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Multispectral plasmon-induced transparency in hyperfine terahertz meta-molecules

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Abstract
We experimentally and theoretically demonstrated an approach to achieve multispectral plasmon-induced transparency (PIT) by utilizing meta-molecules that consist of hyperfine terahertz meta-atoms. The feature size of such hyperfine meta-atoms is 400 nm, which is one order smaller than that of normal terahertz metamaterials. The hyperfine meta-atoms with close eigenfrequencies and narrow resonant responses introduce different metastable energy levels, which makes the multispectral PIT possible. In the triple PIT system, the slow light effect is further confirmed as the effective group delay at three transmission windows can reach 7.3 ps, 7.4 ps and 4.5 ps, respectively. Precisely controllable manipulation of the PIT peaks in such hyperfine meta-molecules was also proven. The new hyperfine planar design is not only suitable for high-integration applications, but also exhibits significant slow light effect, which has great potential in advanced multichannel optical information processing. Moreover, it reveals the possibility to construct hyperfine *N*-level energy systems by artificial hyperfine plasmonic structures, which brings a significant prospect for applications on miniaturized plasmonic devices.

Keywords: metamaterials, hyperfine, multispectral plasmon-induced transparency

(Some figures may appear in colour only in the online journal)

1. Introduction

In the last decade, metamaterials have attracted tremendous research interest for their unique electromagnetic properties that normally do not exist in natural materials [1–13]. Typical electromagnetic metamaterials are artificial composite materials consisting of a periodic array of subwavelength resonators, which are known as 'meta-atoms' or 'meta-molecules' such as split ring resonators (SRRs) [1–5, 7, 8]. Based on the engineered electromagnetic responses in meta-atoms, many novel physical phenomena have been revealed. For instance, mimicry of the electromagnetic induced transparency (EIT) phenomenon in plasmonic metamaterial systems has attracted considerable attention [10–13]. EIT is a quantum interference effect that renders an otherwise opaque medium transparent over a narrow spectral range by a probe laser [14, 15]. This phenomenon allows for a spectrally narrow optical transmission window accompanied with extreme dispersion, which is the key to achieving a dramatic group velocity reduction in propagating light and to realizing diverse applications including ultrafast switching, enhanced optical nonlinearities, slow light and optical data storage [16–18]. In 2008, Zhang *et al* firstly suggested that coupled radiative and dark plasmonic meta-atoms can also realize EIT-like optical properties [10], which is termed plasmon-induced transparency (PIT). The newly developed PIT mechanism relieves the complicated experimental conditions, such as macroscopic apparatus, stable gas lasers and low temperature environments in quantum-mechanical EIT systems, and makes EIT-like chip-scale applications possible. Since then, a variety of PIT metamaterials have been proposed and demonstrated at microwave [11, 19–23], terahertz [24–28], infrared and optical regimes [10, 12, 29–34], and some of which are even superconductive or active metamaterial devices [35–37]. However, the majority of the previous works on metamaterial-based PIT systems only exhibit a single transparency window, which may restrict their applications on miniaturized and multifunctional optical devices. In particular, metamaterial systems possessing multiple transparency windows with slow light properties could add new degrees of freedom in optical information processing, since the information can be stored and retrieved in multiple channels separately. Moreover, metamaterials that supporting multispectral PIT have many fascinating applications in multiband filters, multiband slow light devices and ultrasensitive chemical/biological sensors. For example, a 3D plasmon ruler with extra high sensitivity was realized based on a meta-molecule with double PIT peaks, and it can be used to determine nanoscale distances within chemical or biological species [38]. Very recently, there have been a few attempts to obtain dual or triple PIT responses by inductive coupling [39], dipole and multipole coupling [40, 41], plasmonic hybridization effects [42], or coupled metallic wire and SRRs [43, 44]. Nevertheless, it is still highly challenging to obtain three or more PIT peaks with large group delay in a single meta-molecule.

In this work, we propose and demonstrate a different approach to achieve multispectral PIT in a new type of meta-molecules consisting of hyperfine terahertz metamaterials. The feature size of those meta-molecules is one order smaller than that of conventional terahertz metamaterials. The multispectral PIT effect with double and triple PIT windows in such meta-molecules has been demonstrated by numerical simulations and experimental measurements. Theoretical analysis based on the coupled Lorentz oscillator model was also performed. The hyperfine planar designs not only offer huge group delay within each PIT window, but also are suitable for high-integration applications. Contrasting with some previous schemes, our proposed meta-molecules can support independent coupling between the bright and corresponding quasi-dark mode at each PIT peak, which makes it possible to precisely tailor the group velocity and the delay bandwidth product of the transmitted pulse. The multispectral PIT effects provide a possibility in planar metamaterials for applications toward optical switching, optical data storage, quantum computation and telecommunications at multiple frequencies. Furthermore, the novel planar designs reveal possibilities to establish artificial hyperfine energy level systems that can mimic the functionality of *N*-level atomic systems with multispectral EIT, which is significant for further application of optical quantum information processing.

