Silicon-photonic electro-optic modulators based on graphene and epsilon-near-zero materials

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Abstract: Silicon-photonic modulators are investigated, integrating either graphene or epsilon-near-zero films, tuned by the field effect. Both waveguide and resonance modulation schemes are demonstrated, allowing for compact, efficient, and broadband designs.

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1. Introduction

Graphene and epsilon-near-zero (ENZ) materials are being investigated as promising candidates for implementing dynamically configurable components due to their tunable near-infrared (NIR) optical properties [1, 2]. Graphene exhibits tunable optical conductivity by means of electrical gating, while transparent conducing oxides (TCOs) are capable of manifesting ENZ behavior in the NIR, depending on their free-carrier concentration.

In this work, TCOs and graphene are evaluated for designing integrated amplitude modulators exploiting both in-line and resonance configurations. The examined physical platforms are formed by a silicon-rib (Si-rib) waveguide, integrating either a 10-nm indium tin oxide (ITO) film, Fig. 1(a), or a graphene sheet, Fig. 1(b), separated by the n-doped silicon core (10^{18} cm^{-3}) with a 5 nm layer of high-k dielectric (HfO_2). A V_a bias induces carrier concentration changes in the constituent materials, allowing for tuning their carrier-dependent properties.

The geometric parameters denoted in Figs. 1(a)-(b) are appropriately selected to achieve optimal interaction between the guided mode and the loaded material. Specifically, the TCO-based waveguide features $w \times h$ dimensions equal to 180×220 nm^2 (400×200 nm^2) for the TE (TM) mode, with t being 150 nm (320 nm). A larger silicon core is preferable for the graphene-loaded waveguide, equal to 500×170 nm^2 (520×220 nm^2) for TE (TM) operation. It should be borne in mind that the ENZ effect is principally manifested for polarizations normal to the TCO layer, while the two dimensional (2D) nature of graphene interacts solely with the tangential field components of the guided mode.

2. Methods & Results

A multiphysics computational framework is developed to describe the interplay between solid-state physics and electromagnetics. The field effect is rigorously modelled by means of the Poisson equation, with free carriers following a Fermi-Dirac distribution, complemented with the current continuity equations and the drift-diffusion current density expressions [3]. Then, an electromagnetic mode solver is employed for quantifying the carrier effects in terms of the

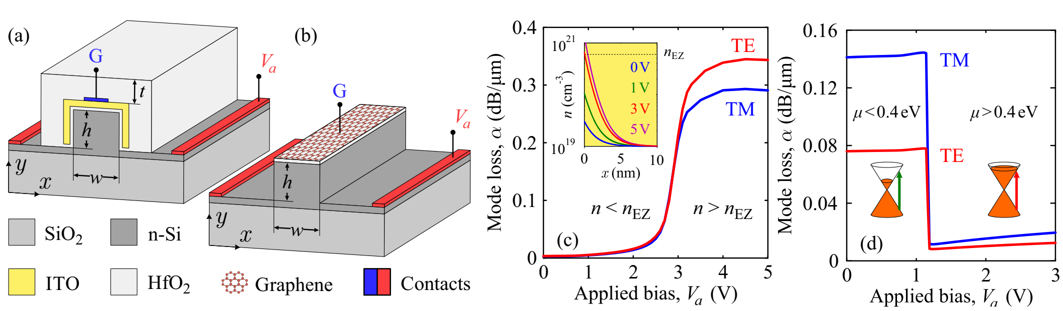

Fig. 1. Si-rib waveguide loaded with (a) an ITO film and (b) graphene. (c)-(d) TE and TM mode loss per unit length as a function of the applied bias for the modulators in (a)-(b), respectively.

