Highspeed Broadband Optical Modulation using Symmetrical Metal-Insulator-Metal Graphene Hybrid Plasmonic Waveguide

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***Abstract*-Optical capacitance effect and metal-insulator-metal mode coupling have been exploited in this work to enhance the light-graphene interaction. Hence, large extinction ratio and high modulation bandwidth are achieved simultaneously.**

I. INTRODUCTION

The tunability of the optical properties of graphene controlling the external electrical bias along with the strong mode confinement in low index dielectric medium offered by the hybrid plasmonic waveguides (HPW) has motivated research on designing high speed optical modulators and switches [1]-[3]. However, among the recently proposed geometries, the modulators with smaller footprints offer low extinction ratio [2], while the ones with larger footprints have high extinction ratio (ER) [1]. Moreover, most of them suffer from large energy consumptions which make them inefficient to implement in nanoscale for highspeed applications [1]. In this work, a symmetrical metal-insulator-metal (MIM) HPW based on graphene has been proposed that can circumvent the problem of this tradeoff between footprint and extinction ratio. Also, the possible low energy consumption (less than 1 fJ/bit) demonstrates its potential for highspeed optical modulation [1].

II. WAVEGUIDE DESIGN AND ANALYSIS METHODOLOGY

The schematic of the proposed optical modulator has been shown in Fig. 1. The geometry of this waveguide is symmetrical about both the x-z and y-z planes with the central axis of the silicon (Si) nanowire along the z-axis. The monoatomic graphene layers are assumed to be of 1 nm thick as in [1], and all the dimensions of the HPW are denoted by respective notations in Fig. 1. Here, a = 100 nm, b = r = 30 nm, and W = 80 nm have been assumed. The Au electrodes are for applying the gate bias voltages. The modal properties and modulation characteristics are obtained employing **E** field based full-vectorial finite element method (FEM) assuming the z-axis as the wave propagation direction. The refractive indices of gold (Au), silicon (Si), silica (SiO_2), graphene, and hexagonal-boron-nitride (hBN) have been derived from [1], [4]. The refractive index of graphene shows strong dependence on the operating wavelength and external electrical bias which is an essential property for designing optical modulator.

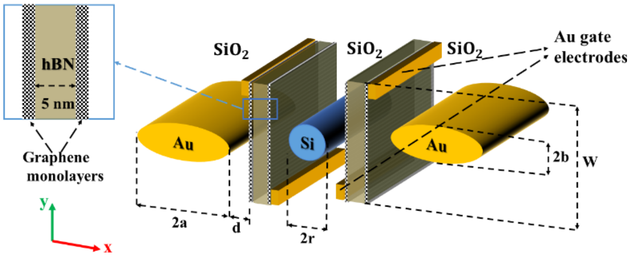

Fig. 1. Schematic of the proposed optical modulator.

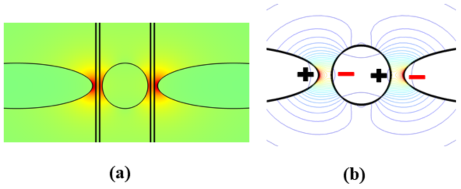

Fig. 2. (a) E_{norm} distribution of the fundamental gap mode at 'ON' state, and (b) E_{norm} distribution of the fundamental gap mode in the absence of graphene-hBN-graphene layers at $\lambda = 1.55$ µm.

III. RESULTS AND DISCUSSION

A. Modal Characteristics without graphene-hBN-graphene layers

As the graphene-hBN-graphene layers are located in SiO_2 gaps, the fundamental gap mode interacts with the graphene layers as shown in Fig. 2(a). The monopole modes of opposite polarities on Au nanowires induce a dipole mode on Si nanowire and the monopole-dipole-monopole mode coupling is responsible for the evolution of the gap mode as shown in Fig. 2(b) [5], [6]. This mode offers an enhanced interaction between

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the electric field and graphene, hence high mode confinement (about 95% of total propagating mode power) in the gap regions with deep subwavelength mode size (~$\lambda^2/1000$) are achieved at the telecommunication wavelength in the absence of graphene-hBN-graphene layers as shown in Fig. 3. This may be due to the fact that, the discontinuity of dielectric function creates polarization charge at the Si-SiO_2 interface, which interacts with surface plasmons through the SiO_2 gap. Thus, energy coupling takes place in the gap region which is analogically termed as the optical capacitance effect [3]. Another reason could be that, the MIM like mode coupling strengthens the field localization offering an enhanced interaction with graphene as the structure can be thought alike a symmetrical MIM structure with a multilayer dielectric region. The choice of elliptical metallic nanowires contributes further to the reported high field localization [6].

