Subluminal and superluminal terahertz radiation in metamaterials with electromagnetically induced transparency

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Abstract: We propose a scheme to design a new type of optical metamaterial that can mimic the functionality of four-state atomic systems of N-type energy-level configuration with electromagnetically induced transparency (EIT). We show that in such metamaterial a transition from a single EIT to a double EIT of terahertz radiation may be easily achieved by actively tuning the intensity of the infrared pump field or passively tuning the geometrical parameters of resonator structures. In addition, the group velocity of the terahertz radiation can be varied from subluminal to superluminal by changing the pump field intensity. The scheme suggested here may be used to construct chip-scale slow and fast light devices and to realize rapidly responded switching of terahertz radiation at room temperature.

OCIS codes: (020.1670) Coherent optical effects; (160.3918) Metamaterials;

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1. Introduction

The phenomenon of electromagnetically induced transparency (EIT), a typical quantum interference effect, has been extensively investigated mainly in atomic gases [1]. Usually, EIT is observed in a three-level atomic system with a Λ configuration exposed to a strong controlling field and a weak probe field, where two ground states are linked to a common excited state. Using EIT, the absorption of the probe field can be largely suppressed even it is tuned to a strong one-photon resonance. Except for the large suppression of optical absorption, EIT may also result in substantial alternations of many other physical properties, including the drastic change of dispersion that can significantly reduce group-velocity and hence result in slow (subluminal)

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light.

In addition to the single EIT mentioned above, a double EIT has also been observed in a four-level atomic system exposed to three laser fields with a N-type level configuration [1]. In this case, two strong laser fields, named as the controlling and assisted fields, respectively, determine the quantum interference property of the probe field. The double EIT is very useful for optical and quantum information processing and manipulation since the information can be stored and retrieved in multiple channels separately.

Many important applications of EIT have been proposed, including lasing without population inversion [2], enhanced nonlinear optical effect [1, 3], quantum computation and telecommunications [4, 5], quantum memory [6], all-optical switching [7], ultraslow optical solitons [8, 9]. However, the requirement of low-temperature environment and the large size for atomic EIT severely hamper the implementation of EIT in chip-scale applications.

Recently, much attention has been paid to the study of the classical analogues of three-level atomic EIT in various systems, such as coupled resonators [10, 11], electric circuits [12], plasmonic structures [13–16], and so on. Particularly, the plasmonic analogue of EIT in metamaterial structures [17, 18] have attracted growing interest because of their effective medium characters. EIT metamaterials can not only work in the terahertz regime but also can be used to design chip-scale optical devices. Important applications of EIT metamaterials have been proposed, including optical buffers, highly sensitive sensors, ultrafast switches, and electromagnetically induced absorbers, etc [19–21]. However, to authors' knowledge a classical analogue of EIT in four-level atomic system with N-type level configuration has not been realized up to now.

On the other hand, the control of light speed is highly desirable for many practical applications. Although subluminal light has been demonstrated in atomic systems based on EIT [1] and a superluminal light (or called as fast light [22]) has been reported by using the active Raman gain schemes [23–26], a practical system supporting both subluminal and superluminal light propagations are still rare. Recently, some theoretical proposals showed the possibility of changing light propagation from subluminal to superluminal in atomic systems [27]. However, in these proposals, either coupling of the dipole transition forbidden levels are required or some very special level structures are used, which make them hard to be realized practically.

In this article, we propose a scheme to design a new type of optical metamaterial that can mimic the functionality of a four-level N-type atomic system with EIT. Different from the most EIT metamaterials realized up to date where only a single EIT is possible and can only be controlled passively by varying the geometrical parameters of resonator structures [28–34], in our scheme a transition from a single EIT to a double EIT of terahertz radiation may be easily achieved by actively tuning the intensity of the infrared pump field or passively tuning the geometrical parameters of resonator structures. Additionally, in our EIT metamaterial the group velocity of a terahertz radiation can be changed from subluminal to superluminal by adjusting the pump field intensity. The scheme suggested here may be used to construct chip-scale slow and fast light devices and to realize rapidly responded switching of terahertz radiation at room temperature.

