Design of an ultra-compact optical modulator based on a silicon-vanadium dioxide hybrid waveguide

Zhaoyin Sun, Linjie Zhou,∗ Hanyu Zhang, Liangjun Lu, and Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
∗Corresponding author : ljzhou@sjtu.edu.cn

Abstract: We present the design of an electrically driven hybrid Si-VO₂ electro-optic modulator with a length of 1.4 µm. Simulation shows the modulator on-off extinction ratio is 8.7 dB and insertion loss is only 1.9 dB.

OCIS codes: (130.0130) Integrated optics; (250.0250) Optoelectronics; (130.4110) Modulators.

1. Introduction

Electro-optic modulators are essential components in integrated photonic circuits. The silicon modulators have been intensively investigated in recent years. Modulators based on Mach-Zehnder interferometers (MZIs), microring resonators or photonic crystal waveguides have been demonstrated with high performances. However, due to the weak free-carrier plasma dispersion effect in silicon, a long MZI arm length is still required in order to provide a high modulation depth. Although the resonance effect can be used to reduce the device footprint, it also sacrifices the optical bandwidth with higher sensitivity to environmental temperature change [1, 2]. Another approach to make a compact modulator is to use hybrid integration, in which the waveguide is made of silicon and an exotic material that has a large refractive index change to electric field.

Vanadium Dioxide (VO₂) is a particularly promising material for its large change of refractive index in the infrared wavelength range due to the reversible insulator-metal transition (IMT) occurring at near room temperature (∼68°C) [3]. The IMT could also be induced by applying an electric field of 6.5 × 10⁷ V/m [4]. The response speed potentially is very fast in the order of ps. The electrical and optical properties are changed significantly upon phase transition. Near 1550 nm, the complex refractive index changes from 3.243 + 0.346i (semiconductor) to 1.977 + 2.53i (metal) [5]. The refractive index change is three to four orders of magnitude larger than that of silicon, so that it is possible to shrink the device footprint by as much as three orders of magnitude. Furthermore, the small footprint reduces the junction capacitance and parasitic resistance, which in turn results in faster response and lower power dissipation. The excellent phase-change properties of VO₂ make it possible to be used in electro-optic modulators and other integrated photonic devices. Here we present our design of an electro-optic modulator based on the hybrid silicon-VO₂ waveguide. High extinction ratio (ER) and low insertion loss (IL) are achieved based on numerical simulations.

2. Device design and results

Figure 1(a) shows the structure of the Si-VO₂ hybrid modulator. A silicon ridge waveguide with a height of 220 nm and a width of 500 nm is divided into two parts by a narrow vertical slot. The slot is filled with VO₂ in the waveguide region and SiO₂ in the 60-nm-thick slab region. The device is assumed to be covered with a SiO₂ upper-cladding layer. The slot forms a tilt angle with the propagation direction of the waveguide as seen from Fig. 1(b). The front and rear silicon waveguide sections at the two sides of the VO₂ are lightly p-type and n-type doped, and the slab regions beside the waveguide are highly doped so that electrical contacts can be made. When input light of TE polarization propagates into the slab region, it interacts strongly with the VO₂ material. When the VO₂ is in the semiconducting state, light only experiences weak absorption, leading to high transmission at the output port. On the other hand, when the VO₂ is changed to the metallic state, then the absorption is much stronger with highly attenuated transmission. The tilted slot can increase the interaction length and meanwhile provide an adiabatic transition from the silicon dielectric mode to the silicon-VO₂ hybrid slot mode so that the back reflection is reduced. The IMT is enabled by the sandwich structure in which high electric field is formed when the anode (P++ electrode) is reverse-based with respective to the cathode.
and free carriers are injected to the VO$_2$ layer when it is forward-based. Figures 1(c) and 1(d) show the electric field intensity distributions in the cross-section of the Si-VO$_2$ hybrid waveguide. Light is highly absorbed by the metallic VO$_2$.

The key design parameters for such a modulator are the slot width and the slot tilt angle. The modulator insertion loss (IL) is defined as the input-normalized transmission when VO$_2$ is at the semiconducting state. The on-off extinction ratio (ER) is defined as the output power ratio between the semiconducting and metallic states. Figures 2(a) and 2(b) show the simulated ER and IL change as a function of tilt angle for various slot widths from 50 nm to 300 nm. The wavelength is chosen to be 1.55 µm. It can be seen that both the ER and IL increase with a reduced angle if the slot is narrow. It is expectable since the reduced angle means a longer interaction length. For a very wide slot width (e.g., 300 nm), when the angle decreases to 10°, loss at the semiconducting state rises faster than at the metallic state, and therefore, ER experiences slight decrease at 10°. As there is an intrinsic trade-off between the ER and the IL, we define the figure-of-merit as FoM = ER/IL to measure the modulator performance. Figure 2(c) shows the FoM curves.

It reveals that the optimal design should be chosen as slot angle = 20° and slot width = 50 nm. In this case, the device length is 1.4 µm, and the ER and IL are 8.7 dB and 1.9 dB, respectively. We also simulated the optical power reflection as shown in Figs. 2(d) and 2(e). A smaller tilt angle gives a lower reflection due to the smoother mode transformation. The optimal design has very low reflection of around −40 dB at both states.

Figure 3 illustrates the top and side views of the electric field intensity distributions along the propagation direction.
for the optimal design. It is clear that light can pass through the VO₂ slot with low loss when it is in the semiconducting state, while light is blocked with weak transmission at the metallic state. In both states, no standing wave patterns are observed from the input waveguide, indicating negligible back reflection.

Fig. 3. Electric field intensity patterns along the propagation direction (slot angle = 20° and slot width = 50 nm).

Using the wavelength dependent refractive index of VO₂ material [6], we simulated the ER and IL variation with wavelength for the optical design as shown in Fig. 4. The IL reduces towards the short wavelength end. The ER reaches the maximum near 1497 nm and remains a relatively high value across the 100’s nm wavelength range.

Fig. 4. ER and IL as a function of wavelength (slot angle = 20° and slot width = 50 nm).

3. Conclusions

We have proposed an ultra-compact electro-optic modulator based on a Si-VO₂ hybrid waveguide. The modulator design is optimized with numerical simulations. The optimal design gives a device length of 1.4 μm. The ER is 8.7 dB and the IL is 1.9 dB at 1550 nm. It has a broadband response, covering 100’s nm wavelength range. Such a modulator could find applications for future high-density integrated photonic chips.

References