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شفافیت ناشی از پلاسمون تنظیم‌پذیر بر پایه دو مد روشن در صفحه‌های موازی گرافین

سارا خزائی و نصرت‌ا... گرانپایه

دانشکده مهندسی برق، دانشگاه صنعتی خواجه نصیرالدین طوسی، تهران، ایران

چکیده – در این مقاله، پدیده شفافیت ناشی از پلاسمون در بازه فروسرخ میانی تنها با استفاده از دو صفحه گرافین موازی بر روی توری پراشه مورد بررسی قرار گرفته است. مد هدایتی ایجاد شده توسط این ساختار منجر به شکاف‌های شدیدی در طیف انتقال تابش عمود می‌شود که به عنوان تشدید روشن در نظر گرفته می‌شود. پیوندزنی بین دو مد روشن منجر به پاسخ نوری شفافیت القا شده توسط پلاسمون (PIT) می‌شود. عملکرد PIT با تغییر پارامترهای هندسی پراشه سیلیکونی قابل کنترل است. همچنین، بسامد تشدید پنجره شفافیت از طریق تغییرات انرژی فرمی صفحه‌های گرافینی به کمک بایاس الکترواستاتیک به جای تغییر ساختار، قابل کنترل است. از این بررسی، برای طراحی ادوات فوق‌العاده فشرده و مدارهای فوتونی یکپارچه می‌توان بهره برد.

کلید واژه-شفافیت ناشی از پلاسمون، گرافین، تشدید تنظیم‌پذیر، اتصال دو مد روشن

Tunable Bright-Bright Mode Coupled Plasmon Induced Transparency in Parallel Graphene Sheets

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Tunable plasmon-induced transparency (PIT) is realized for the mid-infrared region only by using two parallel graphene sheets over silicon diffractive gratings. The guided-wave resonances (GWRs) of the combined structure create a sharp notch on the normal-incidence transmission spectrum behaving as the bright resonators. The weak hybridization between the two bright modes results in the novel PIT optical response. The performance of the PIT system can be controlled by variation of geometrical parameters of silicon grating. Also, the resonance frequency of transparency window can be dynamically tuned by varying the Fermi energy of the graphene sheets via electrostatic gating instead of refabricating the structures. This study can be used for design of the optical ultra-compact devices and photonic integrated circuits.

Keywords: Plasmon-induced transparency, Graphene, Resonance Tunability, Bright-bright mode coupling

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Tunable Bright-Bright Mode Coupled Plasmon Induced Transparency in Parallel Graphene Sheets

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1. Introduction

Quantum interference between the atomic level and the excitation pathways in laser-activated atomic systems causes electromagnetically induced transparency (EIT). This phenomenon has potential of several applications in slow light technology, enhancing nonlinear effects, signal processing, and optical switching. However, complex experimental requirements have significantly constrained the chip-scale implements of conventional EIT in atomic systems. Coupled resonator systems such as coupled ring resonators and coupled gratings have EIT-like spectral response that overcomes these restrictions [1].

Two plasmonic modes, super radiant (radiative mode) and sub radiant (dark mode) can be coupled to the incident field, depends on how strong an incident light can be coupled into the plasmonic mode. The radiative 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. EIT-like effect is realized by two schemes of bright-dark mode coupling and bright-bright mode coupling. Bright-dark mode coupling is based on the direct destructive interference between a dark mode and a bright mode and bright-bright mode coupling is based on the detuning of two bright modes [2].

Metal-based plasmonic EIT-like effect, has been extensively exploited because of capability to operate at subwavelength scales. Graphene advantages such as flexible tunability, tight field confinement, and low losses at terahertz and mid-infrared frequencies make graphene a promising alternative material to metals for chip-integrated nanophotonics. Recently, plasmonic EIT have been demonstrated in periodically patterned graphene nanostructures. However, these devices have complicated fabrication and limited by the intrinsic loss of the localized surface plasmon modes. To overcome the metal disadvantages, quasiguided-mode resonances with low intrinsic loss, which can be excited in a graphene sheet by coupling with the diffractive field of a grating structure under normal incidence, have been demonstrated [3].