2. EIT metamaterial equivalent to N-type atomic system

The unit cell of present EIT metamaterial structure consists of a cut wire (CW) and two pairs of split-ring resonators (SRRs). As in Ref. [14], we assume Si islands (denoted by the red spots) are positioned in gaps of one SRR-pair, as shown in Fig. 1(a). As the resonances of CW and SRR are both determined primarily by their geometrical dimensions and the size of the subwavelength unit cell ensures that terahertz waves do not diffract at normal incidence, thus the EIT metamaterial array behaves as an effective medium. An incident terahertz beam is collimated on the metamaterial array with the electric field parallel to the CW. An infrared

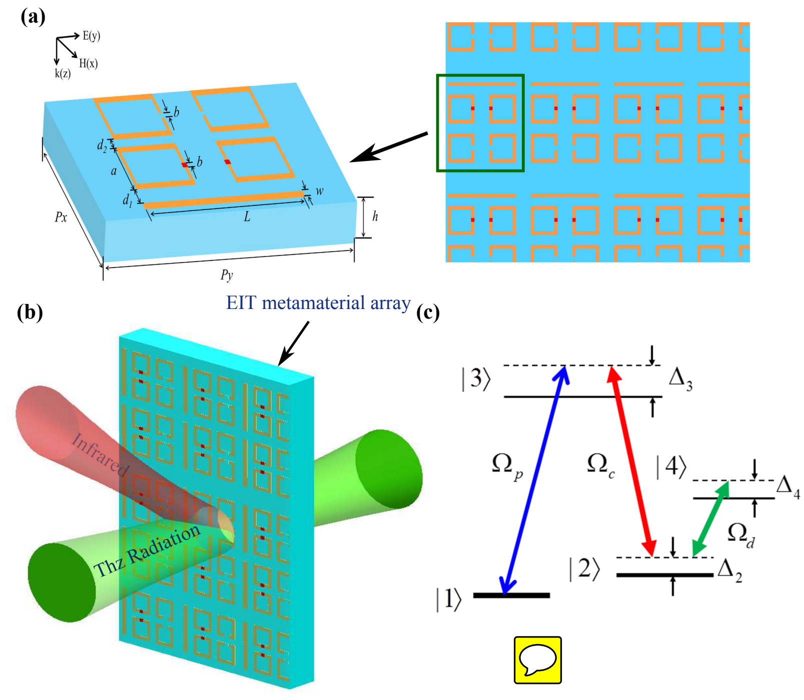

Fig. 1. (a) Schematic of the unit cell. The plasmonic system consists of a bright element (CW) and two dark elements (SRRs). The geometrical parameters are $L = 85$, $w = 5$, $a = 29$, $b = 5$, $d_1 = 10$, $d_2 = 14$, $h = 495$, $P_x = 80$ and $P_y = 120\mu$m, respectively. The right hand of panel (a) is microscopic image of the fabricated metamaterial. (b) Possible experimental arrangement of the optical pump-terahertz probe measurement. (c) Equivalent atomic model. Energy level structure and excitation scheme of the lifetime-broadened four-level N-type atomic system with upper energy level $|4\rangle$, $|3\rangle$ and lower energy levels $|1\rangle$, $|2\rangle$. Δ_2, Δ_3 and Δ_4 are detunings. Ω_p, Ω_c, and Ω_d are half Rabi frequencies of the probe, control, and assisted fields, respectively.

pump beam with a spot diameter being much larger than the terahertz beam diameter enables a uniform excitation aperture for the terahertz transmission. The aim of introducing such optical pump beam is to change the electrical conductivity of the Si islands and hence to actively control characters of the EIT metamaterial. Fig. 1(b) shows a possible experimental arrangement of the optical pump-terahertz probe measurement.

The CW resonator array has a typical localized surface plasmon (LSP) resonance at a frequency within the terahertz regime, while the SRRs support an inductive-capacitive (LC) resonance at the same frequency. In the EIT metamaterial the CW is directly excited by the incident radiation along the CW. However, the SRRs are weakly coupled to the radiation due to the perpendicular orientation of the electric field. The near field coupling between the CW and SRRs excites the LC resonance in the SRRs. Thus, the CW and SRRs serve as the bright and dark modes, respectively, for the radiation excitation.