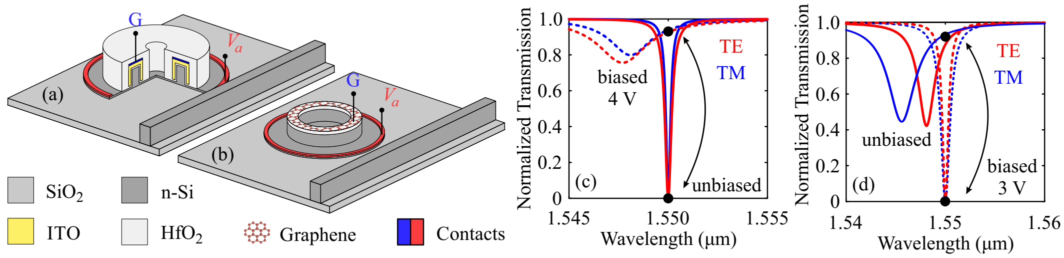

Fig. 2. Si-rib ring resonators integrating (a) an ITO film and (b) graphene. (c)-(d) Normalized transmission as a function of the free-space wavelength for both TE/TM polarizations (red/blue) at the unbiased/biased state (solid/dashed) of the configurations in (a)-(b), respectively.

effective index, n_{eff}. In the case of ring resonators, a spatial transformation is applied, allowing for studying the resonant mode in an axisymmetric approach, avoiding a computationally expensive full 3D analysis. The respective quality factor is rigorously calculated [4] and the transmission is obtained through a coupled-mode theory approach [5]. In all cases, the finite element method (FEM) is employed, implemented using the COMSOL Multiphysics® platform.

With reference to the Si-rib waveguide modulators, their mode-loss per unit length is illustrated in Figs. 1(c)-(d) as a function of the applied bias, considering both TE and TM operation. The TCO-based waveguide modulator, Fig. 1(c), exhibits a step-like mode loss, sharply increasing at 2.9 V, where the electron concentration in ITO reaches the critical value $n_{\mathrm{EZ}} = 6.17 \times 10^{20}$ cm^{-3} for entering the highly lossy ENZ region (inset). Switching between the unbiased state and 4 V allows for modulating the light intensity, with the TE operation benefitting from its dual interaction with ITO. An IL as low as 0.03 dB is introduced for a 3-dB modulation length less than 10 μm in both cases. A similar step mode-loss behavior is observed for the graphene-loaded waveguide, Fig.1(b), exhibiting a drop at 1.2 V, after which the chemical potential μ exceeds 0.4 eV, prohibiting any interband transitions at 1.55 μm (insets). In this case, the TM mode outperforms the respective TE, owing to the greater overlap of its tangential E_z component with graphene. Despite the weaker modulation effect compared to the TCO-based design, toggling between 0-1.5 V results in a 3-dB modulation length equal to 23 μm (45 μm) for the TM (TE) mode with an IL penalty around 0.3 dB.

Moreover, resonance modulation schemes are investigated, Fig. 2(a)-(b), featuring theoretically infinite extinction ratios (ERs) and reduced footprints. Their operation principle consists in perturbing the critically coupled ring resonator by electrically induced changes. With reference to Figs. 2(c)-(d), the ring resonators are selected to be critically coupled at their low loss state (high quality factor, Q_i), which corresponds to the unbiased (biased) state of TCO (graphene) with reference to Figs. 1(c)-(d). By introducing losses and thereby decreasing Q_i, the transmission level rises, shifting at the same time the resonance wavelength (detuning) due to the respective changes in the real part of TCO permittivity (imaginary part of graphene conductivity). Radii down to 2 μm (3 μm) are achievable for the TCO (graphene) ring resonator, while the IL is calculated around 0.3 dB. The energy consumption is anticipated in the sub-pJ/bit range, with the switching speed of the waveguide modulators well-exceeding 100 GHz [3].

3. Conclusions

Electro-optic modulators based on graphene and epsilon-near-zero materials are demonstrated, developed on the well-established and low-loss silicon photonic technology, suggesting promising candidates for on-chip optical modulation.

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