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Nonlinear digital out-of-plane waveguide coupler based on nonlinear scattering of a single graphene layer

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ABSTRACT

A new mechanism for out-of-plane coupling into a waveguide is presented and numerically studied based on nonlinear scattering of a single nano-scale Graphene layer inside the waveguide. In this mechanism, the refractive index nonlinearity of Graphene and nonhomogeneous light intensity distribution occurred due to the interference between the out-of-plane incident pump light and the waveguide mode provide a virtual grating inside the waveguide, coupling the out-of-plane pump light into the waveguide. It has been shown that the coupling efficiency has two distinct values with high contrast around a threshold pump intensity, providing suitable condition for digital optical applications. The structure operates at a resonance mode due to band edge effect, which enhances the nonlinearity and decreases the required threshold intensity.

1. Introduction

The main methods for coupling the out-of-plane light into a slab waveguide are grating and prism coupling techniques [1–4]. One of the challenge of prism coupling technique, especially for commercial applications, is its sensitivity to the mechanical instability. Also for the common grating coupling method, it is necessary to use expensive high-resolution lithography technology to fabricate a grating with submicron period. Here we introduce a novel easier technique for out-of-plane coupling by using nonlinearity scattering of a Graphene (Gr) layer inserted inside the waveguide. In the proposed method, interference between the scattered light in the waveguide due to nonlinear refractive index of Gr layer and the out-of-plane pump light lead to a non-homogeneous intensity distribution on the Gr layer, providing a virtual grating with submicron period and increasing the coupling efficiency for the input light into the waveguide.

Gr as a new monolayer material has been attracted a great deal of attentions in recent years for designing new electro optical [5–9] and nonlinear devices [10–13]. Gr has strong nonlinearity [14–19] and constant absorption in a wide range of wavelength spectrum from UV to far infrared bands [20,21]. However, in spite of strong refractive and absorption nonlinearity of Gr, up to now, mainly the saturation absorption effects in Gr and its derivatives (such as Gr oxide) arisen from Gr absorption nonlinearity (imaginary part of nonlinear refractive index) are used for designing nonlinear devices such as Q-switches [10,11] or optical limiters [12,13]. This is because Gr also has relatively large absorption (2.3%) in comparison with its low thickness (0.34 nm). Due to low thickness of Gr, it is usually used as a composite with a linear host material, thus for nonlinear devices, in order to have suitable volume fraction of Gr in the host material, it is necessary to use a large number of Gr layers which will lead to a high absorption. To overcome this challenge, here we use the resonance due to the band edge effect of a periodic multilayer with a single layer of Gr inside it to reduce the required pump intensity.

2. The structure to be studied

The schematic of the proposed structure is shown in Fig. 1. This structure includes, 4 periods of Si/SiO_2 layers with a Gr layer all coated on a thick Si substrate. The Si layer with a Gr layer inside forms a waveguide in the horizontal direction. The materials are selected for maximum compatibility with silicon technology. The thickness of the Si and SiO_2 layers are $0.8a$ and $0.2a$ with a being selected properly so that the resonator has a resonance wavelength of 1550 nm (the commonly used wavelength in optical communication) for the light incident from the top side. The Gr layer shown in Fig. 1 is considered inside the 3rd

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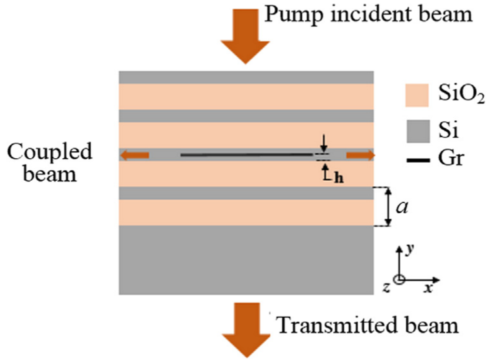

Fig. 1. Structure studied. It consists of a multilayer of SiO_2 and Si, and a Gr layer in one of the Si layers that are coated on a thick Si layer. The structure is illuminated vertically.

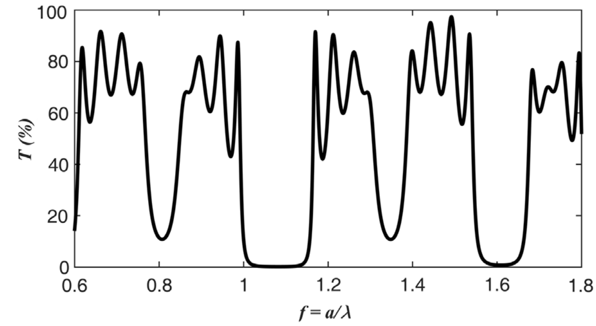

Fig. 2. The transmission coefficient without Gr versus normalized frequency ($f = a/\lambda$).

Si layer (from the top side) at the position that has maximum light resonance intensity.

