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石墨烯和对称开口谐振环超材料中可调谐的双等离激元诱导透明现象

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摘　要:提出了由石墨烯和两对对称开口谐振环构成的等离激元诱导透明(PIT)超材料结构,该 PIT 超材料结构之间的耦合形式为暗-亮-暗模式.通过有限元方法模拟,观察到双 PIT 透明窗口,通过改变石墨烯的费米能级或者改变开口谐振环的几何参数来动态地调制 PIT 窗口.理论结果表明,当石墨烯与两对对称的开口谐振环之间的相互作用距离为 0.5 μm、石墨烯费米能级为 1.5 eV 时,可得到最优的双透明窗口.双 PIT 效应在非线性器件、可调谐传感器、开关和慢光器件等方面有潜在的应用价值.

关键词:超材料;太赫兹;石墨烯;类电磁感应透明
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Tunable Double Plasmon-Induced Transparency Windowsin Metamaterial Formed by Symmetric Graphene and Split Ring Resonators Structure

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Abstract: A Plasmon-Induced Transparency (PIT) metamaterial was proposed comprised of a graphene patch and two pairs of split ring resonators (SRRs) symmetrically. The coupled PIT molecule is termed as dark-bright-dark molecule. By using the finite element method simulation, the PIT metamaterial exhibits double sharp-induced transparency peaks was observed. the PIT windows can be dynamically modulated at the terahertz regime by tuning the Fermi energy in graphene and varying the geometric parameters of the metamaterial. Theoretical calculations show thatthe interaction distance between graphene and two pairs of symmetrically SRRs is 0.5 microns and the graphene Fermi level is 1.5 eV, the optimal double transparent window is obtained. The PIT effects may have some potential applications in nonlinear devices, tunable sensors, switches, and slow light devices.

Key words: Metamaterial; Terahertz; Graphene; Plasmon-induced transparency
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0 Introduction

Electromagnetically Induced Transparency (EIT) is a fascinating optical transparency phenomenon that occurs in three-level atomic systems and gives rise to a narrow transparency window in the broad

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absorption spectrum[1]. EIT is caused by destructive quantum interference between different excitation pathways of the excited state[2]. Recently, many studies have demonstrated that metamaterial can mimic this EIT effect in classical structure[3-5]. In particular, the Plasmon Induced Transparency (PIT) has attracted enormous attention because of its potential applications in nonlinear optics, slow light, storage for optical information processing, amplification without inversionand signal processing[6-13]. PIT results from the destructive interference by the plasmon coupling between two resonators. One of the resonators can be directly excited by the incident electromagnetic field and called bright mode, whereas the other resonator cannot be excited by the incidence and thus is called dark mode[14-15]. In addition, many metamaterial structures have been proposed to introduce the PIT effect both in theory and experiment[16-20]. The PIT effect in artificial metamaterial atom is considered as a destructive interference between the bright mode and dark mode. The PIT effect can be dynamically tuned in metamaterials, having attracted a lot of interest in the terahertz regime. Active control the PIT effect of metamaterials will enable dynamic tunability of their optical response and will potentially expand the range of applications.

It is well known that graphene is a monolayer of honeycomb carbon lattice, which has aroused increasing attentions for its fantastic properties such as high electron mobility, excellent ability to support Surface Plasmon Polaritons (SPPs) and tunable surface conductivity[21-26]. Furthermore, the Fermi energy of graphene could be dynamically tuned by using the external electrostatic gating[21-25]. Graphene hence can be considered as a new class of active plasmon material and an excellent platform for active control of the PIT effect. Therefore, the combination of graphene and metamaterials has importantly potential applications.

In this paper, based on the terahertz PIT metamaterial designed by Dr. Zhao et al [27], we propose and investigate the PIT metamaterial formed by a graphene patch and two pairs of Split Ring Resonators (SRRs) operating in the THz region. This PIT metamaterial is analogous to a four-level-like system with a tripod configuration in an atomic medium. The graphene patch acts as the bright atom to stimulate the inductive-capacitive (LC) resonance in two pairs of metal SRRs as the dark atoms. The coupled PIT molecule is termed as dark-bright-dark molecule[28-29]. As we know, the PIT effect results from the destructive interference between the bright mode and dark mode. In our design, the PIT-induced single dark resonance is swapped for another dark resonance called double dark resonance[30-31]. By numerical simulation, we explore more complex PIT phenomenon induced by the near field coupling and obtain two induced transparency windows. In addition, we study plasmon double dark resonances for four-level tripod structure models using the Finite Element Method (FEM) simulation and the theoretical analysis. Furthermore, the dramatic modulation of the PIT transmission window is achieved by tuning the Fermi level in grapheme and varying the geometric parameters of the PIT metamaterial which may offer potential applications in tunable sensors, optical switchers and slow light devices.

