Dual-band electromagnetically induced transparency effect in a concentrically coupled asymmetric terahertz metamaterial

Koijam Monika Devi, Dibakar Roy Chowdhury, Gagan Kumar, and Amarendra K. Sarma

ARTICLES YOU MAY BE INTERESTED IN

A polarization independent electromagnetically induced transparency-like metamaterial with large group delay and delay-bandwidth product
Journal of Applied Physics 123, 173101 (2018); https://doi.org/10.1063/1.5023684

Active control of polarization-dependent near-field coupling in hybrid metasurfaces
Applied Physics Letters 113, 061111 (2018); https://doi.org/10.1063/1.5040162

Active control and switching of broadband electromagnetically induced transparency in symmetric metadevices
Applied Physics Letters 111, 021101 (2017); https://doi.org/10.1063/1.4993428
Dual-band electromagnetically induced transparency effect in a concentrically coupled asymmetric terahertz metamaterial

Koijam Monika Devi,1, a) Dibakar RoyChowdhury,2 Gagan Kumar,1 and Amarendra K. Sarma1
1Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India
2Mahindra Ecole Centrale, Jeedimetla, Hyderabad 500043, Telangana, India

(Received 20 May 2018; accepted 23 July 2018; published online 10 August 2018)

We propose a scheme to achieve a dual-band electromagnetically induced transparency (EIT) effect in a planar terahertz metamaterial (MM), comprising an inner circular split ring resonator (CSRR) concentrically coupled to an outer asymmetric two-gap circular split ring resonator (ASRR). The scheme is numerically and theoretically analyzed. The dual-band EIT effect occurs as a result of the near field coupling between the resonant modes of the resonators comprising the MM configuration. It is observed that the dual-band EIT effect in the MM structure could be modulated with an in-plane rotation of the CSRR structure. The dual-band EIT effect is also examined by varying the asymmetry of the ASRR and the size of the inner CSRR. A theoretical model based upon the four-level tripod-system provides an intuitive explanation about the underlying coupling mechanism responsible for the dual-band EIT effect in the proposed MM structure. Our study could be significant in the development of multi-band slow light devices, narrowband absorbers, etc., in the terahertz regime. Published by AIP Publishing. https://doi.org/10.1063/1.5040734

I. INTRODUCTION

Over the past decade, research in metamaterials (MMs) has been gaining momentum owing to its ability in controlling electromagnetic waves through careful design at the subwavelength scale.1–2 Numerous artificial structures have been investigated1–9 extensively for the realization of negative refractive index, super lenses, optical cloaking, sensing, etc. Recently, MM structures have also been found to mimic the quantum phenomenon in the classical regime.10–14 One such quantum phenomenon is the electromagnetically induced transparency (EIT). In EIT, an atom that absorbs a particular light signal is rendered transparent by shining another light signal having nearly the same resonance frequency.15,16 In MMs, the EIT effect usually occurs as a result of destructive interference between a bright and a dark mode resulting from the structural composition of the MM structure.10–12 The bright mode is directly excited by the incident light and exhibits a much broader linewidth compared to the dark mode which is excited either by the incident light directly or via coupling to the bright mode.17–20 Recent studies have revealed that the EIT effect can occur not only through electric coupling but also due to the magnetic coupling21 between the bright and the dark mode in the MM structure. Rigorous theoretical studies as well as experimental investigations have revealed its potential in various applications,22–26 such as switches, sensors, slow light modulations, etc. The EIT effect in MMs has been realized in planar structures comprising metal strips, coupled split ring resonators, etc. in the gigahertz27–32 as well as terahertz23–37 regime. Several studies have also been reported on the dynamic tuning of the EIT effect through the incorporation of non-linear media or semiconductor materials34–38 at the unit cell level of the MM structures. The EIT effect has also been demonstrated by breaking the symmetry of the resonant structures39 in the MM structures.

Recently, considerable interest has also been given to realize the dual-band EIT effect in MMs, in which two transparency windows are induced, through the careful arrangements of the resonators. In MMs, the dual-band EIT effect occurs as a result of the net coupling between the bright-dark-dark modes or bright-bright-dark modes of the MM structures.40–42 Due to its double tunable transparency windows, the dual-band EIT phenomenon in MMs has the potential to realize multiband slow light systems, narrowband absorbers, etc. In spite of the significant interest, only limited amount of work has been reported to investigate and explore the applications of this effect. So far, very few MM configurations40–45 comprising metal strips, split ring resonators (SRR), hybrid structures, etc., have been investigated for the realization of this effect. In the terahertz regime, the dual-band EIT effect has been investigated in MM comprising a central metal strip coupled to a split ring resonator (SRR) and a two-gap SRR.46 The dual-band EIT effect and slow light behavior have also been studied in a MM structure comprising three coupled meta-atoms,41 for a wide range of oblique incident angles, wherein the effect has been achieved through the simultaneous interactions of the bright mode, dark mode, and quasi-dark mode. In another recent study, Xu et al.42 have demonstrated the dual-band EIT effect through symmetry breaking in a terahertz MM structure comprising two concentric square SRRs with their gaps aligned parallel to each other. However, none of these previous studies have investigated the dual-band EIT effect using asymmetric circular split ring resonators (CSRRs). As such, there is ample scope to explore the dual-band EIT effect in

