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Plasmon induced transparency and refractive index sensing in a new type of graphene-based plasmonic waveguide

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A B S T R A C T

The plasmon induced transparency (PIT) effect is investigated in a graphene-based waveguide, which is composed of a graphene bus waveguide side-coupled with a graphene strip directly and a graphene ring indirectly. Conventional numerical simulations based on finite element method (FEM) are used to study the transmission properties through optimizing the relevant parameters, and it is proved that the simulation results agree well with the analytical results. Then as one of the potential application branches of the PIT-like effect, the property of refractive index sensing with a higher sensitivity of 4160 nm/RIU is further studied. The result can help to deepen the understanding of PIT-like effect and nano sensor, and it would be also beneficial for the studies and applications of nanoscale graphene-based optical devices.

1. Introduction

In recent years, the effect of quantum interference has become one of the research hot spots in the field of physics because many physical phenomena are generated in quantum optics and atomic physics, such as electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA). The EIT is generated by quantum interference between pumping and probing field, which occurs in three-level atomic system [1,2]. Compared with the EIT in atomic systems, the plasmonic analogue of EIT or plasmon induced transparency (PIT) has attracted much attention due to its significant advantages and wide practical applications, such as sensor [3,4], active plasmonic switch [5,6], polarization conversion [7], and so on. However, most of these structures mentioned above are composed of metallic materials and in real application, it is often needed to change their geometrical parameters to realize the dynamic control of the PIT-like window, which significantly limit the scope of their applications. Meanwhile, not only the metallic structures will have larger propagation losses but also it will have difficulties in controlling the permittivity, and it will also result in a lower ability of active modulation. To overcome these shortcomings, many approaches have been focused on the structures using graphene material [8–11] in recent years to achieve dynamic tunability of PIT phenomenon.

Graphene, known as a type of two-dimensional material of which the carbon atoms are packed in honeycomb like crystal lattice [12,13], has attracted particular attention in recent years due to its remarkable electronic and optical properties [14–16]. The latest research results show that enhanced performance of light-controlled conductive switching can be achieved in hybrid cuprous oxide/reduced graphene oxide (Cu2O/rGO) nanocomposites [17]. In [18], tunable photoluminescence of water-soluble AgInZnS-graphene oxide (GO) nanocomposites and their application in-vivo bioimaging are reported. It is well-known that in the mid-infrared and terahertz frequency ranges, graphene can be used as an alternative to the traditional noble-metal plasmonics. To excite the plasmons in graphene-based waveguide, the periodically patterned graphene structures [19], sub-wavelength dielectric gratings [20], have been used in the experiments. Compared with traditional noble metal materials working in visible and near infrared frequencies, graphene has some major advantages [21] such as low loss, extreme mode confinement capacity and dynamic tunability [10,11]. The stronger confinement of plasmons in graphene can create strong light–matter interactions and can be potentially used to build different types of optical devices. Moreover, in contrast to the noble metals, the most notable property of graphene is that its surface conductivity can be flexibly altered by either chemical doping or gate voltage [22–25] without refabricating the structure. Based on these unique characteristics, the graphene has certainly turned to be a very promising material for optical devices analogue to those using noble metals, including absorber [26], sensor [27] and PIT applications [10,28–30].

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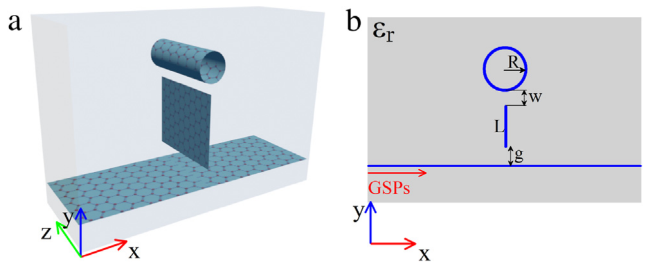

Fig. 1. (a) 3D schematic diagram and (b) Side view of the graphene-based PIT waveguide structure.

In [31], plasmon-induced absorption in a single graphene sheet with two air cavities side-coupled to a graphene nanoribbon is investigated. In [32], the authors demonstrated that PIT can be achieved by placing a flat monolayer graphene under a sinusoidally curved graphene layer. In [33], multi-mode PIT in dual graphene ring resonators is studied, and in [34], multicavity-coupled graphene-based waveguide system as well as its PIT transmission is demonstrated. In [35], the authors have theoretically investigated the PIT characteristics using coupled mode theory (CMT) in integrated graphene waveguides with direct and indirect couplings. Recently, Wang et al. investigated the Fano resonance and its sensing application in an improved grating-coupled graphene structure [36].

However, as far as we know, few results have been found for the research of PIT in a graphene-based waveguide coupled to a vertically placed graphene strip resonator except for Ref. [30], where the authors use two graphene sheets with finite length placed symmetrically on both sides of the graphene bus waveguide as two detuned side-coupled resonators to achieve the PIT-like phenomenon. However, the two resonators are both standing-wave (SW) cavity, and it is well-known that the couplings between a bus waveguide and a traveling-wave (TW) cavity or SW cavity are different [35]. Thus inspired by the special properties of graphene and the reported research results, this paper is to design a new type of graphene-based PIT waveguide system, where a vertical placed graphene strip is used as a resonator, and at the same time, it is side-coupled with a graphene ring on the top and with a graphene bus waveguide at the bottom. Meanwhile, the ring resonator works as a TW cavity while the strip resonator works as a SW cavity. Then in this paper, the effects of the structural parameters and chemical potential of the graphene on the transmission characteristics are studied in detail. In addition, the refractive index sensing performance based on the PIT-like effect is also to be calculated. This proposed compact plasmonic structure may pave a new way for the flexible and tunable PIT-like properties in the application of compact integrated photonic devices.