1 Proposed structure

As depicted in Fig. 1(a), the unit cell of the PIT metamaterial consists of a rectangular graphene and twoSRR pairs, where the geometric parameters are as follows: $P_x=50$ μm, $P_y=25$ μm, $a_1=15$ μm, $b_1=9$ μm, $a_2=10$ μm, $b_2=7$ μm, $w=1$ μm, $g=1.4$ μm, $d=2.4$ μm, $\delta_0=5$ μm, $b_3=11$ μm and $D=1.5$ μm. This structure is analogous to a four-level-like system with a tripod configuration in an atomic medium[32], as shown in Fig. 1(b). This meta-material structure is placed on a dielectric substrate with permittivity $\varepsilon_d=4$. The SRRs pair array is made from 100 nm thick gold which is modeled as a lossy metal with a conductivity of $\sigma_{gold}=4.56\times10^7$ S/m[27]. The optical conductivity of graphene layer σ_s is a sum of the intraband and interband described by Kubo's formula[33]. However, in the THz region, intraband transition dominates, ($\sigma_{intra}\gg\sigma_{inter}$), the surface complex conductivity of graphene σ_s is approximately given by a Drude-like term as[22,25]

$$\sigma_s(\omega)=\frac{iE_f e^2}{\pi\hbar(\hbar\omega+i\gamma)} \tag{1}$$

where ω is the angular frequency of incident light, e is the electron charge, E_f is the Fermi energy level in graphene, and $\gamma=(e\hbar\upsilon_f^{\,2})/(\mu E_f)$ is the damping constant, where $\upsilon_f=10^6$ m/s denotes the Fermi velocity of

Dirac fermions in graphene, $\mu=10\ 000\ \mathrm{cm^2/(V \cdot s)}$ is the electron mobility[34-35]. The complex permittivity of graphene can be obtained by the relation $\varepsilon=1+\mathrm{i}\sigma_s/(\varepsilon_0\omega t)$, where ε_0 is the vacuum permittivity. The thickness of graphene is assumed as $t=1$ nm in this work. In the simulation, the propagation direction of the incident plant wave is perpendicular to the plane and the incident electric field E is along the y axis direction[27].

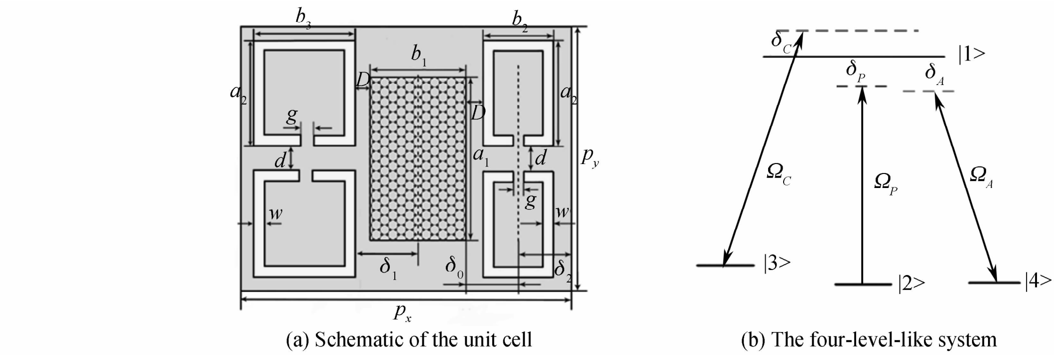


Fig. 1 Schematic of the unit cell and the four-level-like system[32]

2 Results and discussion

The PIT molecule consists of a dark-bright-dark triatomic molecule. The plasmon resonance in the graphene patch, acting as the bright mode, can be excited directly by the normal incident electric field with its polarization along the y-axis. Whereas the fundamental LC resonance in the SRR pair cannot be excited, thus acting as the dark mode[14-15]. But the LC resonance in two SRRs pairs can be excited due to that the graphene patch causes an asymmetrically near-field distribution of the SRRs to the surroundings[36]. Then, the destructive interference between the bright and two dark modes lead to the induced transparency windows.

For studies of corresponding relation, a four-level atomic system is used[32], as shown in Fig. 1(b). A probe field with Rabi frequency Ω_P interacts with the transition labeled $|1\rangle\leftrightarrow|2\rangle$. Two coupling fields with Ω_C and Ω_A drive the $|1\rangle\leftrightarrow|3\rangle$ and $|1\rangle\leftrightarrow|4\rangle$ atomic transitions, respectively. δ_P, δ_A, and δ_C are the detuning of the probe field and the coupling fields. Consequently, the possible pathways to dressed states induced by the coupling fields Ω_C and Ω_A the probe field Ω_P transparent via destructive quantum interference[32].

