Optimization of Slot Waveguide Modulator Based on Epsilon-Near-Zero Effect

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Abstract: Multi-slot electro-optic waveguide modulators based on carrier-induced epsilon-near-zero effect are theoretically investigated. The extinction ratio of the tri-slot modulator is 1.02 dB/µm, which is higher than the single- and dual-slot modulators. © 2020 The Author(s)
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1. Introduction

Electro-optic modulators are the key drivers for optical communication and signal processing of photonic integrated circuits on silicon, which demand higher modulation efficiency, smaller device dimension, and CMOS-compatibility [1-2]. Significant development has been carried out in the Si-based modulator, such as conventional Mach-Zehnder modulators and silicon-on-insulator (SOI) resonator-based modulators, which suffer from large footprint or complex fabrication process [2]. Transparent conducting oxides (TCOs) such as indium tin oxide (ITO) has been actively studied in modulator applications. Owing to its close-to-zero permittivity, which is also known as epsilon-near-zero (ENZ), it can achieve high-efficiency performance and CMOS-compatibility [3]. In this work, a tri-slot waveguide modulator is designed and it yields high modulation depth (~1.02 dB/µm) compared with the traditional slot waveguide modulators [4,5].

2. Device Design and Results

The complex permittivity of the ITO based on the Drude model [4] is depicted in Fig. 1(a), indicating that the optical properties of ITO are carrier-dependent in the near-infrared regime. The behavior of ITO changes from a low-lossy dielectric to a high-lossy metal as the carrier concentration increases towards the region of $\varepsilon_{real} = 0$. Meanwhile, $\varepsilon_{imag}/|\varepsilon|^2$, which is inversely related with the propagation loss, reaches to the minimum value. In this work, the modulation performance of the tri-slot modulator based on ENZ effect of ITO is investigated at the wavelength of 1.55 µm. The ITO layer embedded in the Si-waveguide results in either low loss (ON-state) or high loss (OFF-state) by applying a bias voltage to adjust the carrier concentration.

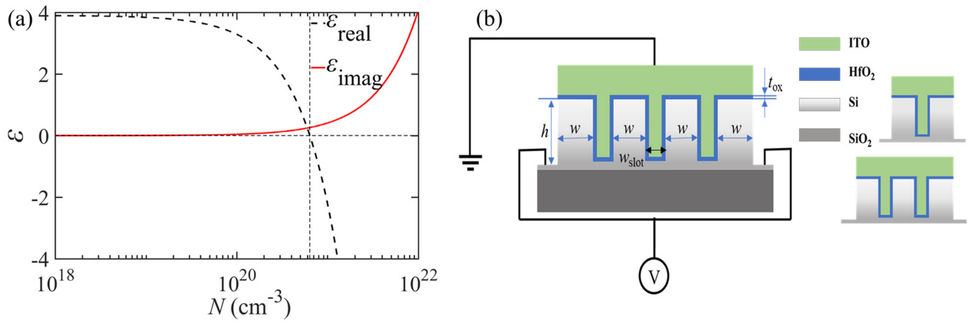

Fig. 1. (a) The real part (ε_{real}) and imaginary part (ε_{imag}) of ITO permittivity (ε) as a function of the carrier concentration at the wavelength of 1.55 µm. (b) Schematic of the proposed tri-slot modulator based on the ENZ effect, where the insets show the cross-section of single-slot and dual-slot with the same slot structure parameters and fixed Si rail width of 180 nm.

The cross-section of the proposed modulator integrated on the SOI platform is presented in Fig. 1(b). The main components of the tri-slot modulator are the three successive material layers: donor-Si, insulator hafnium dioxide (HfO_2), and ITO cladding, which together form the MOS-like configuration to achieve tunable carrier concentration when a voltage bias is applied. The ITO layer is formed by Sn doping at 10^{19} cm^{-3}, which is the minimum bulk electron concentration attainable in ITO to avoid being Mott insulator [6]. High-k dielectric such as HfO_2 with $\varepsilon_{HfO2} = 25$ is chosen. Here, the width (w) and height (h) of the four silicon rails are 180 nm and 220 nm, respectively. The slot structure comprises of 100 nm thick top covering ITO and 30 nm filling slot (w_{slot}), which is composed of 5-nm thick HfO_2 coating layer (t_{ox}) and 20-nm thick ITO filling layer in the slot (t_{ITO}). For electrical connection, illustrated in

Fig. 1(b), ITO, which behaves as degenerate semiconductor with a larger number of electrons, is connected to the ground, and the silicon is applied a forward bias (V).