2. Implementation of multispectral plasmon induced transparency

In achieving a PIT effect, a significant difference in the linewidth of the two plasmonic resonance modes involved is required. The bright plasmonic resonance mode usually exhibits a strong coupling to the radiation field with large linewidth and thus low quality factor. In contrast, the dark/quasi-dark plasmonic resonance mode [10, 43–45] normally couples with the incident field much more weakly with narrow linewidth and large quality factor [46], which leads to the analogy of the dark mode with a metastable level in an atomic EIT system. The destructive interference between strongly coupled bright and dark/quasi-dark modes results in a well-defined narrow transparent window within a broadband resonance dip. The PIT effect can also be interpreted by a quantum destructive interference between two different excitation transition pathways in the three-level atomic system, where the metastable energy level is necessary for the realization of such an effect. Therefore, a straightforward strategy to setup a *N*-level energy system and realize multispectral PIT is to introduce more meta-atoms with different dark/quasi-dark modes, which could induce different metastable energy levels. It is worth noting that all the eigenfrequencies of the dark/quasi-dark modes have to be distinctly distributed within the resonance profile of the bright mode—i.e. the eigenfrequencies should be very close and their linewidths in spectra ought to be narrow enough. Apparently, introducing hyperfine dark/quasi-dark meta-atoms is an ideal solution to this problem. It not only offers necessary narrow-band plasmonic modes with close eigenfrequencies and induces hyperfine metastable energy levels, but also exceedingly reduces complex interaction between different quasi-dark plasmonic modes and makes precise modulation of PIT windows possible.

To verify this approach, a triatomic meta-molecule with hyperfine meta-atoms was firstly designed to mimic the double EIT in four-level atomic systems. The triatomic meta-molecule consists of a closed ring (CR) and two hyperfine SRR meta-atoms, as shown in figure 1(a) and (b). For the radiative dipole ring CR, which is strongly coupled to external field as a bright meta-atom, spectral broad-linewidth resonance is supported due to radiative damping. The sharp LC mode supported by the hyperfine SRR couples weakly to the radiation field with small dissipation factor and can be regarded as a quasi-dark mode [45]. Indeed, both the bright CR and quasi-dark SRR interact with the incident electric field, but the relative coupling strength is in sharp contrast, which makes the EIT effect possible. To make sure that the eigenfrequencies of quasi-dark LC modes were located within the dipole resonance profile of bright CR, the meta-molecules were designed and modeled by full field electromagnetic simulation using a finite difference time-domain (FDTD) algorithm. In our simulations, the permittivity of gold was described by the Drude model, $\varepsilon(\omega) = 1 - \omega_p^2/(\omega^2 + i\gamma\omega)$, where $\omega_p = 1.37 \times 10^{16}$ rad s^{-1} is the plasma frequency and $\gamma = 4.08 \times 10^{13}$ rad s^{-1} is the damping rate [47]. The meta-molecules were placed on a semi-infinite silicon substrate with a refractive index of 3.4.