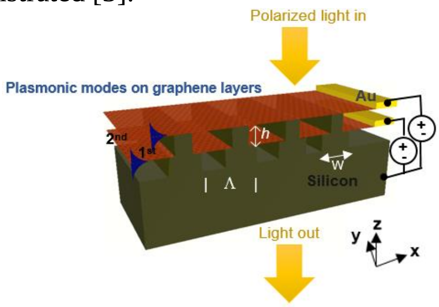
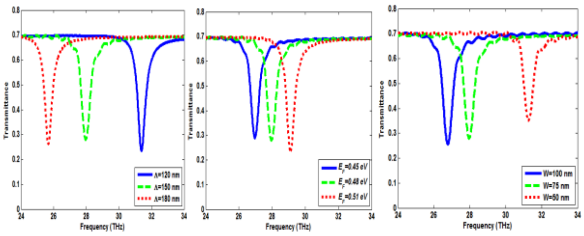


Fig. 1.Schematic view of the coupled graphene and grating structure for demonstration of PIT

In this work, the structure composed of two parallel-coupled graphene sheets is analysed. Guided-wave resonance (GWR) in the graphene sheets is the outcome of diffractive gratings. GWR of structure, make a sharp notch in the normal-incidence transmission spectrum because of the coupling between optical wave and graphene plasmonic wave, hence there is optical transmission at the resonance frequency that serving as the bright mode. Original Plasmon induced transparency (PIT) optical response with transparency window at terahertz frequencies is due to weak hybridization between the two bright modes with the frequency detuning. Resonance frequency of the PIT can be modulated actively by variation of the Fermi energy of the graphene in addition to the change in the geometry parameters.

2. Analysis Method

The schematic view of the proposed structure is shown in Fig. 1. The 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. The grating period Λ and grating width W is formed by patterning and etching shallow trenches on a silicon wafer. Graphene is simulated as an ultra-thin anisotropic material with a thickness of $\Delta = 1$ nm. The in-plane permittivity of graphene is $\varepsilon_{\square} = 1 + i\sigma / \omega\varepsilon_0\Delta$, where σ, ω ,and ε_0 stand for graphene's surface conductivity, the light angular frequency, and vacuum permittivity. While the out-of-plane permittivity is a constant $\varepsilon_{\perp} = 2.5$, Graphene's surface conductivity is written as [4] $\sigma = ie^2 E_F / \pi\hbar^2 \left(\omega + i\tau^{-1}\right)$, where *e*, E_F, and $\hbar$ are the electron charge, the Fermi energy level, and the reduced Planck's constant, respectively. $\tau = \mu E_F / \left(e\upsilon_f^2\right)$ displays the relaxation time, where $\upsilon_f = c/300$ is the Fermi velocity, *c* is 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 $10^4 cm^2 V^{-1} S^{-1}$.



(a) (b) (c)

Fig. 2. Transmittance spectra of one single graphene sheet placed on silicon diffractive grating with (a) three different grating periods with $E_F = 0.48eV$ and W=75 nm, (b) three different Fermi levels with graphene period of $\Lambda = 150nm$ and W=75 nm, and (c) three different grating widths with $E_F = 0.48eV$ and $\Lambda = 150nm$.

The surrounding media are assumed to be air with $\varepsilon_r = 1$. Only the transverse magnetic (TM) polarized SPP modes are noteworthy in this work. The incident plane waves are irradiated along the z direction. The finite-difference time domain (FDTD) method with periodic boundary conditions are applied along the x and y directions and perfect matched layers (PML) are applied in the z direction. The mesh size of graphene along the x and z directions are respectively set as 1 and 0.1 nm. Electrical gating moves Graphene Fermi energy by Au electrodes placed on the graphene layer.