2. Geometry and theoretical model

The graphene-based waveguide system designed to demonstrate the PIT-like phenomenon is shown is Fig. 1. It consists of a graphene ring and a graphene bus waveguide with a vertical graphene strip placed in between. The graphene bus waveguide and strip can be made by chemical vapor deposition (CVD) method [37–39], and the graphene layer can tightly coat a dielectric nanowire due to van der Waals force [40] to form the ring resonator. The input optical power can only be coupled to the graphene ring indirectly through the near-field coupling with graphene strip. The length of graphene strip is L, the radius of graphene ring is R, the separation distance between the strip and the ring is w, and that between the strip and bus waveguide is g. The overall system is embedded in a background material with a relative permittivity of ε_r. Graphene is treated as an ultra-thin two-dimensional material with a thickness of $t = 0.5$ nm [41], because the surface conductivity of graphene remains constant when its effective thickness varies, and the mode properties, i.e. the refractive index, are actually insensitive to the specific value of the thickness, as long as it is small enough. Its equivalent dielectric constant can be calculated by [42]:

$$\varepsilon_g = 1 + \frac{i\sigma(\omega)}{\omega\varepsilon_0 t} \tag{1}$$

where ω is the frequency of the incident light, ε_0 is the vacuum dielectric constant, $\sigma(\omega)$ is the surface conductivity of graphene, which can be expressed by the Kubo's formula [43]

$$\begin{aligned}\sigma(\omega) = {} & \frac{i2e^2k_BT}{\pi\hbar^2\left(\omega+i\tau^{-1}\right)}\ln\left[2\cosh\left(\frac{E_f}{2k_BT}\right)\right] \\ & + \frac{e^2}{4\hbar}\left[\frac{1}{2}+\frac{1}{\pi}\tan^{-1}\left(\frac{\hbar\omega-2E_f}{2k_BT}\right)\right. \\ & \left. - \frac{i}{2\pi}\ln\frac{\left(\hbar\omega+2E_f\right)^2}{\left(\hbar\omega+2E_f\right)^2+4\left(k_BT\right)^2}\right]\end{aligned} \tag{2}$$

where $T = 300K$ is room temperature, k_B is the Boltzmann's constant, $\hbar$ is the reduced Planck's constant, and e is the electron charge. The electron relaxation time is expressed as $\tau = \mu E_f/eV_F^2$, where $V_F = c/300$ is the Fermi velocity, E_f is the chemical potential, and $\mu = 2.0\text{m}^2/\text{Vs}$ is the DC mobility of graphene [41,44]. In our analysis, the incident light is assumed to be in the mid-infrared wavelength range where the intraband transition is dominant, and under this condition, the optical conductivity of monolayer graphene can be simplified as:

$$\sigma(\omega) = \frac{ie^2E_f}{\pi\hbar^2\left(\omega+i\tau^{-1}\right)} \tag{3}$$

In this paper, the chemical potentials of the graphene waveguide, graphene strip and graphene ring are respectively set as E_{f1}, E_{f2} and E_{f3}. During the simulation, only the transverse magnetic (TM) polarized graphene surface plasmon (GSP) mode is considered throughout this paper. To excite the plasmon waves in practice in the real structure, one can refer to the method of Refs. [20,45,46]. The fundamental GSP mode is injected from the left side of the bus graphene waveguide. The transmission spectra and field distributions are simulated by the Comsol Multiphysics based on the finite element method (FEM), and the 2D-RF Module with perfectly matched layer (PML) absorbing boundary condition is used. Convergence tests are done in the processes of mesh generation to ensure the accuracy of the calculation. During simulation, non-uniform mesh is used and the mesh size in graphene layer is 0.1 nm, and extremely refined mesh size is used in other area.

It should be noted that in [35], PIT phenomenon using graphene strip resonators placed parallel to the bus waveguide is studied. But here, compared with the Refs. [8] and [35], a vertical graphene strip resonator is used in the structure. As we have found that the difficulty of manipulating the PIT effect will increase if the parallel graphene strip is used in the proposed structure. That is because it will increase the direct coupling between the graphene bus waveguide and the ring resonator even though the whole structure will become compact. What is more, according to the CMT [35,47], if one considers a waveguide composed of a bus waveguide side-coupled with only a ring resonator or a strip resonator, the transmission can be respectively written as

$$T_{ring} = \left|\frac{i\left(\omega-\omega_0\right)+\kappa_i-\kappa_e}{i\left(\omega-\omega_0\right)+\kappa_i+\kappa_e}\right|^2 \tag{4.1}$$

or

$$T_{strip} = \left|\frac{i\left(\omega-\omega_0\right)+\kappa_i}{i\left(\omega-\omega_0\right)+\kappa_i+\kappa_e}\right|^2 \tag{4.2}$$

where ω_0 is the resonant frequency, κ_i and κ_e are respectively decay rates due to intrinsic loss and waveguide coupling loss. Thus one will have the minimum transmission rates as $T_{ring} = \left|\frac{\kappa_i-\kappa_e}{\kappa_i+\kappa_e}\right|^2$ and $T_{strip} = \left|\frac{\kappa_i}{\kappa_i+\kappa_e}\right|^2$ when resonance occurs. Usually, $\kappa_i \ll \kappa_e$ is always satisfied as long as the waveguide size is much smaller than the working wavelength, and then the minimum transmission T_{strip} is less than T_{ring},