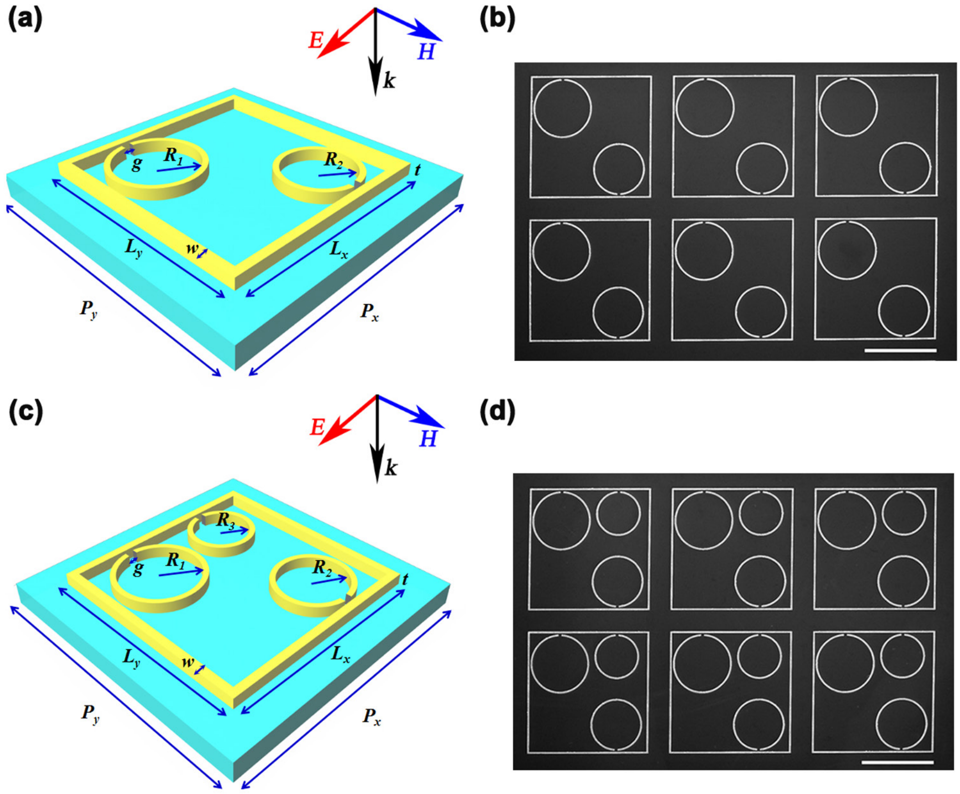

Figure 1. (a) Schematic and (b) scanning electron micrograph images of hyperfine triatomic meta-molecule. The geometrical parameters are: $P_x = P_y = 40$ μm, $L_x = L_y = 34$ μm, $R_1 = 16$ μm, $R_2 = 14$ μm, $g = 1$ μm, $w = 400$ nm and $t = 200$ nm, respectively. (c) Schematic and (d) scanning electron micrograph images of hyperfine tetratomic meta-molecule. The outer diameter of SRR3 is $R_3 = 12$ μm, and the other dimensions are the same as those of the triatomic meta-molecule. The scale bar is 20 μm.

Geometric parameters of the meta-molecule are as follow: the lattice constant is $P_x = P_y = 40$ μm, the length of the CR is $L_x = L_y = 34$ μm, the thickness of the meta-molecules is $t = 200$ nm, the diameters of SRR1 and SRR2 are $R_1 = 16$ μm and $R_2 = 14$ μm, respectively. The distance between CR and SRRs is 400 nm, and each SRR has a gap width of $g = 1$ μm. All the meta-atoms have the same line width of $w = 400$ nm, which is much smaller than those of traditional THz metamaterials, and thus termed as 'hyperfine' meta-atoms. Corresponding meta-molecule patterns were fabricated by high-resolution e-beam lithography technique, then 200 nm gold were deposited on a thick high-resistivity double-side polished silicon substrate utilizing thermal evaporation, and subsequently followed by a lift-off procedure. Terahertz time domain spectroscopy (THz-TDS) was then employed to measure both the phase and amplitude responses from the samples with electric field polarization parallel to the gap of the inner SRR. The transmitted electric field was recorded in the time domain, and a bare silicon substrate was used as reference for the transmission measurements. The frequency dependent complex transmission coefficient of the metamaterials was extracted from the ratio of the Fourier transformed amplitude spectra of the samples to the reference, defined as $|\tilde{t}(\omega)| = \left|\widetilde{E}_{\mathrm{sam}}(\omega)/\widetilde{E}_{\mathrm{ref}}(\omega)\right|$, where $\widetilde{E}_{\mathrm{sam}}(\omega)$ and $\widetilde{E}_{\mathrm{ref}}(\omega)$ are Fourier transformed time traces of the transmitted electric fields of the sample and silicon reference, respectively. The experimental results reveal a good agreement with the simulations.

All the experimental and simulation results exhibit evident double PIT peaks in the triatomic meta-molecule, as shown in figures 2(a) and (b). We can observe that there are two distinct transparency windows appear around $\omega_{\mathrm{D1}} = 0.99$ THz and $\omega_{\mathrm{D2}} = 1.24$ THz for the triatomic system. The slow light effect, quantified by the group delay (τ_{g}) values extracted from the phase of the pulse propagating through the metamaterials, is another essential character of PIT metamaterials. In order to demonstrate this property in our designed meta-molecules, we calculate the group delay of the electromagnetic wave packet through the meta-molecules relative to the silicon substrate with $\tau_{\mathrm{g}} = -1/2\Pi\partial\varphi/\partial\omega$, where φ is the transmission phase shift and ω is the frequency of incident THz waves [19, 22, 35, 37]. Figure 2(c) shows the corresponding group delay spectrum for the triatomic meta-molecule. The group delays at ω_{D1} and ω_{D2} reach as high as 5.9 ps and 5.8 ps, respectively, which indicates that a THz pulse with a central frequency located in the transparency window will be significantly slowed down while propagating through the meta-molecules. These results are about two to four times larger than the values of previous double PIT designs [43], and comparably large for applications in THz devices [37].

