ARTICLE IN PRESS

Optics Communications (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Tunable multiple plasmon induced transparencies in parallel graphene sheets and its applications

Sara khazaee, Nosrat Granpayeh*

Center of Excellence in Electromagnetics, Faculty of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Plasmon-induced transparency
Graphene
Resonance tunability
Wavelength demultiplexer
Bright-bright mode coupling
Electro-optic switch

ABSTRACT

Tunable plasmon induced transparency is achieved by using only two parallel graphene sheets beyond silicon diffractive grating in mid-infrared region. Excitation of the guided-wave resonance (GWR) in this structure is illustrated on the normal incident transmission spectra and plays the bright resonance mode role. Weak hybridization between two bright modes, creates plasmon induced transparency (PIT) optical response. The resonance frequency of transparency window can be tuned by different geometrical parameters. Also, variation of graphene Fermi energy can be used to achieve tunability of the resonance frequency of transparency window without reconstruction and re-fabrication of the structure. We demonstrate the existence of multiple PIT spectral responses resulting from a series of self-assembled GWRs to be used as the wavelength demultiplexer. This study can be used for design of the optical ultra-compact devices and photonic integrated circuits.

1. . Introduction

The electromagnetically induced transparency (EIT) phenomenon which causes a narrow transparency window in absorption spectrum of an atomic system, is the result of quantum interference [1]. This phenomenon has the potential of several applications in slow light technology, enhancement of nonlinear effects, signal processing, and optical switching [2]. However, quantum EIT effect is achieved under extreme experimental conditions [3]. Fortunately, EIT-like spectral response in various nanostructure such as coupled ring resonators [4,5] and coupled gratings [6] has been achieved. Two plasmonic modes, super radiant (bright mode) and sub radiant (dark mode), can be coupled to the incident field depend on how strong an incident light can be coupled to the plasmonic mode. The bright mode, which strongly couples to the incident field, has a large scattering cross section and a low quality factor due to the radiation coupling. On the other hand, the dark mode, which weakly couples to the incident light, normally has a significantly larger quality factor [7]. Two ways of creating EIT-like effect are bright-dark mode coupling, based on destructive interference between bright and dark mode [7–9] and bright-bright mode coupling, based on detuning the two bright modes [10,11].

The plasmon induced transparency (PIT) is an EIT like effect that utilizes the surface plasmon polariton (SPPs) benefits [12], such as electromagnetic confinement into sub-wavelength scales and overcoming the diffraction limit [13,14]. Recently, metals are replaced by graphene, a one-atom-thick material with unique and fantastic optical advantages such as lossless propagation and tunability of conductivity and plasmonic resonance only by variation of the Fermi energy [15,16]. Proposed graphene structures that create tunable EIT-like response [17–19], have almost complicated patterned nanostrips and limitation on transparency windows linewidths, due to localized surface plasmon excitation [20–22]. Recent researches have demonstrated that the graphene sheets with diffractive grating structures have simpler structure in fabrication and support plasmonic mode with less intrinsic loss, compared to the graphene nanostrips with localized surface plasmon modes. This structure has ability to create guided-wave resonances which are obvious in normal incident transmission spectra. Thereupon, plasmonic wave excitation in graphene sheets occurs by guided-mode resonance, which couples the normal incident optical waves to plasmonic wave [23]. Furthermore, multi-channel applications such as wavelength demultiplexer [24], can utilize multi EIT-like effect, and the same as multi-channel metallic plasmonic structures, graphene reveals this behavior [25–27].

In this work, we utilize two parallel graphene sheets to achieve tunable PIT effect. Graphene sheets are placed on silicon diffractive grating. Sharp notches in the normal incident transmission due to guided-wave resonance excitation, are observed and play bright mode role. According to the graphene property, plasmonic frequency tuning by variation of the graphene sheets Fermi energy, two bright modes close to each other can be obtained. Weak hybridization of two bright modes, demonstrates the PIT response at mid infrared frequencies.

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* Corresponding author.
E-mail address: granpayeh@eetd.kntu.ac.ir (N. Granpayeh).

http://dx.doi.org/10.1016/j.optcom.2017.02.033
Received 7 January 2017; Received in revised form 9 February 2017; Accepted 13 February 2017

Please cite this article as: Khazaee, S., Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.02.033

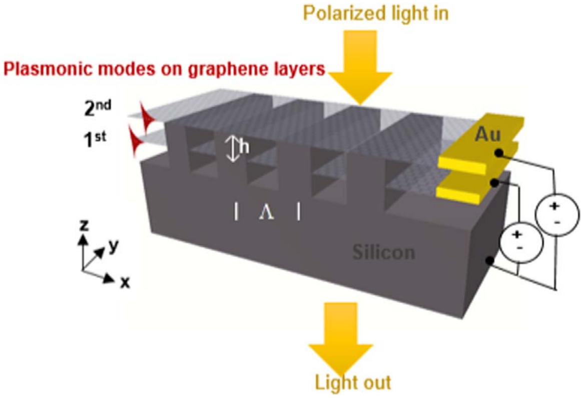

Fig. 1. Schematic view of coupled graphene and grating structure for demonstration of PIT.

Transparency window adjustment was realized electrically or geometrically even in multiple EIT-like case achieved by adding more graphene sheets. To the best of our knowledge, utilizing the graphene sheets for achieving the PIT effect based on two bright mode coupling is considered for the first time, which has the advantages of simple structure with low loss; while the PIT effect based on bright-dark mode coupling by using graphene sheets has recently been achieved [28].

This paper is organized as follows. In Section 2, simulation method is described. In Section 3, PIT effect in mid-infrared in graphene sheets is explained and discussed. In Section 4, electrical and geometrical tunability of PIT structure is studied. An analytical model is employed in Section 5 to verify the numerical results. In Section 6, practical applications of PIT are proposed and analyzed. The paper is concluded in Section 7.