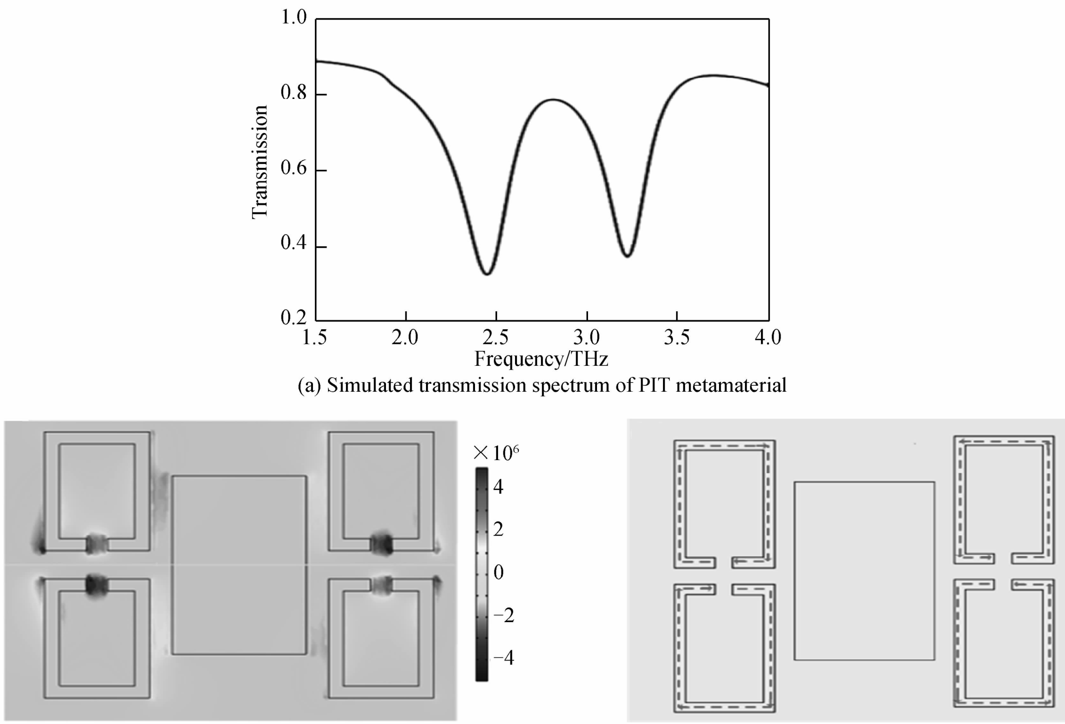
The PIT effects are determined by the plasmon resonance in the graphene patch, the LC resonance in two SRR pairs, and the coupling interaction between the graphene patch and two SRR pairs.

The plasmon resonance frequency in the graphene patch results from σ_s of graphene if the geometry parameters of graphene are fixed. Based on Eq. (1), σ_s can be changed by controlling its E_f, which can be easily realized by tuning the magnetic fields, gate voltage or chemical doping[21-26]. Thus, the dipolar plasmon resonance frequency of the graphene patch can be controlled by varying E_f in graphene. When E_f decreases, σ_s decreases, then, the resonance strength of graphene patch is gradually weakened. Furthermore, the dipolar plasmon resonance frequency of the graphene patch is red-shifted. Decreasing of E_f resembles the reduced energy difference between $|1\rangle$ and $|2\rangle$, and resultsin a red shift of the detuning δ_P in Fig. 1(b).

It is known that the width of the SRR pair (b_2 or b_3) determines the LC resonating frequency. The variation of b_2 and b_3 resembles the detuning of the coupling field δ_A and δ_C in Fig. 1(b). Here, b_2 is fixed, which imply $\delta_A=0$, i. e., the LC resonating frequency of the right SRR is unchanged. The stretching of b_3 resembles the increasing of δ_C. The LC resonating frequency of the left SRR is also red-shifted when b_3 widens. The increasing of δ_C means the decreasing of Ω_C, the coupling effect between the graphene patch and the left SRR pair is weakened, graphene patch cannot activate the LC resonance in left SRR pair due to the large frequency difference between the LC resonance and the plasmon resonance. Finally, the PIT effect becomes weak.

The coupling strength between the graphene patch and two SRR pairs can be adjusted by controlling their spatial distance D. The larger the separation D, the weaker the interaction becomes. The coupling interactions between the graphene patch and two SRR pairs resemble Ω_C and Ω_A, the smaller D implies the stronger Ω_C and Ω_A, and represents the better PIT effects. When D keep on increasing, the electric field around two SRR pairs is caused by graphene patch will weaken and hardly activates the LC resonance in SRRs. At last, LC resonance in SRRs and the PIT windows will not be obtained.