B. *Modulation Performance of the Modulator*

The extinction ratio (ER), 3-dB modulation bandwidth (f_{3dB}), and energy consumption per bit (E_{bit}) have been calculated following the procedure as outlined in [2]. At the telecommunication wavelengths the chemical potential (μ_c), which is related to the external gate bias voltage (V_g) as indicated in [1], has been reported to be 0.42 eV at 'ON' state and 0.53 eV at 'OFF' state in this case. For decreasing gap width (d), the electromagnetic energy coupling in the SiO_2 gap increases further as in the parallel plate capacitance of electrical circuit. Consequently, the ER value increases due to an enhancement of mutual interaction between graphene and the electric field. On the other hand, the mode size decreases with the decrease in gap size resulting in smaller active region. This smaller active region is responsible for larger bandwidth and lower energy consumption per bit reducing the effective capacitance formed by each graphene-hBN-graphene layer as described in [2]. Evidently, for d = 2 nm, ER = 62 dB, f_{3dB} = 300 GHz, E_{bit} = 0.84 fJ/bit, and $A_{eff} = \lambda^2/2900$ with only 2.1 μm long active region at the telecommunication wavelengths have been obtained as shown in Fig. 4. Even at larger gap width, the modulation characteristics are appreciable [1], [2]. Furthermore, at λ= 1.2 μm, the performance parameters ER = 124 dB, f_{3dB} = 335 GHz, E_{bit} = 2.8 fJ/bit, and at λ = 2 μm, ER = 36.5 dB, f_{3dB} = 153 GHz, E_{bit} = 0.5 fJ/bit confirm the multiwavelength operability of this modulator.

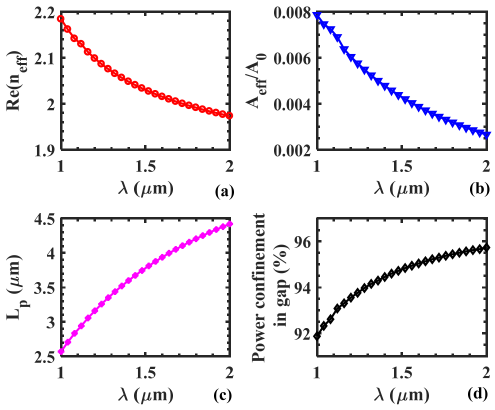

Fig. 3. (a) Real part of effective index (Re(n_{eff})), (b) effective mode area (A_{eff}), (c) propagation length (L_p), and (d) power confinement in SiO_2 gaps for variable wavelength (in the absence of graphene-hBN-graphene layers).

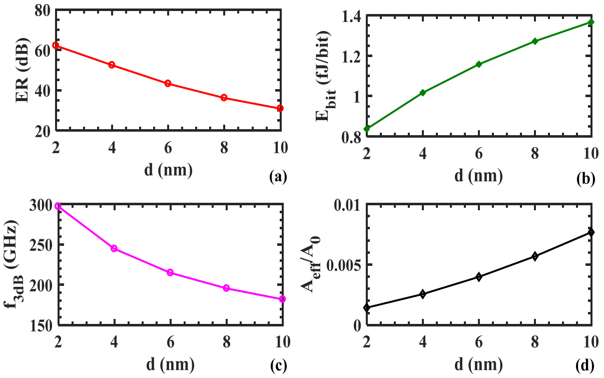

Fig. 4. (a) Extinction ratio (ER), (b) energy consumption per bit (E_{bit}), (c) 3-dB modulation bandwidth (f_{3dB}), and (d) effective mode area for variable gap size at λ = 1.55 μm.

IV. CONCLUSION

It is seen that the proposed HPW even with its smaller footprint renders both large extinction ratio (as high as 62 dB) and high modulation bandwidth (~300 GHz), and thus breaking the tradeoff between these parameters encountered by most of the proposed modulators. Moreover, the multiwavelength operability with very low energy consumption (about 0.84 fJ/bit) proves the nanoscale implementation compatibility of the proposed geometry. Therefore, this HPW shows a good promise in highspeed broadband optical modulation.

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