2. . Simulation method

The schematic view of the proposed structure is shown in Fig. 1. The two monolayer graphene sheets are separated by silicon diffractive gratings which are used underneath the graphene sheets to facilitate the excitation of plasmonic waves in graphene. Without graphene, due to the value of Bragg wavelength of silicon grating which is out of the mid infrared range, this structure passes the light in this frequency range with only a uniform loss. The grating period Λ is formed by patterning and etching shallow trenches on a silicon wafer. Graphene is treated as an ultra-thin anisotropic material with a thickness of $\Delta = 1$. The in-plane permittivity of graphene is $\varepsilon_{\parallel} = 1 + i\sigma/\omega\varepsilon_0\Delta$, whereas the out-of-plane permittivity is a constant $\varepsilon_{\perp} = 2.5$, corresponding to the graphite permittivity, where σ, ω, and ε_0 stand for graphene's surface conductivity, the light angular frequency, and vacuum permittivity [29]. Graphene's surface conductivity is written as [29], $\sigma = ie^2E_F/\pi\hbar^2(\omega + i\tau^{-1})$ where e, E_F, and $\hbar$ are respectively the electron charge, the Fermi energy level, and the reduced Planck's constant. $\tau = \mu E_F/(ev_f^2)$ represents the relaxation time, $v_f = c/300$ is the Fermi velocity, c is the speed of light in free space, and μ is the DC mobility of graphene. In this work, we assume that μ for all graphene sheets is $10^4 cm^2V^{-1}S^{-1}$ [30].

For simplicity, the surrounding medium is assumed to be air with $\varepsilon_r = 1$. The incident plane wave is along the z direction and only the transverse magnetic (TM) polarized SPP modes are considered throughout this work. The finite-difference time domain (FDTD) method with periodic boundary conditions along the x and y direction and matched layers (PML) in the z direction are applied. The mesh size of graphene along the x and z directions are respectively set as 1 nm and 0.1 nm.

3. . Graphene PIT system

We consider the design of one bright element in which there is only one single graphene sheet placed on silicon diffractive grating. Figs. 2(a) and (b) show the transmittance spectra of one single graphene sheet placed on silicon diffractive grating with respectively three different grating periods with E_F=0.48 eV and three different Fermi levels with grating period of Λ=150 nm. Resonances in transmission spectra in Fig. 2 are due to plasmonic guided-wave resonance (GWR) excitation and can be controlled by adjusting the graphene Fermi level or variation of the grating period. For the grating periods of 120, 150, and 180 nm the resonance frequencies are 31.38, 27.97, and 25.67 THz, respectively. Also, for the Fermi levels of 0.45, 0.48, and 0.51 eV, the resonance frequencies are 26.96, 27.97, and 29.11 THz, respectively.

In the next step, to demonstrate the PIT phenomenon, the structure with two graphene sheets (Fig. 1) was numerically analyzed. It was considered that there are two resonance frequencies in the transmittance spectrum, as illustrated in Fig. 3. Additionally, decreasing the grating height, h, or the distance between the graphene sheets enhance the coupling strength, as depicted in Fig. 3(a). Also, a red and blue shift occur for the first and the second resonance frequency, respectively.

As shown in Fig. 3(a), hybridization of two graphene sheets, with h=60 nm, shifts the initial resonance frequencies of uncoupled graphene sheets of 26.17 and 27.22 THz to 25.16 and 27.95 THz, respectively. As the height h increases, resonance frequencies become closer to their initial values, due to weak hybridization. Figs. 3(b) and

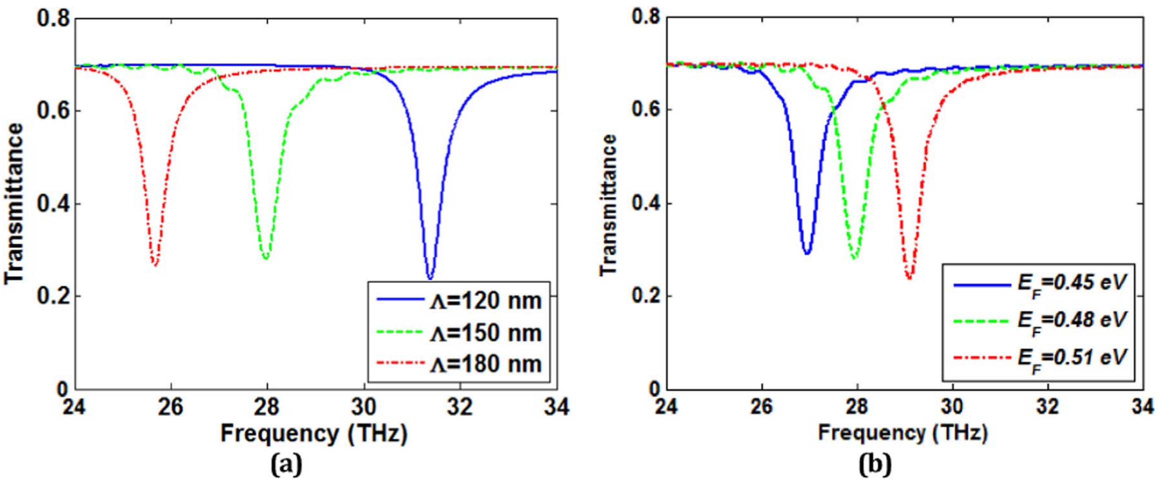

Fig. 2. Transmittance spectra of one single graphene sheet placed on silicon diffractive grating with three different (a) grating periods with E_F=0.48 eV and (b) Fermi levels with grating period of Λ=150 nm.