For the illumination, we consider a Gaussian beam with the full width at half maximum (FWHM) of 4.5 μm. The polarization of the beam is in z-direction, as shown in Fig. 1. In this structure, the multilayer structure forms a vertical resonator due to band edge effect and the resonance of light in the resonator can enhance the light intensity at the Gr.

3. Calculation method

In order to study the response of the proposed structure to the pump light, we use nonlinear 2D FDTD numerical method. Due to very small thickness of the Gr layer (0.34 nm) in comparison with the mesh size (d) in FDTD simulations ($d = 1/70a$), we use a composite model in which we consider Si and Gr inside a single mesh as a composite layer with dielectric constant as [22,23].

$$\varepsilon_c \approx \varepsilon_d + i\frac{\sigma_0}{\omega\varepsilon_0 d_g}\rho \tag{1}$$

where $\varepsilon_d = 12$ is the dielectric constant of silicon, σ_0 is the conductivity of Gr whose value in linear regime (low light intensities) is 6.08×10^{-5} Ω^{-1}, $\rho = d_g/d$ is the filling factor of Gr in the composite layer, ε_0 is the permittivity of free space, and $d_g = 0.34$ nm is the thickness of the Gr layer.

In common nonlinear FDTD simulations, for the change of refractive index (n), mainly instantaneous response is considered in Kerr effect as:

$$\Delta n = n_2 I \tag{2}$$

where $n_2 = 10^{-7}$ $\mathrm{cm^2/W}$ [14] is the nonlinear refractive index of Gr and I is the intensity. As the nonlinearities of Si and SiO_2 are much less than that of the Gr, we ignore them in a good approximation. The assumption of instantaneous response is because the rise time or fall time in light intensity in optical systems is commonly much smaller than the rise time of the refractive index in nonlinear Kerr effect (that is commonly in order of 10 fs). However, this is not correct for the return or fall time of the refractive index to its initial value in the absence of input light). Thus in many applications, especially for optical cavities it is necessary to consider the effect of the fall time of refractive index. For this purpose, in our FDTD simulations, the Gr refractive index increment (Δn_g) is calculated as follows:

$$\frac{d}{dt}\Delta n_g > \frac{\beta n_2 I}{\tau} - \frac{\Delta n_g}{\tau} \tag{3}$$

$$\beta = 1/(1 + I/I_s)$$

where $\tau = 100$ fs [24] is the fall time of the refractive index change and $I_s = 600$ $\mathrm{MW/cm^2}$ [14] is the saturation intensity for Kerr effect in Gr. Then the increment of the equivalent dielectric constant of the composite layer is calculated by:

$$\Delta\varepsilon_c = \rho\Delta\varepsilon_g. \tag{4}$$

Considering k_g as the Gr imaginary refractive index and $\varepsilon_g = Re\{(n_g + ik_g)^2\}$ then $\Delta\varepsilon_g$ can be calculated by

$$\Delta\varepsilon_g = \Delta\left(n_g^2 - k_g^2\right). \tag{5}$$

By considering that in Gr, increasing of intensity leads to decreasing of its absorption [9], we have:

$$\Delta\left(k_g^2\right) < 0. \tag{6}$$

Thus from Eq. (5) we can obtain:

$$\Delta\varepsilon_g > \Delta\left(n_g^2\right). \tag{7}$$

Thus, the minimum nonlinear scattering and minimum required intensity for the required scattering can be calculated by only considering $\Delta\varepsilon_g$ for omitting the influence of absorption nonlinearity on it.

4. Results

At first, in order to calculate the suitable position of the Gr layer and also the thickness of the Si and SiO_2 layers for obtaining suitable resonance in the desired operation wavelength of $\lambda = 1550$ nm, the transmission spectrum of the structure without Gr layer is calculated respect to the normalized frequency ($f = a/\lambda$) as shown in Fig. 2. Due to considering a fixed operating wavelength, we can treat the permittivity of the materials being constant. As can be seen from Fig. 2, there are some resonance modes due to bandgap edge effects. The resonance modes can enhance field in the structure and thus can enhance the nonlinear effect of Gr. It is noticeable that Fig. 2 shows that there exist band gaps where the transmission is very low in the proposed structure with only a few number of periods. Therefore, for further study we select the bandgap edge at $f = a/\lambda \approx 0.99$ of normalized frequency. As a result, the suitable period for the operating wavelength of $\lambda = 1550$ nm is $a \approx 1530$ nm. At this wavelength, the intensity distribution inside the structure is shown in Fig. 3. From Fig. 3, the suitable position for Gr layer is obtained by the position of the maximum to be at the height of $h/a \approx 0.03a$ at the 3rd Si layer (as shown in Fig. 1).

In order to study the effect of Gr layer, in Fig. 4 the transmission spectrum around the desired normalized frequency for various number of Gr layers is shown. By increasing the number of Gr layers one can expect stronger nonlinear effect and thus lower required pump intensity. However as can be seen from Fig. 4, increasing of the Gr layer on the other hand leads to decrease of the quality factor of resonator and thus lower intensity. Regarding this fact, therefore, we consider the case that there is only one Gr layer in the scattering region in the following.