Now we adapt the widely used coupled Lorentz oscillator model to analyze the near field interaction between the two elements in an EIT metamaterial unit cell. Each cell can be regarded as a four-level atom involving a ground state $|1\rangle$ and three excited states $|2\rangle$, $|3\rangle$, and $|4\rangle$ with N-type level configuration (Fig. 1(c)). The LSP bright mode resonance in the CW corresponds to the dipole-allowed transition $|1\rangle \rightarrow |3\rangle$. The first SRR-pair simultaneously couples to the CW and the second SRR-pair corresponding to the transitions $|3\rangle \rightarrow |2\rangle$ and $|2\rangle \rightarrow |4\rangle$, respectively. The coupling between the CW and the second SRR-pair is very weak and hence can be ne-

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glected. A destructive interference may occur between the pathways $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \rightarrow |3\rangle \rightarrow |2\rangle \rightarrow |3\rangle$, and between the pathways $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \rightarrow |3\rangle \rightarrow |2\rangle \rightarrow |4\rangle \rightarrow |2\rangle \rightarrow |3\rangle$, which can result in the double EIT phenomenon.

It is instructive to first analyze the quantum destructive interference character in the four-level atomic EIT system shown in Fig. 1(c). A weak probe field of angular frequency ω_p and wavevector $\mathbf{k}_p$, i.e., $\mathbf{E}_p(\mathbf{r},t) = \mathbf{e}_p\mathscr{E}_p(\mathbf{r},t)e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)} + \text{c.c.}$, drives the transition $|1\rangle \rightarrow |3\rangle$; a strong control field of angular frequency ω_c and wavevector $\mathbf{k}_c$, i.e., $\mathbf{E}_c(\mathbf{r},t) = \mathbf{e}_c\mathscr{E}_c(\mathbf{r},t)e^{i(\mathbf{k}_c\cdot\mathbf{r}-\omega_c t)} + \text{c.c.}$, drives the transition $|2\rangle \rightarrow |3\rangle$; in addition, a strong assisted field of angular frequency ω_d and wavevector $\mathbf{k}_d$, i.e., $\mathbf{E}_d(\mathbf{r},t) = \mathbf{e}_d\mathscr{E}_d(\mathbf{r},t)e^{i(\mathbf{k}_d\cdot\mathbf{r}-\omega_d t)} + \text{c.c.}$, drives the transition $|2\rangle \rightarrow |4\rangle$. Here $\mathbf{e}_c$, $\mathbf{e}_p$, and $\mathbf{e}_d$ are, respectively, unit vectors denoting the polarization of the control, probe, and assisted laser fields, with $\mathscr{E}_c$, $\mathscr{E}_p$, and $\mathscr{E}_d$ being their corresponding envelopes. Under electric-dipole and rotating-wave approximations, the equations of motion governing atomic dynamics read

$$i\frac{\partial}{\partial t}\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -\Omega_p^* & 0 \\ 0 & -d_2 & -\Omega_c^* & -\Omega_d^* \\ -\Omega_p & -\Omega_c & -d_3 & 0 \\ 0 & -\Omega_d & 0 & -d_4 \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} \tag{1}$$

where a_j $(j = 1,2,3,4)$ is the probability amplitude of the state $|j\rangle$; $d_j = \Delta_j + i\gamma_j$ with $\Delta_3 = \omega_p - (\omega_3 - \omega_1)$, $\Delta_2 = \omega_p - \omega_c - (\omega_2 - \omega_1)$, and $\Delta_4 = \omega_p - \omega_c + \omega_d - (\omega_4 - \omega_1)$ being the one-, two-, and three-photon detunings, respectively; γ_j is the decay rate and ω_j is the eigenfrequency of the state $|j\rangle$; $\Omega_p = (\mathbf{p}_{31}\cdot\mathbf{e}_p)\mathscr{E}_p/\hbar$, $\Omega_c = (\mathbf{p}_{32}\cdot\mathbf{e}_c)\mathscr{E}_c/\hbar$, and $\Omega_d = (\mathbf{p}_{42}\cdot\mathbf{e}_d)\mathscr{E}_d/\hbar$ are respectively the half Rabi frequencies of the probe, control, and assisted fields, with $\mathbf{p}_{ij}$ being the electric dipole matrix element associated with the transition from $|i\rangle$ to $|j\rangle$.

