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کنترل اپتیکی جذب امواج تراهرتز-مادون قرمز در یک نانوساختار گرافنی کوانتیزه شده توسط میدان مغناطیسی قوی

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چکیده – کنترل جذب و پاشندگی میدان الکتریکی کاوشگر ضعیف در یک نانوساختار گرافنی تحت میدان مغناطیسی قوی مورد بررسی قرار گرفته است. در این ساختار با اعمال میدان الکترومغناطیسی در محدوده تراهرتز- مادون قرمز ویژگی‌های جذب و پاشندگی میدان کاوشگر ضعیف بررسی می‌شود. خواص اپتیکی خطی گرافن با استفاده از نظریه اختلال و روش ماتریس چگالی بحث شده است. نشان داده شده است که جذب یک پالس نور از یک مقدار بیشینه به مقدار صفر یا برعکس توسط پارامترهای فاز نسبی و شدت میدان‌های اعمال شده قابل کنترل می‌باشد. بنابراین، این مدل می تواند به عنوان یک سوئیچ تمام نوری در بسیاری از سیستم‌های ارتباطی و شبکه های کوانتومی نوری مورد استفاده قرار گیرد.

کلید واژه- نانوساختارگرافن، امواج تراهرتز-مادون قرمز، جذب و پاشندگی

Optically controlled absorption of terahertz-infrared radiations in a graphene nanostructure under strong magnetic field

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Abstract-The optical properties of a weak probe light by applying coupling fields in Landau-quantized graphene nanostructure is investigated. In this structure the electromagnetic field of terahertz-infrared radiations interfere with the electromagnetic field of the short-wavelength probe field and this effect changes the absorption and dispersion characteristics of the probe field. The linear steady state properties of the graphene by means of perturbation theory and density matrix method are discussed. We show that the absorption of a light pulse can be switched from large absorption to nearly transparent case or vice versa by controlling the coupling field's intensities and relative phase of the applied fields. Therefore, this model can be used as an all-optical switch which is suitable for next generation of future all optical quantum communicational system and networks.

Keywords: Graphene nanostructure, Terahertz-infrared radiation, Dispersion and Absorption

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1. Introduction

Recently there has been an increasing interest in optical properties of solid state systems such as semiconductor quantum wells (QWs) and quantum dots (QDs) [1]. On the other hand, recently several nonlinear optical phenomena based on quantum coherence and interference in the magnetized graphene had been theoretically discussed [2]. It has been shown that graphene in a strong magnetic field has a giant infrared optical nonlinearity with compare to the other known materials [3]. Also, ultraslow propagation of infrared solitons in graphene under an external magnetic field have been discussed [4]. In this paper, we analyse the absorption and dispersion of a weak probe beam in a four-level quantized graphene system under an external magnetic field. It is important method for high speed all optical switch of graphene-based devices for the next-generation of all-optical systems and networks.

2. Model and Equation

Each consider that a 2D graphene crystal nanostructure in the presence of strong magnetic field with four energy levels configuration as shown in Fig. 1. The selected transitions of dipole in graphene conform by the special selection rules i.e. $|\Delta n| = \pm 1$, where n is the energy quantum number. The optical transitions between neighbouring Landau Levels (LLs) in graphene for a magnetic field in the range of 0.01-10T, fall into the infrared or terahertz (THz) regime ($\hbar \nu_c = \sqrt{B(Tesla)}meV$).

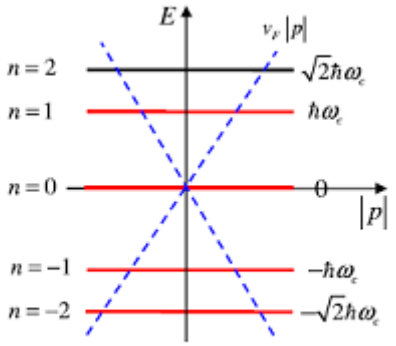

Figure 1. (a) LLs near the K point superimposed on the electronic energy dispersion without a magnetic field. The magnetic field condenses the original states in the Dirac cone into discrete energies. The LLs in graphene are unequally spaced: $\propto \sqrt{B}$.