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. Fig. 2(a-c) show the transmittance spectra of one single graphene sheet placed on silicon diffractive grating. Plasmonic GWR is clearly defined as a transmission dip, which its resonance frequency can be controlled by adjusting the Fermi level of graphene, variation of the grating period and grating widths as shown in Table 1:

Table 1: GWR frequencies for different geometrical parameters

Λ (nm)	W(nm)	E_F(eV)	Resonance frequency(THz)	
			Numeric	Analytic
120	75	0.48	31.38	31.15
150	75	0.48	27.97	27.86
180	75	0.48	25.67	25.4
150	100	0.48	26.77	26.72
150	75	0.48	27.97	27.86
150	50	0.48	31.27	31.37
150	75	0.45	26.96	26.97
150	75	0.48	27.97	27.86
150	75	0.51	29.11	28.71

Quasiguided resonance which is excited in the graphene sheets, creates a single transmission notch at *f*=27.97 THz. The quasiguided resonance play the bright mode role in our system and are not excited by the normal incident light, due to the large wavevector difference between the plasmonic wave and the free space light . To directly excite the quasiguided mode a silicon grating is introduced to compensate the wavevector mismatch based on the mth-order phase matching condition [3]:

$$k_0 \operatorname{Re}\left(n_{eff}\right) = \left|k_x + mG_x\right| \quad (1)$$

where, $k_x = k_0 \sin\theta$, $k_0 = 2\pi/\lambda$ is the wavevector of the light in free space, θ is the incident light angle, $G_x = 2\pi/\Lambda$ is the reciprocal lattice unit vector, and n_{eff} is the effective refractive index of the TM waveguide mode in the graphene, which can be obtained by solving the dispersion equation [3]:

$$\varepsilon_r \left[\left(n_{eff} k_0\right)^2 - \varepsilon_r k_0^2\right]^{-1/2} = -\frac{i\sigma}{2ck_0\varepsilon_0} \quad (2)$$

According to Equation. (1), the resonance frequency of the quasiguided mode can be estimated using $f_r = c / \left[\Lambda \operatorname{Re}\left(n_{eff}\right)\right]$ for normal incidence. As depicted in Fig. 2(a), a transmission notch at 27.97 THz is observed owing to the excitation of the quasiguided resonance in the graphene by defining the silicon grating, period of $\Lambda = 150\,nm$, h=100 nm, the graphene Fermi energy $E_F = 0.48eV$, and W= 150 nm. According to Equation. (2), $\operatorname{Re}\left(n_{eff}\right)$ equals 70.83 and the quasiguided resonance frequency f_r is 28.21 THz, which shows good agreement with the numerical result. The numerical and analytical results in other frequencies are compared in Table 1.

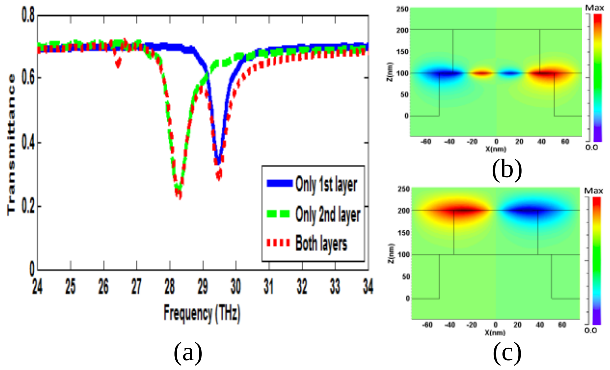


Fig. 3. (a) The PIT spectra of the first, second, and both graphene sheets. The distributions of y-component of electric field in one grating period at frequencies of (b) 29.48 THz, c) 28.27 THz for $\Lambda = 150nm$, h=100 nm, W=75 nm $E_{F1} = 0.49eV$,and $E_{F2} = 0.48eV$