In order to further confirm the design principle, a new quasi-dark SRR meta-atom was introduced to the triatomic meta-molecule to imitate the triple EIT in five-level atomic systems. The diameter and gap width of the newly added SRR3 are $R_3 = 12$ μm and $g = 1$ μm, respectively. In contrast to the transmission spectra of triatomic meta-molecules, the

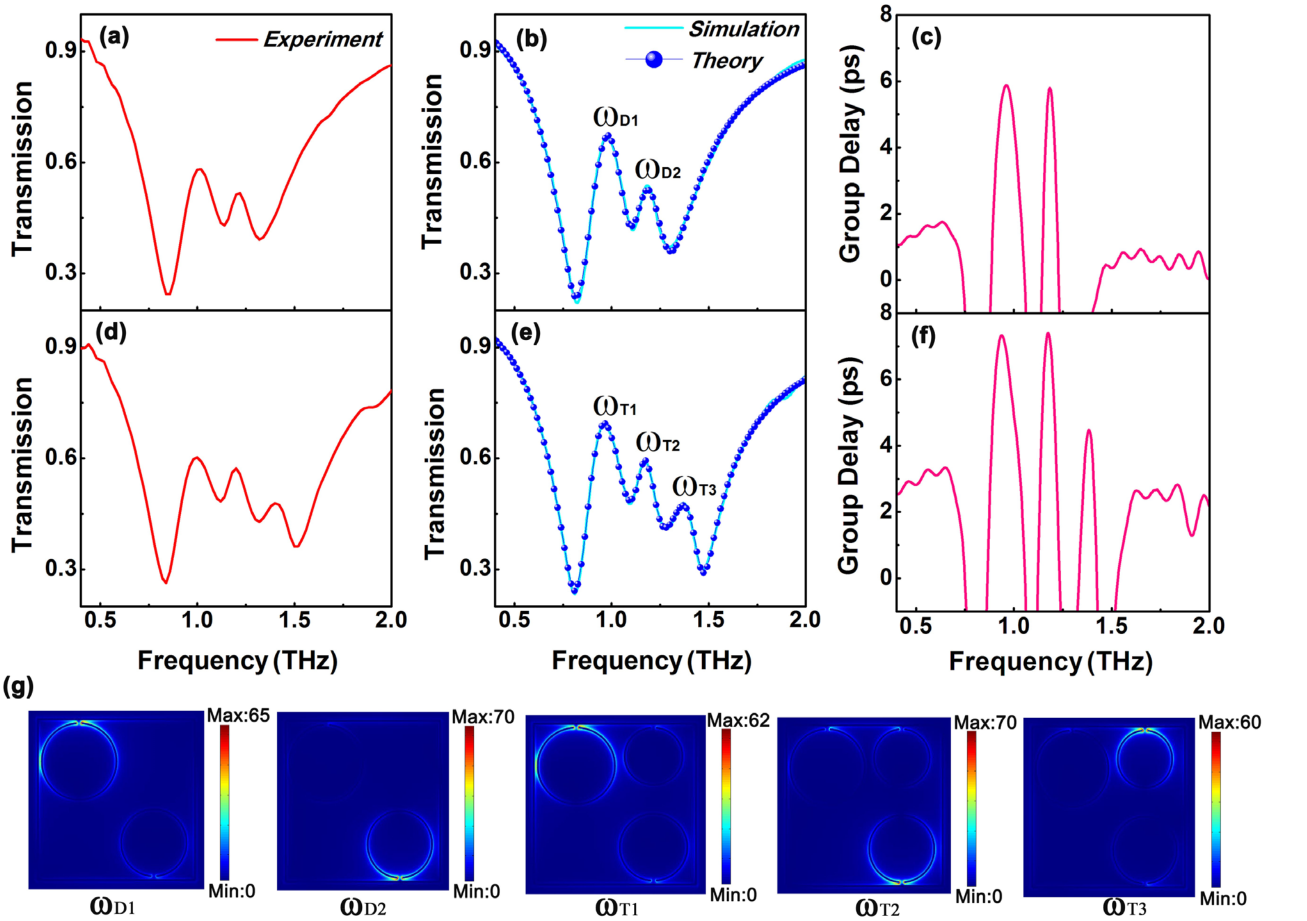

Figure 2. Multispectral PIT in triatomic and tetratomic meta-molecules. Red, cyan and pink curves represent the corresponding experimental transmittance ((a) and (d)), simulated transmittance ((b) and (e)), and calculated group delay ((c) and (f)), respectively. Blue lines with circles represent the fitted curves calculated from the coupled Lorentz oscillator model. Obvious double PIT peaks (ω_{D1}, ω_{D2}) and triple PIT peaks (ω_{T1}, ω_{T2} and ω_{T3}) can be found in the transmission spectra. (g) The electric field distribution on the surface of meta-molecules at resonance ω_{D1}, ω_{D2}, ω_{T1}, ω_{T2} and ω_{T3}, respectively.

two PIT peaks (ω_{D1}, ω_{D2}) in the triatomic molecule still exist in the spectra of a tetratomic molecule with very slight red-shifts ($\omega_{T1} = 1$ THz, $\omega_{T2} = 1.2$ THz), and a new PIT peak $\omega_{T3} = 1.4$ THz appears at a higher frequency, which is induced by the meta-atom SRR3, as illustrated in figures 2(d) and (e). Interestingly, when the quasi-dark SRR3 was introduced to the system, accompanied by the appearance of the new transmission peak (ω_{T3}), the group delay of the other two transparent windows were significantly enhanced, as shown in figure 2(f). The corresponding group delay at ω_{T1}, ω_{T2} and ω_{T3} are as high as 7.3 ps, 7.4 ps and 4.5 ps, respectively. The huge group delay that occurs in the transparency windows is extremely attractive for enhanced light-matter interactions and nonlinear effects.