According to the abovetheoretical analysis, it is found that the better PIT phenomena can be obtained with the small frequency differences between the plasmon resonance and LC resonance, and the strong coupling effect between the graphene patch and the two SRRs pairs.



(a) Simulated transmission spectrum of PIT metamaterial

(b) Distributions of x-component of electric field E_x at 2.82 THz.

(c) Distributions of surface current in the two SRR pairs at 2.82 THz

Fig. 2 Impact of Fermi energy in graphemeand the parameters of PIT metamaterial on modulating PIT windows

In the following, by numerical calculation, we discuss the impact of Fermi energy in graphene and the parameters of PIT metamaterial on modulating PIT windows by using FEM simulation based on commercial software (COMSOL).

As shown in Fig. 2(a), we numerically simulate the transmission spectrum of PIT metamaterial when Fermi energy $E_f=2$ eV, the separation $D=1.5$ μm, and the width of the SRRs $b_3=b_2=7$ μm. Obviously, a prominent and broadened PIT window with a peak frequency at 2.82 THz and two transmission dips at 2.44 and 3.22 THz is observed on the transmission spectrum. This is corresponding to no detuning ($\delta_C=\delta_A=0$) in Fig. 1(b). The meta-material with equal width of symmetric double SRRs pairs satisfies a degenerate tripod atomic system. Therefore, the energy is coupled from the bright mode to the two dark modes through two parallel channels, resulting in the increase of PIT transparent window bandwidth[29]. This is a simple super position of the original EIT effect, similarly observed in microwave[32]. So, we only observe one broad transparency windows when $b_3=b_2$. In addition, its transmissivity reaches up to 0.7887 which is strong evidence manifesting the destructive interference between the graphene patch and the SRR pairs.

In order to illustrate the underlying mechanism of the proposal PIT meta-material structure, Fig. 2(b) and (c) display the distributions of the$x$ component of the electric field E_x and surface current at the resonance transparency peak 2.82 THz. From Fig. 2(b), it is shown that strong E_x concentrates around the gaps of two SRR pairs, demonstrating the strong excitation of LC resonance in two SRR pairs at the same frequency 2.82 THz. In addition, the directions of electric field E_x in left and right SRR pairs are opposite. These phenomena strongly demonstrate the coupling effect between the graphene patch and two SRR pairs, and a large amount of energy is coupled to two SRR pairs[27]. From Fig. 2(c), the PIT effect is enhanced due to that the surface current circulates mainly in the two SRR pairs with opposite directions at 2.82 THz while no distinct current appears in the graphene patch. The surface current distributions along the two SRR pairs circumference are symmetric, which indicates that the electromotive force between two SRRs pairs is balanceable[29]. The results once again prove the existence of LC resonance in two SRR pairs.

However, more interesting PIT phenomena occur at the asymmetric structures. We can control the coupling strength, and modulate the PIT transmission spectrum by varying the geometrical parameters of meta-material and Fermi energy in graphene.

Firstly, we observe PIT phenomenon by changing the width of the left SRRs pair b_3 with $E_f=1.5$ eV, $D=1.5$ μm, and $b_2=7$ μm. The other parameters of metamaterial are fixed, as shown in Fig. 1. When b_3 increases, the PIT effect with double transparency windows are obtained, as depicted in Fig. 3. The destructive interference between the bright and two dark modes enhances the PIT effect, leading to two transparency windows at 2.44 THz and 2.78 THz at $b_3=9$ μm, as shown in Fig. 3(a). Their transmissivities reach up to 0.685, and 0.746, the peak-to-peak separation is 0.34 THz. In addition, three transmission dips at 2.18 THz, 2.60 THz, and 3.02 THz are observed, and their transmissivities are 0.454, 0.567 and 0.561. When b_3 keeps on increasing, as shown in Fig. 3(b)-(d), the transmissivity of left peak increases obviously, and that of right peak slightly changes. The peak-to-peak separation widen evidently. The right transparency window almost stay, the left one moves to the left. In Fig. 3(d), two