Equation (1) can be solved by searching for the solutions $a_j = \tilde{a}_j e^{-i\lambda t}$ with the eigenvalue λ. After substituting these solutions into Eq. (1), we obtain the equation

$$\lambda\begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \\ \tilde{a}_3 \\ \tilde{a}_4 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -\Omega_p^* & 0 \\ 0 & -\Delta_2 & -\Omega_c^* & -\Omega_d^* \\ -\Omega_p & -\Omega_c & -d_3 & 0 \\ 0 & -\Omega_d & 0 & -\Delta_4 \end{pmatrix}\begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \\ \tilde{a}_3 \\ \tilde{a}_4 \end{pmatrix}, \tag{2}$$

where γ_2 and γ_4 have been neglected since they are usually much smaller (three orders smaller) than the other parameters. Equation (2) has a zero eigenvalue, i.e. $\lambda = 0$, if the condition $\Delta_2\Delta_4 - |\Omega_d|^2 = 0$ is satisfied. The corresponding eigenvector is found to be

$$|\psi_{\text{dark}}\rangle = \frac{1}{\sqrt{1 + \frac{|\Omega_p|^2}{|\Omega_c|^2} + \frac{|\Omega_p|^2|\Omega_d|^2}{\Delta_4^2|\Omega_c|^2}}}\left(|1\rangle - \frac{\Omega_p}{\Omega_c}|2\rangle + \frac{\Omega_p\Omega_d}{\Delta_4\Omega_c}|4\rangle\right), \tag{3}$$

which does not involve the state $|3\rangle$ (i.e. no atoms are pumped into the excited state) and hence is a dark state. From the equation $\Delta_2\Delta_4 - |\Omega_d|^2 = 0$ one finds two roots of ω_p, i.e. $\omega_p = \omega_\pm$ with

$$\omega_\pm = \frac{(\delta_2 + \delta_4) \pm \sqrt{(\delta_2 + \delta_4)^2 + 4|\Omega_d|^2}}{2}, \tag{4}$$

where $\delta_2 = \omega_c + (\omega_2 - \omega_1)$ and $\delta_4 = \omega_c - \omega_d + (\omega_4 - \omega_1)$. Thus the dark state can be achieved by either $\omega_p = \omega_+$ or $\omega_p = \omega_-$, corresponding to two EIT transparency windows in the probe-field absorption spectrum. This gives rise to the double EIT phenomenon in the N-type atomic system.

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Now we turn to study the interference property of the metamaterial introduced above. Such metamaterial system can be described by the coupled Lorentz oscillator model as did in Refs. [13, 14]

$$\ddot{x}_1(t) + \gamma_1 \dot{x}_1(t) + \omega_0^2 x_1(t) - \kappa_1 x_2(t) = gE, \tag{5a}$$
$$\ddot{x}_2(t) + \gamma_2 \dot{x}_2(t) + \omega_0^2 x_2(t) - \kappa_1 x_1(t) - \kappa_2 x_3(t) = 0, \tag{5b}$$
$$\ddot{x}_3(t) + \gamma_3 \dot{x}_3(t) + \omega_0^2 x_3(t) - \kappa_2 x_2(t) = 0, \tag{5c}$$

where x_j $(j = 1, 2, 3)$ are the amplitudes of bright (represented by x_1) and dark (represented by x_2 and x_3) modes; the dot over x_j denotes time derivative; γ_j $(j = 1, 2, 3)$ represent the damping rates being inversely proportional to the quality factors of elements; $E(z,t) = E_0(z,t)e^{-i\omega t} +$c.c. is the incident radiation, with E_0 being the envelope depending on the slowly varying variables z and t; ω_0 is the resonance frequency, which can be taken as $\omega_0 = 2\pi \times 0.74$ THz in the present example; g is a geometric parameter indicating the coupling strength of the bright mode with the incident radiation E; κ_1 and κ_2 are respectively two coupling coefficients between CW resonator and the first SRR-pair and between the first and second SRR-pairs, which are respectively inversely proportional to the geometrical parameters d_1 and d_2. We assume that the damping rates satisfy the relation $\gamma_3 \ll \gamma_1 \ll \omega_0$. Note that γ_2 can be actively controlled by changing the infrared pump field. In addition, κ_2 can also be modified by adjusting the geometrical parameters of the system.

The solutions of Eq. (5) can be searched in the form $x_j(t) = \tilde{x}_j(\omega)e^{-i\omega t} +$ c.c. $(j = 1, 2, 3)$. It is easy to obtain

$$\tilde{x}_1 = \frac{gE_0(D_2 D_3 - \kappa_2^2)}{D_1(D_2 D_3 - \kappa_2^2) - \kappa_1^2 D_3} \tag{6}$$

with $D_j = \omega_0^2 - \omega^2 - i\gamma_j \omega$. A dark state of the EIT-metamaterial (i.e. no LSP bright modes are excited) is achieved when $\tilde{x}_1 = 0$ which leads to the equation $(\omega_0^2 - \omega^2)^2 - \kappa_2^2 = 0$. Notice that for obtaining the equation we have neglected γ_2 and γ_3 which are usually much smaller than the other parameters. From the equation one gets two real roots of ω, i.e. $\omega = \omega_{r\pm}$ with

$$\omega_{r\pm} = \sqrt{\omega_0^2 \pm \kappa_2}. \tag{7}$$

Thus, transparency windows in the radiation absorption spectrum are opened at $\omega = \omega_{r\pm}$, i.e. a double EIT phenomenon similar to that of the N-type atomic system can also be found in the EIT-metamaterial.