To investigate the underlying physics of the double PIT effect, electric field distributions at every PIT window were also examined, as shown in figure 2(g). We observe that there is an obvious transfer of electromagnetic energy from the bright CR to the quasi-dark SRRs to induce the transparency window. These figures clearly show that only the corresponding quasi-dark SRR meta-atom interacts with the bright meta-atom CR at each PIT peak, and the couplings between other meta-atoms are very weak and negligible. These facts indicate that the transmission windows in our multispectral PIT system are

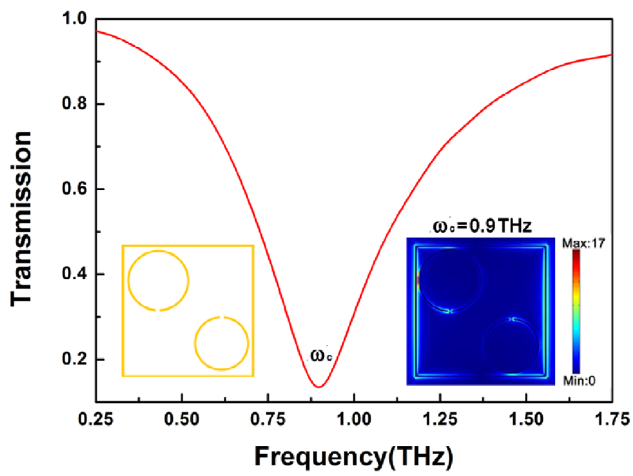

Figure 3. The transmission spectra of the triatomic meta-molecule with the SRR gap facing away from the arms of the CR. The insets are the corresponding schematic of the meta-molecule and the electric field distributions at transmission dip ω_c. The polarization of the incident terahertz field was kept parallel to the gap of SRR.

individually induced from the destructive interference effect owing to the near field coupling between corresponding quasi-dark SRR and bright CR. At the PIT peak, strong electric field

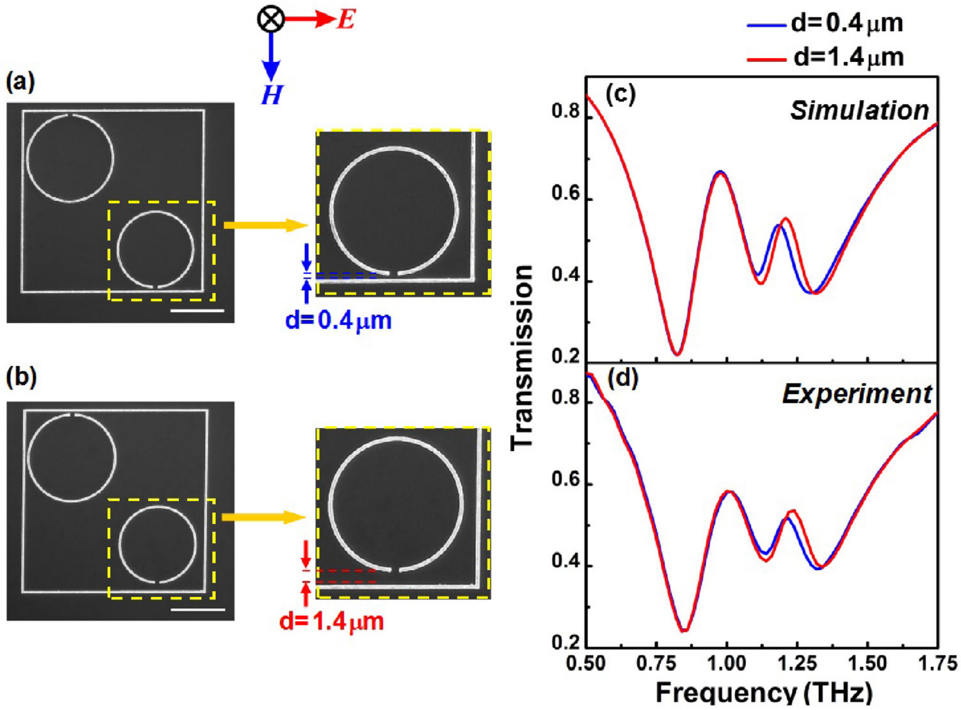

Figure 4. Precise control of single PIT window in a triatomic system. Scanning electron micrograph images of a meta-molecule with three atoms (CR+SRR1+SRR2) are shown in the left column ((a) and (b)). The scale bar is 10 μm. The inset shows the details of the region marked in yellow dotted line. The distance d between CR and SRR2 is (a) 0.4 μm and (b) 1.4 μm. The (c) simulated and (d) measured transmittance spectra for different values of distance parameter d are shown in the right column. The PIT peak around 1.24 THz, which is induced by the coupling between CR and SRR2, shows strong capability of precise and independent modulation by varying the relative location of SRR2.

confinement appears at the corresponding quasi-dark SRR gap and the capacitive coupling between the bright and quasi-dark modes dominates the interaction. The excited LC mode in hyperfine SRR induces extremely weak field in the CR by the destructive interference, which means significant enhancement of optical transmittance at the PIT peak.