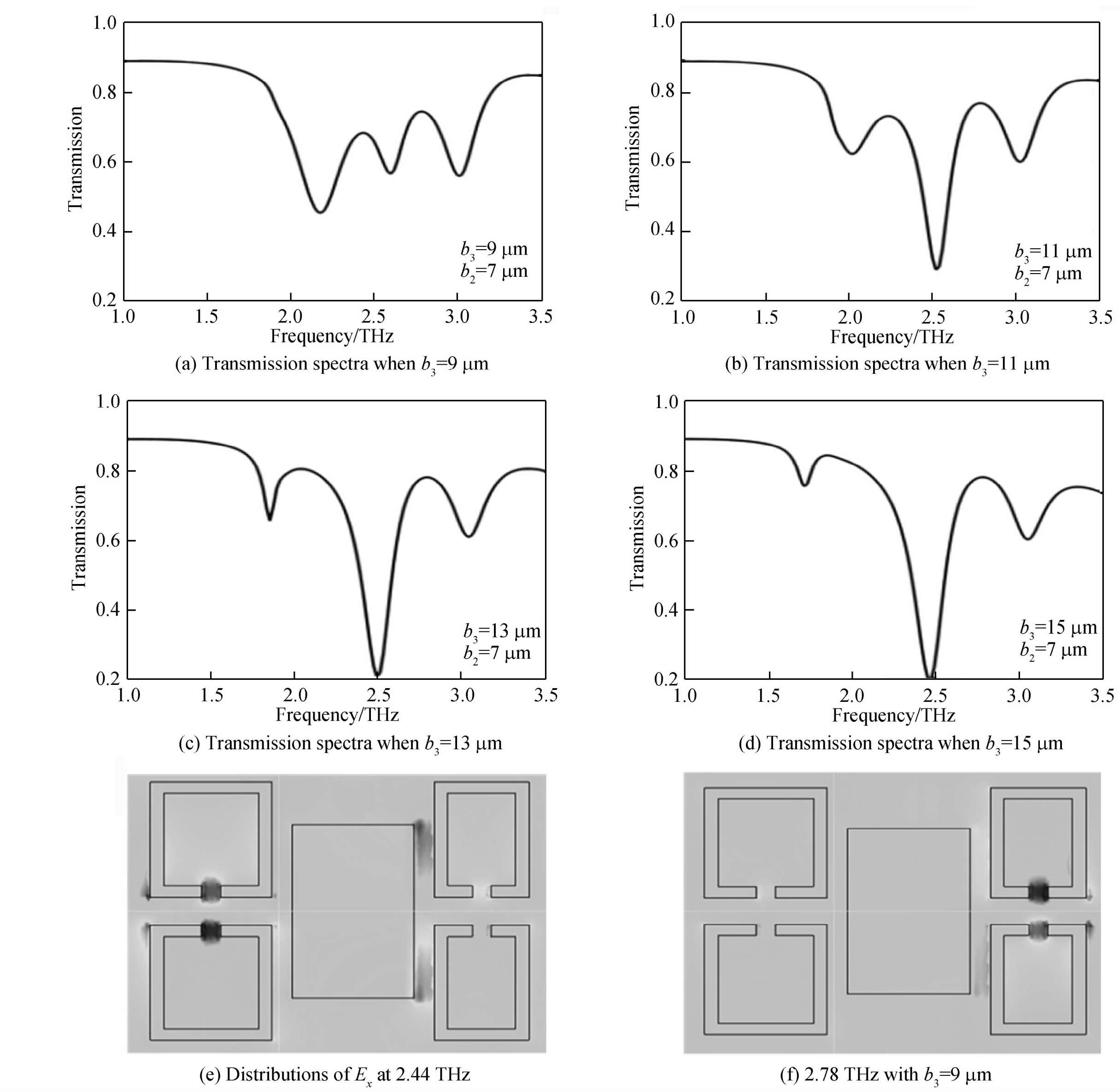
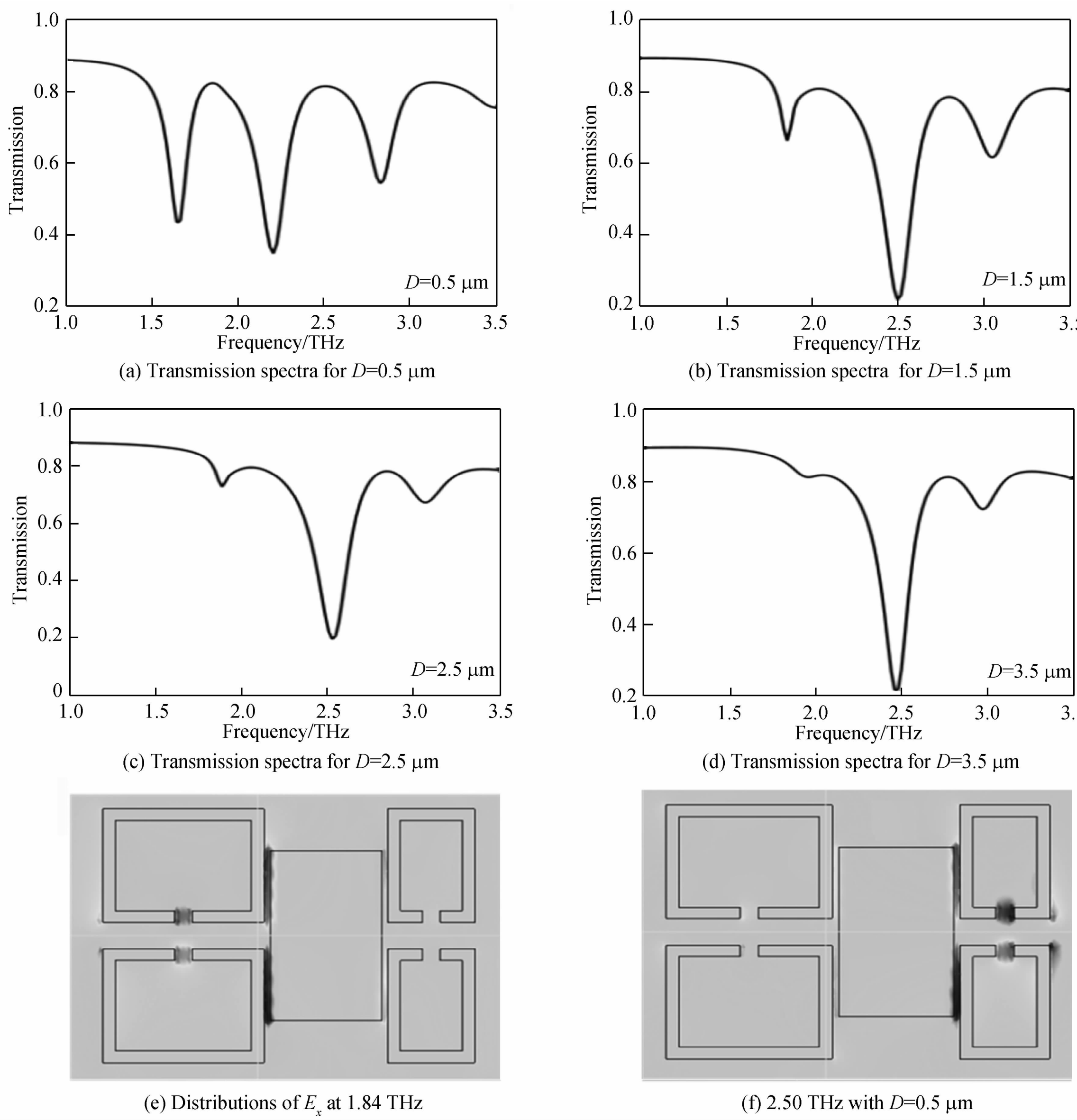