In the terahertz regime (30~300μm or 1~10THz) intersubband transition, the incoming photon energy is (4-41mev) and maybe in the order of electron thermal broadening (KT~ 6meV-25meV for 77K -300K) [5]. Therefore in the conventional structure, both the incoming photon and the environment temperature can directly excite the ground state electrons to the higher energy levels and this problem inhabits the correct optical switching in the high temperature and terahertz applications. Without applying the external optical field for a single-layer graphene and just in the presence of magnetic field the effective-mass Hamiltonian can be written as [6]:

$$\hat{H}_0 = v_F \begin{pmatrix} 0 & \hat{\pi}_x - i\hat{\pi}_y & 0 & 0 \\ \hat{\pi}_x + i\hat{\pi}_y & 0 & 0 & 0 \\ 0 & 0 & 0 & \hat{\pi}_x + i\hat{\pi}_y \\ 0 & 0 & \hat{\pi}_x - i\hat{\pi}_y & 0 \end{pmatrix} \quad (1)$$

Where $v_F = 3\gamma_0/(2\hbar a) \approx 10^6 m/s$ is fermi velocity which is a band parameter ($\gamma_0 \approx 2.8eV$ is the nearest-neighbour hopping energy and $a = 1.42\overset{0}{A}$ is C-C spacing), The Hamiltonian of interaction with incident optical field can be expressed in the following form:

$$\vec{H}_{\text{int}} = v_F \vec{\sigma}.\frac{e}{c}\vec{A}_{opt} \qquad (2)$$

Where $\vec{A}_{opt}$ is the vector potential of the optical field in the generalized momentum operator $\hat{\vec{\pi}}$. A standard equation of dynamical behaviour equation of the system for the density matrix of Dirac electrons in graphene coupled by the infrared laser and terahertz fields, is given by the Liouville's equation $\frac{\partial\hat{\rho}}{\partial t} = -\frac{i}{\hbar}[\hat{H}_{\text{int}}, \hat{\rho}]$. As a result, the density matrix equations of motion in the rotating frame and in the rotating wave approximation are given by:

$$\dot{\rho}_{22} = -\gamma_2\rho_{22} + \gamma_3\rho_{33} + \gamma_4\rho_{44} + i\Omega_{c2}^*\rho_{32} - i\Omega_{c2}\rho_{23} + i\Omega_{c1}^*\rho_{42} - i\Omega_{c_1}\rho_{24},$$

$$\dot{\rho}_{33} = -\gamma_3\rho_{33} + i\Omega_{c_2}\rho_{23} - i\Omega_{c_2}^*\rho_{32},$$

$$\dot{\rho}_{44} = -\gamma_4\rho_{44} - i\Omega_p^*\rho_{41} + i\Omega_p\rho_{14} - i\Omega_{c_1}^*\rho_{42} + i\Omega_{c_1}\rho_{24},$$

$$\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1. \qquad (3)$$

The frequency detuning of applied fields are given by: $\Delta_p = (\varepsilon_{n=1} - \varepsilon_{n=-2})/\hbar - \omega_p$ and $\Delta_c = (\varepsilon_{n+1} - \varepsilon_n)/\hbar - \omega_{THz}$ where $\varepsilon_n = \text{sgn}(n)\hbar\omega_c\sqrt{|n|}$ is the energy of the Landau level for electrons near the Dirac point, with $n = 0, \pm1, \pm2, \ldots$, $\omega_c = \sqrt{2}v_F/l_c$, and $l_c = \sqrt{\hbar c/eB}$ implies the magnetic length. The linear susceptibility ($\chi \propto \rho$) comprises two parts, real and imaginary ($\chi = \chi' + i\chi''$). Note that the real part of the susceptibility χ' corresponds to the dispersion and imaginary part χ'' corresponds to the absorption.

3. Result and discussion

Now, we analyze the numerical results of the above equations and discuss the transient and the steady-state behaviors of the absorption and the dispersion spectra. The probe field absorption and dispersion spectra as a function of probe field detuning is displayed in Fig.2 for two different values of relative phase between applied fields $\Delta\varphi = (0, \pi)$ and coupling field's intensities at $\Omega_{c_1} = \Omega_{c_2} = 5\gamma_0$. Under the resonance condition and for $\Delta\varphi = 0$ a large transparency window with a positive slope of dispersion appears around zero probe field detuning. When the relative phase between applying fields changes to $\Delta\varphi = \pi$, a large probe absorption with negative slope of dispersion is achieved. In fact for $\Delta\varphi = 0$ the system becomes almost transparent to the probe field. So the probe field absorption and dispersion are sensitive to the relative phase.