The propagation dynamics of the envelope E_0 of the terahertz radiation in the metamaterial can be described by Maxwell equation. Under the slowly-varying envelope approximation, the equation reads

$$i\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)E_0 + \frac{\omega}{2c}\chi E_0 = 0, \tag{8}$$

where the susceptibility χ induced in the elements by the electric field E is directly proportional to the bright mode x_1 and is proportional to the number of unit cells in unit area.

In our numerical example, the system parameters are chosen as $\kappa_1 = 0.1\,\text{THz}^2$, $\kappa_2 = 0.05\,\text{THz}^2$, $\gamma_1 = 0.05$ THz, $\gamma_2 = 0.025$ THz, and $\gamma_3 = 0.025$ THz for the absence of the infrared pump field. When the infrared pump field is applied, the parameters γ_1, γ_3, κ_1, and κ_2 do not change significantly, while the damping rate γ_2 is increased obviously from 0.025 THz (corresponding to the pump power 0 mW) to 0.271 THz (corresponding to the pump power 1350 mW). Physically, the incensement of γ_2 is caused by the increased conductivity of the Si islands under photoexcitation [14].

Shown in Fig. 2 is the normalized susceptibility χ/χ_0 as a function of frequency and pump-

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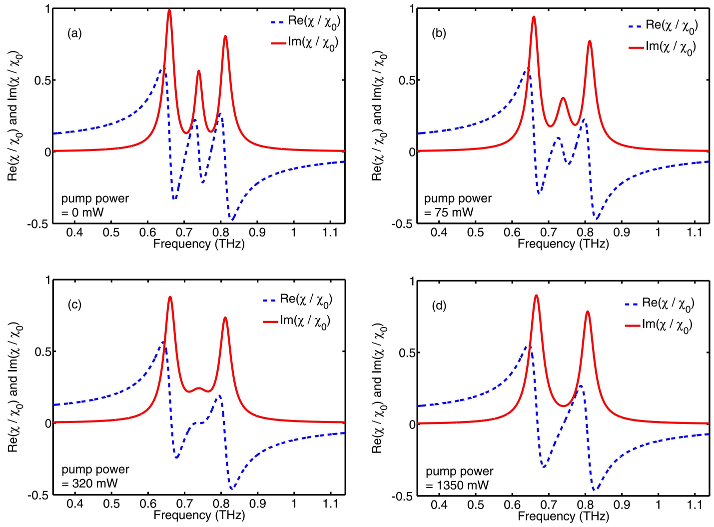

Fig. 2. The real part $\mathrm{Re}(\chi/\chi_0)$ (blue dashed line) and imaginary part (red solid line) of the normalized susceptibility χ/χ_0 as a function of frequency and the pump-field intensity. The power of the infrared pump field is taken as 0 (a), 75 mW (b), 320 mW (c), and 1350 mW (d), respectively.

field intensity, with χ_0 being the normalization constant. The real part $\mathrm{Re}(\chi/\chi_0)$ (blue dashed line) and imaginary part $\mathrm{Im}(\chi/\chi_0)$ (red solid line) of χ/χ_0 characterizes the dispersion and absorption properties of the terahertz radiation, respectively. Fig. 2(a) is for the case without the infrared pump field. We see that two transparency windows corresponding to the double EIT.

When increasing the pump-field power to 75 mW, one has $\gamma_2 = 0.041$ THz, the absorption of the terahertz radiation near the resonance becomes weaker than that in Fig. 2(a), as shown in Fig. 2(b). The separation between the two EIT transparency windows becomes also narrower. However, it becomes flatter in comparison with Fig. 2(a). The slope of the dispersion becomes zero when the power of the pump field arrives to 320 mW, which leads to $\gamma_2 = 0.083$ THz, as shown in Fig. 2(c).