As a proof of our coupling mechanism, we performed a structural study of the effect of the gap position of SRR in the coupled triatomic system on the behavior of the transmission spectrum. The transmission spectrum of the hyperfine triatomic meta-molecule exhibits an interesting gap position dependence on PIT peaks as shown in figure 3. As the split gap in SRR is facing away from the arms of CR, there is only a single resonance observable in the transmission spectrum and no PIT window occurs (see figure 3). From the electric field distribution it is evident that this resonance originates from the strong excitation of dipole resonance of CR and relatively weak excitation of SRRs, which give rise to a broad band resonance in the spectrum. In this case, both the CR and SRRs are excited by the incident field and strongly couple to the free space, while the coupling between them is rather weak and thus the PIT peaks collapse. The observed vanishment of the transmission peak can also be interpreted as the degradation of the destructive interference between the fields of the quasi-dark and bright meta-atoms. All the results and analysis above indicate that the capacitive coupling in the coupled resonator system is dominant, thus the coupling effect between the SRR and CR is strongly related to the relative gap position of the inner SRR. However, the inductive coupling between the corresponding quasi-dark SRR and bright CR is relatively weak and insusceptible here as the magnetic coupling [48] between the resonators is not so sensitive to the gap position of inner SRR due to symmetry constraints.

Here, we note that the coupling mechanism in our multispectral PIT system is distinct from the hybridization between two dark meta-atoms in a bright–dark–dark/quasi-dark system, or averaged coupling effect between the bright meta-atoms in a bright–bright–dark system [43, 44]. In our scheme, only the specific quasi-dark mode could be strongly coupled to the bright mode at each PIT peak, and the coupling between other meta-atoms are exceedingly restrained. This mechanism, unlike other double EIT systems with external perturbation of the background environment or with self-hybridization of the dark modes [35, 43], has direct analogy to the traditional atomic EIT systems in which the coupling between the dark atoms (e.g. gaseous atoms) is generally negligible. Furthermore, the independent coupling between the specific quasi-dark and bright modes make it possible to precisely control the transparent windows at will, highlighting our design principle for the realization of multispectral PIT in a metamaterial system.

3. Precise manipulation of plasmon induced transparency

Manipulation of transparent windows in PIT systems allows us to precisely tailor the group velocity and the delay bandwidth product of the transmitted THz pulse. In our multispectral PIT system, each PIT spectral response hinges on the coupling between the constituent corresponding quasi-dark and bright meta-atoms and is thus sensitive to the structural configuration. Therefore, the precisely controllable modulation of PIT peaks was demonstrated by physically changing the spatial configurations of the meta-molecule. Obviously, meta-molecules with hyperfine meta-atoms require less space than traditional ones, which not only greatly benefit high-integrated chip application, but also make it possible for the modulation of the PIT peak by varying the relative position of SRRs in the CR. As illustrated in figure 4, in the triatomic meta-molecule, when the distance between the quasi-dark meta-atoms (SRR2) and the bottom arm of CR is increased from 400 nm to 1.4 μm, the corresponding PIT peak blue-shifts from 1.21 THz to 1.24 THz and the transmission is slightly enhanced, whereas the other PIT peak remains exactly the same. The observed frequency blue shift of the transmission peak indicates the increased coupling strength within the coupled meta-molecule system. The boosted transmission is mainly due to the enhancement of resonance in the quasi-dark SRR and suppressed radiative nature of the bright CR as they are coupled at an appropriate distance of separation [25]. From another point of view, the observed enhancement in the transmission amplitude is due to the increase in the coupling strength as well as in the amount of destructive interference between the meta-atoms, and vice versa. The hyperfine terahertz meta-molecules show adequate capability of accurate controlling of the multichannel slow light process and high-precision position detection.

