB. Even the device can work by a swing of 1 V. This work makes the carrier-depletion Mach-Zehnder silicon optical modulator easier to be integrated in a CMOS chip. The power consumption will be only 400 fJ/bit, with the help of a DC block termination.

REFERENCES