Fig. 3 Transmission spectra with various widths of the left SRRs pair b_3

transparency windows are at 1.86 THz and 2.78 THz. Their transmissivities reach up to 0.843, and 0.781, the peak-to-peak separation is approaching to 1.00 THz. At the same time, the left transmission dip decreases and moves to left, the middle one increases and moves a little to left, and the right one hardly changes. Three transmission dips are at 1.72 THz, 2.48 THz and 3.06 THz, and their transmissivities are 0.755, 0.200 and 0.603. In short, the width of the left SRRs pair b_3 does not affect largely on the right peak and dip. With $b_3=9$ μm, Fig. 3(e) and (f) exhibit the distributions of E_x at the resonance transparency peak 2.44 THz and 2.78 THz, respectively. From Fig. 3(e), it is shown that strong E_x concentrates around the gaps of left SRR pair at 2.44 THz, indicating the strong excitation of LC resonance in left SRR pair. At the same time, the coupling effect between the graphene patch and left SRR pair become stronger, the large amount of energy is coupled to left SRR pair. But in Fig. 3(f), the strong E_x concentrates around the gaps of right SRR pair at 2.78 THz, presenting the strong excitation of LC resonance in right SRR pair. The coupling effect between the graphene patch and right SRR pair is very strong, and a large amount of energy is coupled to right SRR pair.