As the pump field arrives the power 1350 mW, the absorption of the terahertz radiation near the resonance frequency is almost vanished, as shown in Fig. 2(d). In this situation, two EIT transparency windows are merged into one corresponding to the single EIT.

Besides the active control for realizing the transition from the double EIT to the single EIT (thus the crossover from the superluminal to the subluminal propagations, see in the next section) by changing the infrared pump field, we can also realize such transition by passively changing the geometrical parameters of resonator structures. Specifically, we can vary the distance d_2 between two SRR pairs, which is associated with the coupling coefficient κ_2. Decreasing d_2 can increase κ_2, corresponding to the increase of the half Rabi frequency Ω_d in the N-type atomic system.

Shown in Fig. 3 is the normalized susceptibility χ/χ_0 as a function of the frequency and κ_2. The other parameters are the same with those used in Fig. 2. Fig. 3(a) shows the case of $\kappa_2 = 0$. We see that only one EIT transparency window is opened, corresponding to a single-EIT. When increasing κ_2 [see Fig. 3(b)-(d)], a small absorption appears in the center of the EIT transparency window and the single EIT transparency window splits into two EIT transparency windows gradually. That is to say, the single EIT is transferred into the double EIT when κ_2 is

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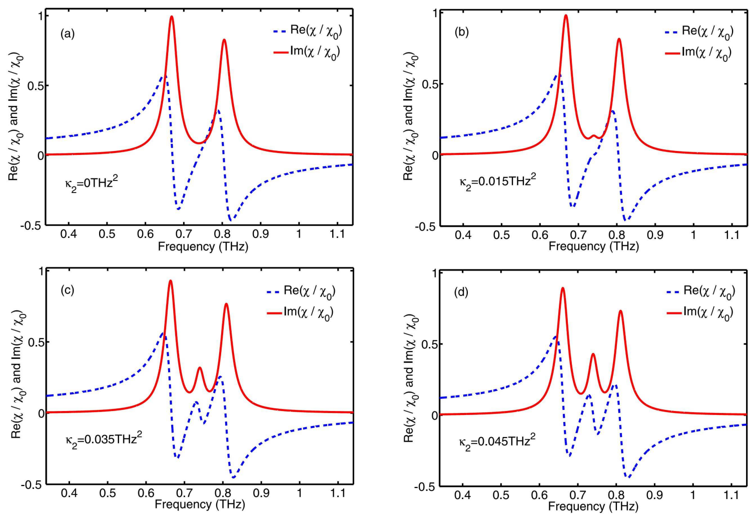

Fig. 3. The real part $\mathrm{Re}(\chi/\chi_0)$ (blue dashed line) and imaginary part $\mathrm{Im}(\chi/\chi_0)$ (red solid line) of the normalized susceptibility χ/χ_0 as a function of frequency and the coupling coefficient κ_2. Coupling coefficient κ_2 is taken as 0 (a), $0.015\,\mathrm{THz}^2$ (b), $0.035\,\mathrm{THz}^2$ (c), and $0.045\,\mathrm{THz}^2$ (d), respectively.

increased.

3. Transition from subluminal and superluminal propagations of terahertz radiation

We now show that the EIT metameterial proposed here can be used to realize subluminal propagation, superluminal propagation, and their transition of terahertz radiation in a single metamaterial system. Note that the group velocity of the system can be expressed as $V_g = c/n_g$, where the group index n_g is defined by

$$n_g = 1 + \mathrm{Re}\chi(\omega) + \frac{\omega}{2}\frac{\partial \mathrm{Re}\chi(\omega)}{\partial \omega}. \tag{9}$$

Using the result of χ, the expression of n_g can be written down explicitly, but it is very lengthy and hence omitted here.

If $n_g > 1$, the group velocity of the radiation is smaller than c, thus the propagation of radiation is subluminal. However, if the $0 < n_g < 1$ or $n_g < 0$, the group velocity of the radiation is larger than c or it becomes negative, thus the propagation of radiation is superluminal. Particularly, a negative group velocity means that the peak of the emerging pulse occurs at an earlier time than the peak of the pulse at the entrance to the medium [22].

Fig. 4(a) and Fig. 4(b) show the group index n_g and the absorption coefficient $\alpha = \frac{\omega_0}{2c}\mathrm{Im}(\chi)$ as functions of the power of the infrared pump field, respectively. From Fig. 4(a), we see that with the increase of the pump power the group index changes from -350 to nearly 50. The region $n_g < 1$ corresponds to the superluminal propagation and the region $n_g > 1$ corresponds to the subluminal propagation. We get $n_g = 1$ (i.e. the group velocity equals c) when the pump power is about 320 mW.

