The 26th Iranian Conference on Optics and Photonics (ICOP 2020), and the 12th Iranian Conference on Photonics Engineering and Technology (ICPET 2020). Kharazmi University, Tehran, Iran, Feb. 4-5, 2020

Kharazmi University

مدلسازی جداکننده پلاریزاسیون تنظیم‌پذیر گرافن پلاسمونیک

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چکیده- در این مقاله طراحی و تحقیق یک تقسیم‌کننده پلاریزا سیون تنظیم‌پذیر مبتنی بر اثر پلا سما در محدوده فرکانسی نزدیک فرو سرخ ارائه شده ا ست. با درنظر گرفتن گرافن بعنوان یک ماده نوری تنظیم‌پذیر، انواع جداکننده مدهای TM و TE پیاده سازی شده‌اند. ساختار پیشنهادی این قابلیت را دارد که گرافن پلا سمون‌ها را تحریک کند و با اعمال ولتاژ خارجی قابل کنترل ا ست. با درنظرگرفتن این ویژگی تزویج قوی بین نور ورودی و گرافن پلاسمون برای بهبود نسبت خاموشی مد نظر قرار می‌گیرد. بالاترین مقدار نرخ انقراض برای ساختار پیشنهادی ۲۱ دسی‌-بل و ابعاد ساختار ۱۲۹۰ نانومتر×۴میکرومتر×۲میکرومتر است. این نتایج مسیری برای توسعه کاربردهایی مانند ادوات مسیردهی نوری پلاسمونیکی فراهم می‌کند.

کلید واژه- گرافن، پلاسمون سطحی، تقسیم کننده پلاریزاسیون

Modelling of a Tunable Graphene Plasmonics Polarization Beam Splitter

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Abstract- The analysis, and realization of a tunable polarization beam splitter based on the plasma dispersion effect at near infrared frequencies are presented. By utilizing graphene as a tunable optical material, various types of splitter including TE and TM are implemented. The structure considered here supports graphene plasmons whose dispersion properties can be harnessed by applying an external voltage to the graphene. By utilizing this feature, coupling of the incident light to the graphene plasmons of the structure is used to enhance the extinction ratio of the proposed structure. The output extinction ratio reached to the values as high as 21 dB and the footprint was reduced to 1290nm×4μm×2μm. This provides a path for development of novel practical on-chip applications such as plasmonic rotator devices.

Keywords: Graphene Plasmonics; Polarization Beam Splitter;

1. Introduction

Due to the increasing transmission demands of optical communication systems, polarization beam splitters (PBSs) play pivotal role in manipulation of optical signals such as photonic integrated circuits (PICs) and medical devices. PBS is an indispensable part of polarization division multiplexing (PDM), which has the function of splitting transverse-electric (TE) and transverse-magnetic (TM) polarization beam to different optical paths and allow the two-mode to be processed independently, thereby doubling the traffic bandwidth. There are some critical criteria to assess a PBS, including footprint of device, polarization extinction ratio (PER), insertion loss (IL), operating bandwidth, fabrication tolerance, and structural complexities. It's critical to design PBS with high performance and compact size. Various types of structures have been reported to analyze PBSs, including Directional Coupler (DC), Multimode Interference device (MMI), Mach-Zehnder interferometer (MZI), photonic crystal (PhC). In recent years, academic community has proposed various structures to improve PBS's criteria. In 2016 Ken-Wei Chang [1] introduced a PBS based on combined hybrid plasmonic waveguide with length of $620\times455\text{nm}^2$ and a reasonable IL, but the ERs was -19dB. CMOS-compatible materials based PBS [2] have been demonstrated with a footprint of $790\times600\text{nm}^2$ and ER 25dB and comparatively high IL. Chia-Chien Huang [3] introduced a PBS that employs an augmented low-index guiding (ALIG) structure using subwavelength gratings (SWG), which improve the IL whereas ER is not high enough. The DC-based PBS demonstrated in [4] has length of 48μm which is unfavorable for high integration of photonic circuits. The above structures suffer from low tunability properties. To solve this issue graphene containing structures are introduced. Although the tunable beam splitting in graphene-based structure has already been reported in the literature, because of lack of attention to the problem of proper coupling between the incident light and graphene surface plasmons, footprint of the structure is large, and therefore requires large tuning electrical voltage. Thus, the goal of the tunable of beam splitting in graphene structures remains an issue to be considered.