Secondly, to better understand the underlying mechanism of the modulation of PIT, we discuss PIT phenomenon by varying the distance D between the two SRR pairs and the graphene patch with $E_f=$ 1.5 eV, $b_2=7$ μm, and $b_3=13$ μm. The other parameters are fixed, as shown in Fig. 1. In Fig. 4(a), when $D=0.5$ μm, we find two transparency windows at 1.84 THz and 2.50 THz, their transmissivities reach



(a) Transmission spectra for D=0.5 μm

(b) Transmission spectra for D=1.5 μm

(c) Transmission spectra for D=2.5 μm

(d) Transmission spectra for D=3.5 μm

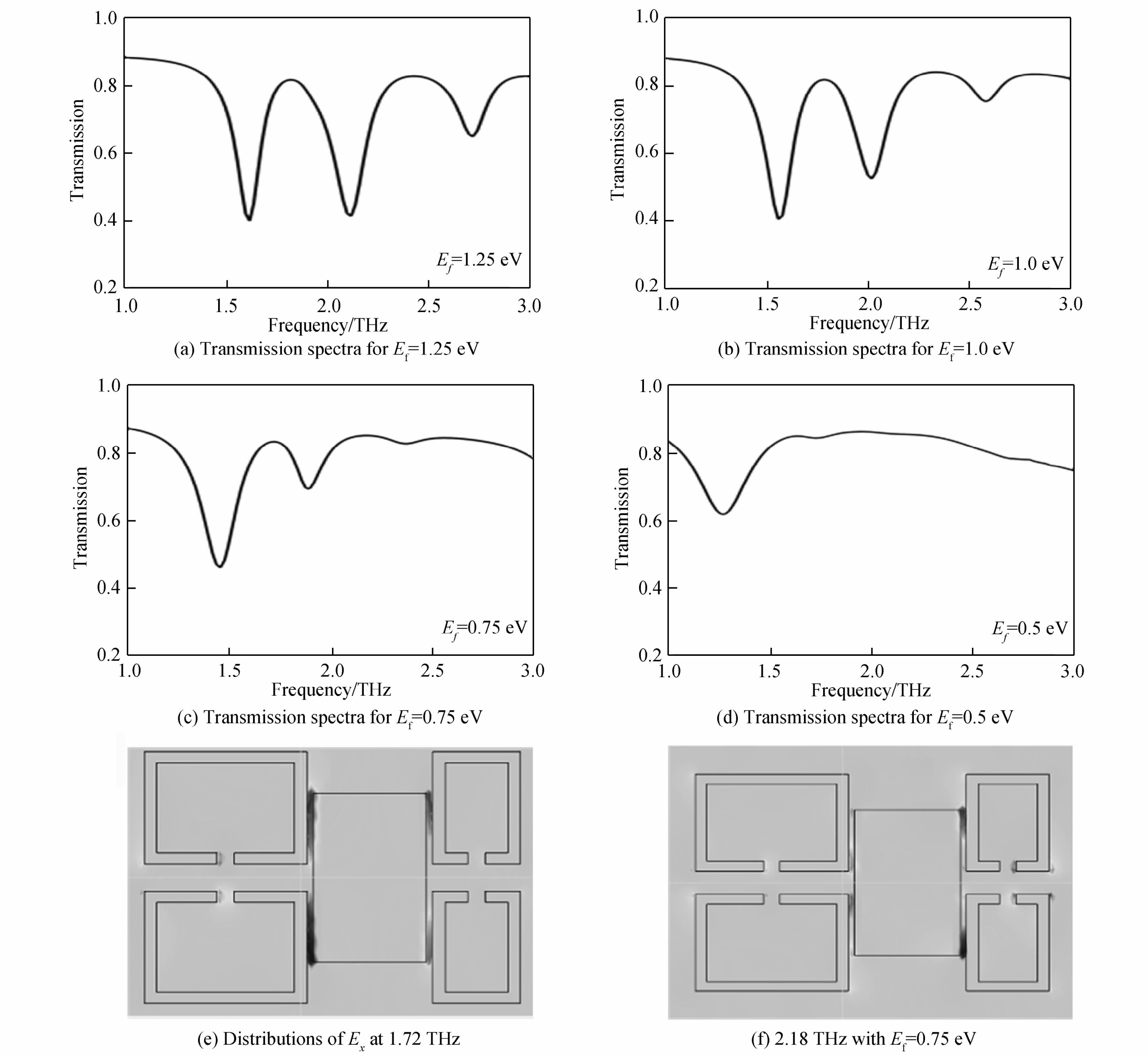
(e) Distributions of E_x at 1.84 THz

(f) 2.50 THz with D=0.5 μm

Fig. 4 Transmission spectrafor various separation D

up to 0.821, and 0.812, the peak-to-peak separation is 0.66 THz. Three transmission dips at 1.64 THz, 2.20 THz and 2.82 THz are also observed, and their transmissivities are 0.430, 0.344 and 0.540. At the same time, it is seen that the interaction between the graphene patch and the two SRRs pairs are stronger, and the double transmission peaks are wider and deeper. When D gradually increases from 1.5 μm to 3.5 μm, the left and right transmission dips all distinctly become small, but the middle one increases, as shown in Fig. 4(c)-(d). In Fig. 4(d), with D=3.5 μm, it is found that two transparency windows are at 2.04 THz and 2.78 THz, their transmissivities reach up to 0.816 and 0.811, and the peak-to-peak separation is approaching to 0.74 THz. In addition, the left transmission dip almost disappears. With D= 0.5 μm, the distributions of E_x at the resonance transparency peak 1.84 THz and 2.50 THz are illustrated in Fig. 4(e) and (f), respectively. From Fig. 4(e), it is shown that strong E_x concentrates around the gaps of left SRR pair at 1.84 THz, indicating the strong excitation of LC resonance in left SRR pair. It is also found that the coupling effect between the graphene patch and left SRR pair are very strong, the large amount of energy is coupled to left SRR pair. But in Fig. 4(f), it can be seen the strong excitation of LC resonance in right SRR pair at 2.50 THz, and a large amount of energy is coupled to right SRR pair.

Finally, we study the PIT phenomena by tuning the Fermi energy E_f in graphene. Fig. 5 shows the transmission spectrum for the PIT metamaterial structure with different E_f. The parameters used are b_3 = 13 μm, b_2 = 7 μm and D = 0.5 μm. The other parameters are fixed, as shown in Fig. 1. When E_f = 1.5 eV,



(a) Transmission spectra for E_f=1.25 eV

(b) Transmission spectra for E_f=1.0 eV

(c) Transmission spectra for E_f=0.75 eV

(d) Transmission spectra for E_f=0.5 eV

(e) Distributions of E_x at 1.72 THz

(f) 2.18 THz with E_f=0.75 eV

Fig. 5 Transmission spectrum with different Fermi energies E_f