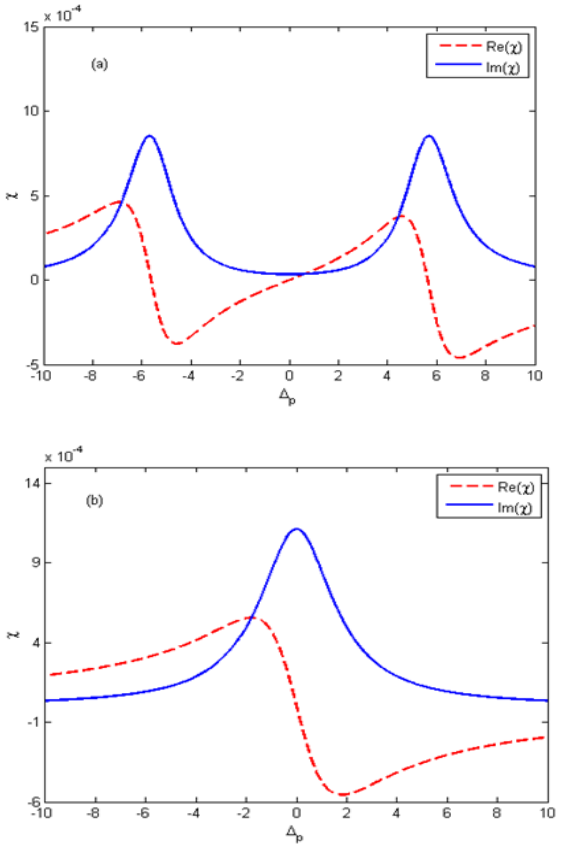

Figure 2. Real (solid) and imaginary (dashed) parts of susceptibility versus probe detuning. The selected parameters are (a) $\Delta\varphi=0$, $\Omega c_1 = \Omega c_2 = 5\gamma_0$ (b) $\Delta\varphi=\pi$, $\Omega c_1 = \Omega c_2 = 5\gamma_0$.

In Fig.3 we plotted the absorption values for $\Delta\varphi = (0, \pi)$ versus Rabi-frequency $\Omega_{c_1} = \Omega_{c_2} = \Omega_c$, when the probe and controlling terahertz signals are in resonance; i.e. $\Delta_p = \Delta_c = 0$. One can obviously see that the absorption for $\Delta\varphi = \pi$ varies monotonically versus Rabi-frequency, whereas for $\Delta\varphi = 0$ decreases with an increase in the intensity of the signal at Rabi-frequency Ω_c. In Fig. 4 shows the absorption of the weak probe field in the graphene medium. We observe that the graphene becomes absorbent for $\Delta\varphi = n\pi (n = 1,3,5,...)$. While the absorption decreases to its minimum for $\Delta\varphi = m\pi (m = 0,2,4,...)$.

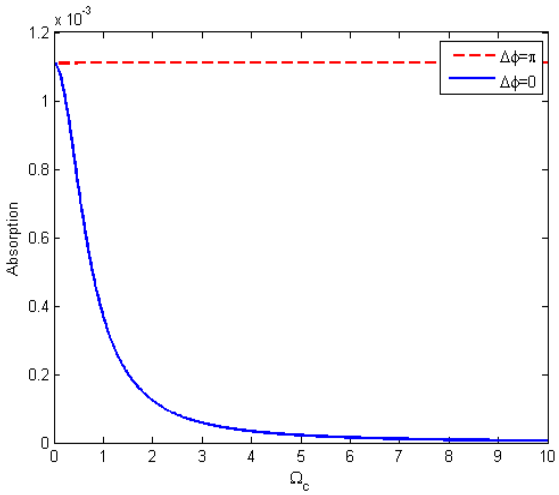

Figure 3. Imaginary parts of susceptibility versus Rabi-frequency for two value of the relative phase Δφ=(0,π), Δc = Δp = 0.

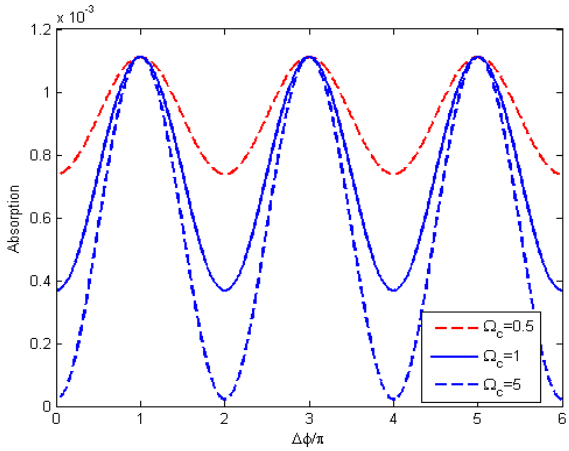

Figure 4. Imaginary parts of susceptibility versus relative phase, the parameters are $\Omega c_1 = \Omega c_2 = (0.5\gamma_0, 1\gamma_0, 5\gamma_0)$, $\Delta c = \Delta p = 0$.

4. Conclusion

The steady state behaviour of a weak probe field absorption and the dispersion in a 2D graphene crystal nanostructure are investigated. It is shown that the absorption and the dispersion of the probe field can be controlled by the intensity of terahertz fields and the relative phase between the applied fields. It has also been shown that the medium can be used as an optical switch in which the propagation of the laser pulse can be controlled with relative phase between the applied fields.

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