2. Model and Theory

The polarization beam splitter (PBS) consists of one stem arms and two symmetric driving arm. Figure 1 shows a three-dimensional view of the proposed PBS and also its cross-section in the x-y plane. The input waveguide region is constructed by graphene which is placed on a SiO_2/Si substrate aligned in a way that the incident light excites the graphene plasmons on the surface of graphene. In this structure, the thickness of graphene is tg= 0.3 nm. The wavelength-dependent dielectric constant of SiO_2/Si is obtained from previous works, and their thickness is standard of t_{Si}=290 nm/1000 nm, respectively. The length of coupling region is L=1.25 μm, and distance between upper and lower arms is d_1= 10 nm. The S-bending region has a cosine arc shape, and the length of this region is 1.25 μm. According to the numerical results, the minimum distance between two output waveguides must be d_2= 0.4 μm to have no crosstalk. Also, the width of waveguide is W= 0.3 μm. Beneath the top surface of each arm waveguide, the carriers are injected into the graphene layer by an externally applied voltage (see Fig. 1(a)). The working principle of the structure is based on the plasma dispersion effect. An unpolarized 1.55 μm (i.e. f=193 THz) incident light with the width of α= 0.5 μm is launched into the input waveguide. With a suitable value of the graphene chemical potential, the graphene plasmons can be excited at the boundary of graphene/SiO_2/Si substrate. The carrier injection regions are biased with an external voltage corresponding to the threshold value of the graphene chemical potential ($2\mu_c=\hbar\omega$). Above this value, the propagation mode of the surface plasmons changes from TE to TM. The threshold can be determined by the sign of the imaginary part of the graphene conductivity. In other words, depending on the applied voltage onto input waveguide, the sign of the imaginary part of the graphene surface conductivity can be tuned correspondingly, which in turn controls the propagation characteristics and thus tunable PBS can be achieved.

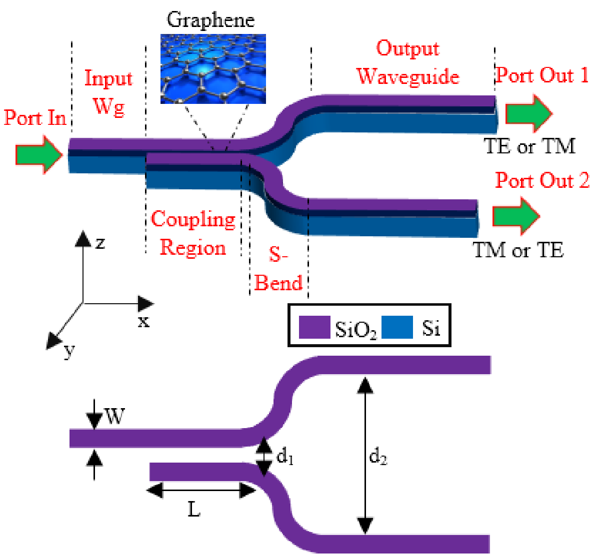

Fig. 1: The structure of the proposed PBS.

2.1. Graphene Surface Conductivity

We consider that a graphene layer is suspended in free space in the x-y plane, where surface conductivity is expressed by Eq. (1).

$$\sigma(\omega, \mathrm{T}, \Gamma, \mu_C(E)) = \hat{x}\,\hat{x}\,\sigma_{xx} + \hat{y}\,\hat{y}\,\sigma_{yy} \tag{1}$$

Here ω is radian frequency, Γ is scattering rate representing the loss mechanism, E denotes external voltage, and μc and T are chemical potential and temperature, respectively. In this work the graphene surface conductivity is derived from Kubo formula in a complex term consisting of interband and intraband. These terms are expressed as:

$$\sigma_{\text{intra}} = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j\tau^{-1})}\left[\frac{\mu_c}{k_B T} + 2\ln(e^{-\mu_c/k_B T} + 1)\right]$$
$$\sigma_{\text{inter}} = -j\frac{e^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - (\omega - j\tau^{-1})\hbar}{2|\mu_c| + (\omega - j\tau^{-1})\hbar}\right) \tag{2}$$

Here, e is the charge of the electron, k_B=1.38×10^{-23} j/k is the Boltzmann constant, $\Gamma=\tau^{-1}$ is the dispersion rate, ħ is the reduced Planck constant, and μ_c is the chemical potential. Surface conductivity of graphene is expressed as

$$\sigma_g = \sigma_{\text{inter}} + \sigma_{\text{intra}} \tag{3}$$

At $0 < |\mu_c| < \hbar\omega/2$, the imaginary part of surface conductivity is negative. In this case, the interband is dominant ($\sigma_{\text{intra}} \approx 0$), and graphene will behave as a semiconductor so that the TE graphene plasmons can be supported. When $|\mu_c| > \hbar\omega/2$ the imaginary part of surface conductivity is positive, and the intraband becomes dominant ($\sigma_{\text{inter}} \approx 0$), and the graphene will behave as metal ultra-thin film supporting a TM graphene plasmons [5].