From Fig. 4(b), we see that α decreases rapidly with the increase of the pump field power. Thus to avoid a large absorption while ensuring the superluminal propagation, a weak pump field is necessary. To this end, we can use a pump field with power a little less than 320 mW, say 300 mW. At this power, $\alpha = 1.50\ \mathrm{cm}^{-1}$ while the group velocity is $-3.3\,c$. On the other hand, the incident radiation propagates only a very short distance (the thickness of a metama-

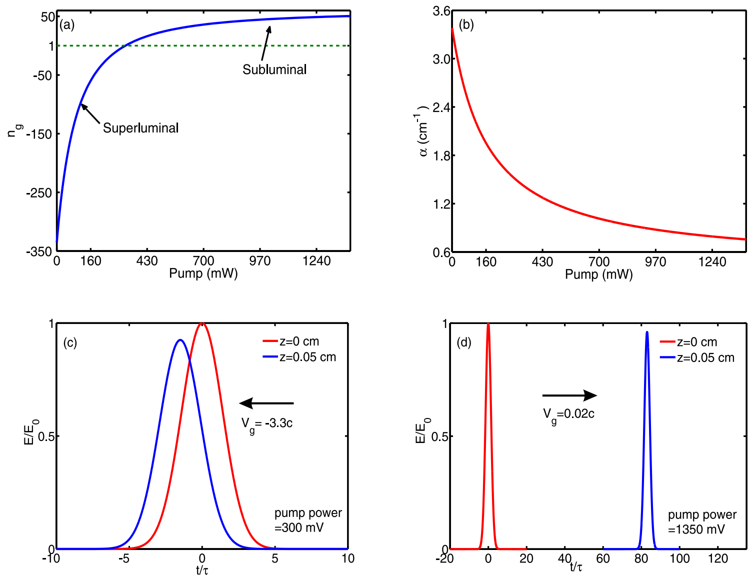

Fig. 4. (a) The group index n_g as a function of the pump power. (b) The absorption coefficient α as a function of the pump power. (c) The superluminal propagation ($V_g = -3.3\,c$) of the terahertz radiation with pump power 300 mW. (d) The subluminal propagation ($V_g = 0.02\,c$) of the terahertz radiation with pump power 1350 mW. The initial condition is $E = E_0 e^{-0.25(t/\tau)^2}$ with $\tau = 10^{-12}$ s.

terial structure is several hundred micrometers) to pass the medium. Thus, the small absorption accompanied by the superluminal propagation will not lead to a serious attenuation of the terahertz radiation. When the power of the pump field is increased to 1350 mW, the absorption is decreased to $\alpha = 0.78$ cm^{-1}. Thus, the group velocity varied from $-3.3\,c$ to $0.02\,c$ can be realized by increasing the pump power from 300 mW to 1350 mW with only a small absorption.

Fig. 4(c) (Fig. 4(d)) shows the superluminal (subluminal) propagation with $V_g = -3.3\,c$ ($V_g = 0.02\,c$) of the terahertz radiation for pump power 300 mW (1350 mW). When plotting the figure, the parameters of the system are chosen as the same as used in Fig. 2. The propagation length is chosen as 0.05 cm. The initial condition is chosen to be $E = E_0 e^{-0.25(t/\tau)^2}$ with $\tau = 10^{-12}$ s. As expected, an evident time advancement -0.5×10^{-12} s is observed in Fig. 4(c), and an evident time delay 83.3×10^{-12} is obtained in Fig. 4(d). However, in both the superluminal and subluminal propagations, the terahertz pulse have slight attenuations due to the existence of small absorption in the system.

4. Summary

We have proposed a scheme for designing a new type of optical metamaterial that can mimic the EIT characters of four-state atomic systems of N-type energy-level configuration. We have demonstrated that in such metamaterial a transition from a single EIT to a double EIT of terahertz radiation may be easily realized by actively tuning the intensity of the infrared pump field or passively tuning the geometrical parameters of resonator structures. In addition, the group velocity of the terahertz radiation can be varied from subluminal to superluminal by changing the pump field intensity. The scheme suggested here may be used to construct chip-scale slow and fast light devices and to realize rapidly responded switching of terahertz radiation at room temperature.