COMSOL Multiphysics is utilized in this work. The drift-diffusion (DD) model, which is a classical model to analyze the semiconductor, is more accurate than the simplified model such as Thomas-Fermi approximation. By increasing the voltage from -1 V to 5 V, the carrier distribution is shown in Fig. 2(a), which indicates the carrier exponentially accumulates in the ITO/HfO_2 interface. The lines show the transition voltage occurs approximately at 3V, with corresponding carrier concentration of 6.37×10^{20} cm^{-3}. The narrow sub-nanometer accumulation layer which is related to the ENZ effect causes propagation loss. The tri-slot modulator has more overlaps between ITO active layers and the confined slot mode, which leads to a higher modulation depth. Carrier-induced permittivity is utilized to calculate the guided mode effective index (n_{eff}) through Finite Difference Eigenmode (FDE) solver.

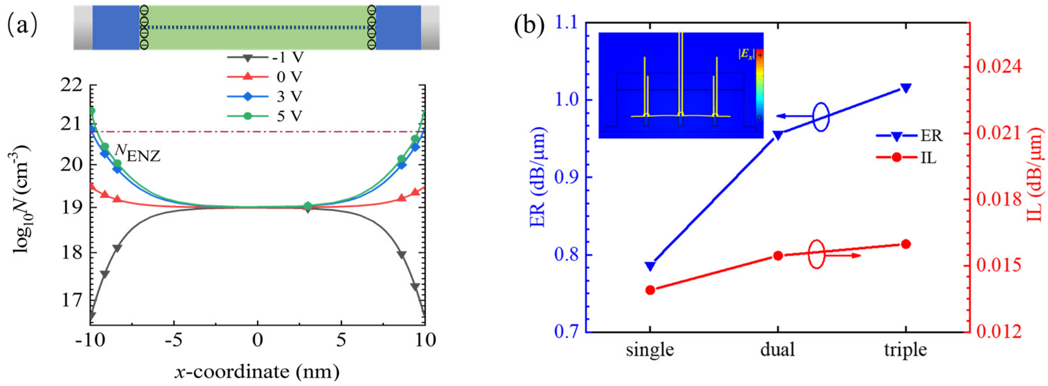

Fig. 2. (a) The carrier concentration (N) distribution in ITO at different voltages in the middle slot. (b) The ER and the IL of three multi-slot modulators. The inset is TE mode distribution of $|E_x|$ of the tri-slot modulator at the OFF-state.

At the ON-state of 0 V, the initial mode loss is 0.016 dB/μm, with corresponding effective index 2.4991+i0.00045. At the OFF-state of 5 V, the mode loss increases to 1.02 dB/μm, with corresponding effective index 2.4901+ i0.02933. Compared with single-slot (~0.78 dB/μm), dual-slot (~0.95 dB/μm) structures in terms of extinction ratio (ER), as shown in Fig. 2(b), the tri-slot modulator yields a higher modulation efficiency and the insertion loss (IL) is almost negligible. The inset shows that the transverse electric (TE) mode distribution in the x-axis supported by the slot modulator, indicating that the ENZ effect in the slot is polarization-dependent.

3. Conclusion

The multi-slot waveguide modulators based ENZ effect of ITO have been theoretically investigated. The tri-slot modulator exhibits a better modulation performance than other slot modulators. Owing to the existence of ENZ effect between ITO and light, it can achieve a compact footprint, a high ER of 1.02 dB/μm, and a negligible IL of 0.016 dB/μm.

Acknowledgements

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