we see two transparency windows at 1.84 THz and 2.50 THz, three transmission dips at 1.64 THz, 2.20 THz and 2.82 THz, just as shown in Fig. 4(a). When E_f keeps on decreasing from 1.25 eV to 0.5 eV, as shown in Fig. 5(a)-(d), it is apparent that the left transmission dip moves slightly to left, the middle one decreases and shifts from 2.20 THz to 1.64 THz, and the right one decreases remarkably and undergoes a slight red-shift. The two transparency windows all shift to the low frequency. As shown in Fig. 5(c) with $E_f = 0.75$ eV, two transparency windows are at 1.72 THz and 2.18 THz, three transmission dips are at 1.46 THz, 1.90 THz and 2.38 THz. When $E_f = 0.5$ eV, the middle and right transmission dips almost disappear, and two transparency windows disappear too. With $E_f = 0.75$ eV, the distributions of E_x at 1.72 THz and 2.18 THz are illustrated in Fig. 5(e) and (f), respectively. From Fig. 5(e), it is shown that E_x mainly concentrates around the gaps of left SRR pair at 1.72 THz, indicating the excitation of LC resonance in left SRR pair. In Fig. 5(f), it can be seen that E_x mainly concentrates around the gaps of right SRR pair at 2.18 THz, and some energy is coupled to right SRR pair.

Overall, the PIT properties in our metamaterial can be controlled by modifying the structure parameters (such as D, b_2 and b_3), and by tuning E_f in graphene. The coupling interaction between the two SRR pairs and the graphene patch can be modulated by varying D. LC resonance frequency can be shifted due to the variation of b_2 and b_3. The resonance frequency of dipolar plasmon resonance in the graphene patch can be controlled by varying E_f in graphene. The optimal structure parameters and Fermi energy lead to the best PIT effect.

4 Conclusions

In this paper, we have proposed a dynamically tunable PIT metamaterial device for the THz waves based on graphene and two symmetrical SRR pairs structure. This PIT metamaterial is analogous to a four-level-like system with a tripod configuration in an atomic medium. The graphene patch acts as the bright atom to stimulate the LC resonance in two pairs of metal SRRs as the dark atoms. By using the finite element method simulation, we have investigated the PIT phenomenon by tuning the Fermi energy E_f in graphene and varying the geometric parameters of the metamaterial. We have found that the LC resonance frequency can be controlled by changing the width of two SRR pairs, the dipolar plasmon resonance frequency of the graphene patch can be manipulated by tuning E_f, and the coupling effect between graphene patch and the two SRR pairs are modulated by the LC resonance frequency, the plasmon resonance frequency, and the distance between the two SRR pairs and the graphene patch. Thus, we have obtained tunable double transparency windows and transmission dip by choosing the appropriate Fermi energy in graphene, the geometric parameters of the metamaterial. These results about the double PIT effect may open up avenues for the development of new types of devices, such as tunable sensors, switchesand slow light devices.

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