4. Theoretical model

For a better understanding, the quasi-dark meta-atoms in such multispectral meta-molecules can be considered as a series of hyperfine SRRs with similar configurations that are split from a traditional terahertz SRR, as shown in figure 5(a). When the conventional SRR is split into different hyperfine SRRs with close eigenfrequencies, the metastable energy level $|\mathrm{SRR}\rangle$ induced by the former conventional SRR will also be split finely into different metastable energy levels. A multispectral PIT meta-molecule with a bright CR meta-atom and N ($N \leqslant 3$) quasi-dark SRR meta-atoms can set up an $(N+2)$-level energy system, as a level scheme for multispectral PIT in a five-level system with four meta-atoms is shown in figure 5(b). Each hyperfine quasi-dark SRR induces a different metastable energy level. It is noteworthy that the upper limit on the possible number of energy states in this system depend on the space within the CR which can accommodate quasi-dark SRRs and detuning (Δ_i) of the resonance frequency of quasi-dark mode from that of bright mode. For the jth ($j \leqslant 3$) quasi-dark meta-atom (SRR$_j$), there are two possible excitation pathways, namely, $|0\rangle - |1\rangle$ and $|0\rangle - |1\rangle - |j+1\rangle - |1\rangle$. The two possible pathways interfere destructively, therefore dramatically reducing extinction and resulting in transmittance window. In such a multiple level energy system, the resonance modes can be considered as coupled Lorentz oscillators [10, 37, 49, 50].

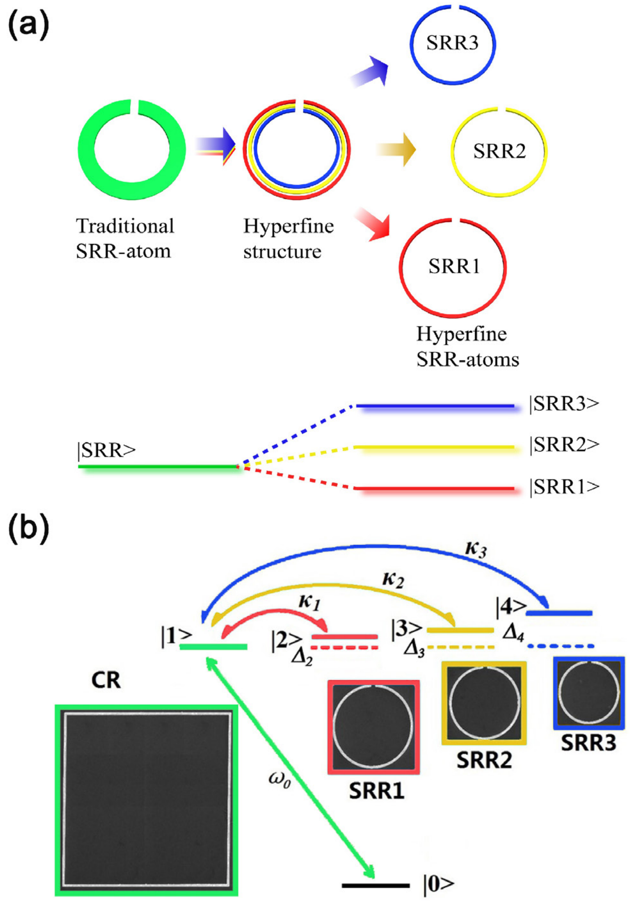

Figure 5. Schematic of physical mechanism for multispectral PIT in hyperfine meta-molecule. (a) A traditional SRR can be considered as a combination of a series of hyperfine SRRs, which can introduce different metastable energy levels. (b) Level scheme for three different quasi-dark LC modes (SRRs) that are coupled to a bright dipole mode (CR) in a schematic five-level system. Δ_i denotes the detuning of the resonance frequency of ith quasi-dark mode from bright mode, and κ_j denotes the coefficient of the coupling between the jth quasi-dark mode and bright mode.

Ignoring the interaction between quasi-dark modes, the plasmonic modes can be described as:

$$\ddot{q}_0(t) + \gamma_0\dot{q}_0(t) + \omega_0^2 q_0(t) + \sum_{j=1}^{N} \kappa_j q_j(t) = g_0\widetilde{E}, \tag{1}$$

$$\ddot{q}_j(t) + \gamma_j\dot{q}_j(t) + \omega_j^2 q_j(t) + \kappa_j q_0(t) = g_j\widetilde{E}, \tag{2}$$

where q_0, q_j,ω_0, ω_j, γ_0 and γ_j indicate the amplitude, resonance frequency and damping rate of the bright and jth quasi-dark modes respectively, κ_j is the coupling coefficient between the bright mode and corresponding jth quasi-dark mode, g_0 and g_j are geometric parameters, $\widetilde{E} = E_0 \mathrm{e}^{\mathrm{i}\omega t}$ is the incident electric field. By solving the above coupled equations (1) and (2), the q_0 and q_j can be expressed as:

$$q_0 = \frac{g_0 - \sum_{j=1}^{N} \kappa_j g_j / C_j}{C_0 - \sum_{j=1}^{N} \kappa_j^2 / C_j} \widetilde{E}, \tag{3}$$

Table 1. Parameters used in coupled Lorentz oscillators model calculations[a].