The PIT effect is demonstrated in transmittance spectra of the structure with h=100 nm. We can see that the excited two graphene sheets are very weakly hybridized, and two resonance modes of 28.27 and 29.48 THz are close to their initial frequencies as shown in `Fig. 3(a). Figures 3(b-c) display the distributions of y-component of electric field at two resonance peaks, for h =100 nm. When frequency is 29.48 THz, only the first graphene sheet is excited by incident light, and the excitation of the second one is very weak, as shown in Fig. 3(b). But for frequency of 28.27 THz, the second graphene sheet is excited by incident light strongly, and the excitation of the first one is weak, as depicted in Fig. 3(c). Moreover, by detuning of resonance frequency, the high transparency peak appears at 28.99 THz.

4. Electrical and Geometrical Tunability

Strong relation between conductivity of graphene and Fermi energy is used for tuning the PIT frequency. By tuning the Fermi energy, the electron density of graphene is changed, so variation of the resonance frequencies of graphene plasmonic nanostructures occur.Figure 4(a) illustrates the transmission spectra for three different Fermi levels. The resonance blue shift can be seen as the Fermi energy increases Also, by a small change in the Fermi energy, the transparency window can be easily tuned over a broad range of frequency. But in metal based systems, tuning the window of the EIT-like system has different tunability method. Fig 4(b) demonstrates the spectral response of the graphene for three different Λ in the range of 90-150 nm. The PIT phenomenon can be utilized for design of nano-scale Photonic devices such as filters, multi/demultiplexers, switches, etc.

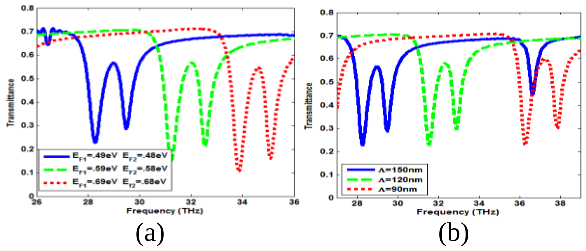


Fig. 4. The spectral response of the graphene sheets with different (a) Fermi energy for h=100 nm and (b) grating period for =75 nm , W $\Lambda = 150nm$ h=100 nm, W=75 nm, $E_{F1} = 0.49eV$, and $E_{F2} = 0.48eV$.

5. Conclusion

We have investigated a graphene-based electromagnetic induced transparency (EIT)-like structure composed of two parallel graphene sheets in mid-infrared wavelength range by using the finite difference time domain (FDTD) method. Utilizing graphene sheets create PIT effect response with simpler structure. The two sheets serving as bright modes couple with each other, bright modes frequencies are different due to various diffractive grating dimensions placed under each graphene sheet. Weak hybridization between the two sheets results in the plasmon induced transparency (PIT) optical response. The performance of the PIT system can be affected by varying the distance between the two sheets. The PIT spectral response can be manipulated by adjusting the Fermi energy of the graphene sheets via electrostatic gating, instead of refabricating the nanostructure. The proposed system, promising for design of practical nano-scale photonic devices and photonic integrated circuits.

References

[1] M. Kim, S. Lee and S. Kim, "Plasmon-Induced Transparency in Coupled Graphene Gratings," Plasmonics, vol. 10, p. 1557–1564, 2015.

[2] C. Hu, L. Wang, Q. Lin, X. Zhai, X. Ma, T. Han, and J. Du, "Tunable double transparency windows induced by single subradiant element in coupled graphene plasmonic nanostructure," Appl. Phys. Express, vol. 9, pp. 52001(1-4), 2016.

[3] W. Gao, J. Shu, C. Qiu, and Q. Xu, "Excitation of PlasmonicWaves in Graphene by Guided-Mode Resonances," ACS, vol. 9, pp. 7806-7813, 2012.

[4] F. H. L. Koppens, D. E. Chang, and F. J. García de Abajo, "Graphene Plasmonics: A Platform for Strong Light–Matter Interactions," *Nano Lett.*, vol. 8, pp. 3370–3377, 2011.