3. Results

In the following, we analyze the PBS operation of the structure by using the numerical method of finite-difference-time-domain (FDTD) for simulation.

Case 1: (the TE mode)

Using the FDTD method in Lumerical Package and the dispersion relation given in section 2, the field profile for the TE polarization incident light is plotted in Fig. 2. The chemical potential of graphene for input waveguide is set to μ_c=0.4 eV (for Fig. 2(a)) and μ_c=3.4 eV (for Fig. 2(a)), respectively.

Case 2: (the TM mode)

When appropriate chemical potentials are provided, the proposed device can operate as TM PBS. In this case, a TM incident light is injected into input waveguide and propagates through the arms, and the outputs are obtained from output ports. The chemical potential of graphene for input waveguide is set to μ_c<0.4 eV (for Fig. 3(a)) and μ_c=3.4 eV (for Fig. 3(a)), respectively. As can be seen the propagation length is 4 μm. By considering strong coupling condition insertion loss as small as 0.9 dB is obtained for both of ports.

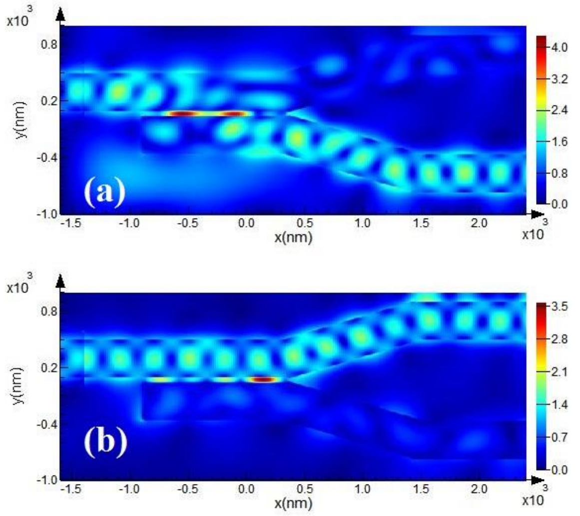

Fig. 2: Propagation of TE graphene plasmons under $0<|\mu_c|<\hbar\omega/2$ the condition for a: lower arm, and b: upper arm.

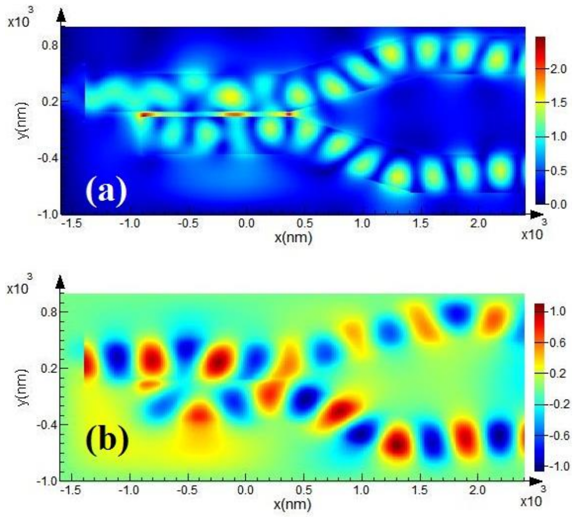

Fig. 3: Propagation of TE graphene plasmons under $0<|\mu_c|<\hbar\omega/2$ the condition for a: lower arm, and b: upper arm.

3.1. Comparison

To further evaluate the results of this investigation, our calculation for the tunable TM/TE polarized light beam from the interface of a graphene containing structure is compared against the previously reported results in Table 1.

Table I. Comparison of this work with previous works

Param. / Ref.	Footprint (nm)	λ(μm)	ER(dB)	Tune
[1]	620*620*540	1.3-1.7	19	No
[2]	$600*790^2$	1.4-1.6	25	No
[3]	$2900*2250^2$	1.5-1.6	18	No
[4]	$>5000^3$	1.4-1.6	15.7	No
This work	2000*4000*1290	1.4-1.6	21	Yes

4. Conclusion

We proposed a tunable PBS based on the plasma dispersion effect at near-infrared frequencies. By considering the tunable optical properties of graphene, two types of splitter including TE/TM were demonstrated. To enhance the extinction ratio, the strong coupling condition has been considered. The output extinction ratio reached the values as high as 21 dB and the footprint was reduced to 1290nm×4μm×2μm.

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