	ω_0	ω_1	ω_2	ω_3	γ_0	γ_1	γ_2	γ_3	κ_1	κ_2	κ_3	g_0
CR	0.90				0.67							0.82
SRR1		1.1				0.12						0.28
SRR2			1.3				0.12					0.29
SRR3				1.5				0.12				0.30
3-atoms	1.04	0.99	1.23	—	0.68	0.17	0.18	—	0.22	0.20	—	0.89
4-atoms	1.10	0.94	1.18	1.44	0.80	0.17	0.11	0.17	0.29	0.20	0.24	0.95

[a] The g_0 in the triatomic and tetratomic meta-molecules represent the coupling strength of counterpart CR to the external field. The g_j in the triatomic and tetratomic meta-molecules is rather small (less than 0.01) and not shown in the table.

$$q_j = \frac{g_j - \kappa_j\left(g_0 - \sum_{j=1}^{N}\kappa_j g_j/C_j\right)\Big/\left(C_0 - \sum_{j=1}^{N}\kappa_j^2/C_j\right)}{C_j}\widetilde{E}, \tag{4}$$

with $C_j = \omega_j^2 - \omega^2 + \mathrm{i}\gamma_j\omega$. The energy dissipation of the meta-molecule system can be described as follows:

$$P(t) = \frac{\sum_{j=0}^{N} g_j\widetilde{E}\dot{q}_j}{|\widetilde{E}|^2} = \frac{\mathrm{i}\omega\sum_{j=0}^{N} g_j q_j\widetilde{E}}{|\widetilde{E}|^2}. \tag{5}$$

Transferring this equation to the frequency domain via Fourier transformation leads to:

$$P(\omega) = \mathrm{i}\omega g_0 A + \sum_{j=1}^{N}\mathrm{i}\omega g_j\frac{g_j - \kappa_j A}{C_j}, \tag{6}$$

$$T(\omega) = 1 - |P(\omega)|^2, \tag{7}$$

where $A = \left(g_0 - \sum_{j=1}^{N}\kappa_j g_j/C_j\right)\Big/\left(C_0 - \sum_{j=1}^{N}\kappa_j^2/C_j\right)$.

The parameters in equation (7) were calculated by fitting the transmission spectra of multispectral PIT meta-molecule systems and the results are shown in table 1. It is evident that the simulated and experimental curves are reproduced nearly perfectly by the fitted results, as shown in figure 2. From the calculated results, the g_j of the SRR$_j$ is in close proximity to zero ($g_j < 0.01$) in the composite meta-molecules, which means the coupling strength of SRR$_j$ to the external field is rather weak and thus the SRR$_j$ meta-atom is 'quasi-dark'. The resonance frequencies of SRRs are distributed around the eigenfrequency of the CR, and the dissipation factor γ_j in each hyperfine SRR is nearly six times smaller than γ_0 in the bright mode, which gives rise to the narrow transmission windows. The coupling between the bright CR and quasi-dark SRRs with small γ_j and close ω_j results in the anticipated multispectral PIT. Intriguingly, the theoretical results indicate that the equivalent resonance eigenfrequency ω_0 in the CR slightly blue-shift from 1.04 THz to 1.10 THz, and the equivalent detuning between the quasi-dark modes and bright mode are reduced, when the quasi-dark SRR3 is introduced to this system. This can be interpreted as the sensitive perturbation of the newly added quasi-dark meta-atom to the localized plasmonic modes [42, 51]. The perturbation is mutual and therefore there is slight variation in the resonance frequencies (ω_1, ω_2) and corresponding coupling coefficients (κ_1, κ_2) of quasi-dark meta-atoms when the eigenfrequency of the outer CR changes. Additionally, reducing the equivalent detuning also enhanced the coupling strength and destructive interference between the fields of the quasi-dark SRRs and bright CR, which result in the strengthened group delay of PIT peaks when SRR3 is added into the triatomic meta-molecule (see figures 2(c) and (f)).

Such quantitative results strongly substantiate our expectation on multispectral PIT mechanism. The destructive interference between the fields of the quasi-dark SRRs and bright CR drastically reduces the inherently radiative losses owning to suppression of radiative coupling of the system at the multiple resonance frequencies, which facilitates the multispectral PIT effects. It is worth mentioning that the proposed mechanism clearly indicates that more transmission windows can be obtained by introducing hyperfine quasi-dark SRRs into this system. This promising prospect greatly highlights the hyperfine metamaterial concept for multispectral PIT applications.

5. Conclusions

In conclusion, an intuitive approach for multispectral PIT phenomenon has been presented by utilizing meta-molecules with combined hyperfine meta-atoms at terahertz frequencies. The simulated and experimental results are in good agreement with theoretical predictions. Large group delay, more than 4 ps within each transmission window, was successfully obtained in such hyperfine meta-molecules. Furthermore, the PIT window in hyperfine meta-molecule shows a sensitive dependence on the position of hyperfine SRR atoms in the CR, and thus precisely control of the PIT window in multispectral meta-molecules was achieved in both experiment and simulation. The strategy we proposed here opens up an alternative avenue for achieving multispectral PIT effect, and provides a possibility to set up artificial hyperfine energy level systems for plasmonic applications on miniaturized and versatile THz devices.

Acknowledgments

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