a)Electronic mail: koijam@iitg.ernet.in
MMs, in order to achieve an effective modulation of the transparency windows as well as to thoroughly understand the underlying physical mechanisms causing the effect. Therefore, more rigorous and detailed analysis using a simplistic design is required to effectively control and tune the dual-band EIT effect in MMs for the realization of its potential applications.

In this article, we examine the dual-band EIT effect in a simple terahertz MM geometry comprising an inner CSRR concentrically coupled to an outer asymmetric two-gap circular split ring resonator (ASRR). The dual-band EIT effect in the proposed MM configuration occurs due to the coupling of the resonant mode of the CSRR structure to the EIT response of the ASRR structure. It may be noted that the effect in the proposed MM occurs due to the coupling of two meta-atoms (i.e., the CSRR and the ASRR), as opposed to earlier studies\(^\text{41}\) where the effect occurs as a result of the coupling between three meta-atoms. Although the dual-band EIT effect has been studied earlier, the novelty of our work lies in the modulation of the transparency windows through the rotation of the CSRR in the proposed MM structure. The circular structure of our proposed MM configuration provides an extra degree of freedom in controlling the dual-band EIT effect arising in the structure. Here, we investigate the modulation of the dual-band EIT effect by rotating the inner CSRR in the \(x\)-\(y\) plane, in our proposed MM structure. The dual-band EIT effect diminishes with an increase in the rotation angle of the CSRR and finally vanishes with an orthogonal rotation of the CSRR. The modulation of the effect is further achieved by varying the asymmetry in the ASRR and the size of the CSRR in the proposed metamaterial. A theoretical model based on a Four Level Tripod (FLT) system clearly elucidates the coupling mechanism in the MM structure. The design, numerical results, and the theoretical model are discussed in Secs. II, III and IV, respectively, followed by a brief conclusion in Sec. V.

II. DESIGN OF THE METAMATERIAL STRUCTURE

The schematic diagram of the proposed asymmetric terahertz MM structure is illustrated in Fig. 1. The meta-molecule of the MM structure comprises an outer ASRR placed concentrically with respect to an inner CSRR. The ASRR and CSRR structures, made of aluminium metal having a thickness of 200 nm, are placed on a silicon substrate of thickness \(h = 10 \mu m\), with a dielectric permittivity of 11.9. The periodicity of the MM structure is taken as \(p = 80 \mu m\). The outer radius of the CSRR and the ASRR is denoted by \(r_1\) and \(r_2\), respectively. “\(g\)” represents the split gaps of the ASRR and the CSRR, while “\(w\)” represents the width of both resonators. “\(\theta\)” denotes the rotation angle of the CSRR with respect to the incident polarization, while “\(\phi\)” is the asymmetry parameter of the ASRR. The parameters \(r_2 = 29 \mu m\), \(g = 3 \mu m\), and \(w = 5 \mu m\) are fixed for all the numerical simulations. The numerical simulations have been performed using the finite difference frequency domain solver in CST Microwave Studio. The MM structure is simulated under unit cell boundary conditions in the \(x\)-\(y\) plane. An adaptive mesh size of the order of \(\lambda/10\), where \(\lambda\) is the wavelength of the incident radiation, is employed. Open boundary conditions were set along the direction of light propagation. The simulations are performed for the y-polarized incident terahertz wave.

The terahertz transmission response of the CSRR structure, ASRR structure, and the coupled MM structure for the y-polarized incident terahertz waves is shown in Figs. 2(a)–2(c). Figure 2(a) represents the transmission of the CSRR structure at \(\theta = 0^\circ\) and \(r_1 = 13 \mu m\). It is evident from the figure that the CSRR gets excited by the linearly polarized terahertz beam and has a narrow resonance dip at a frequency, \(f = 0.82\) THz. On the other hand, the ASRR structure exhibits an EIT-like transmission profile having a transparency window from 0.6 THz to 0.81 THz with a transmission

![FIG. 1. Schematic diagram of the concentrically coupled asymmetric terahertz MM structure.](image)

![FIG. 2. Terahertz transmission profile vs. frequency for (a) CSRR with \(\theta = 0^\circ\) and \(r_1 = 13 \mu m\), (b) ASRR with \(d = 12 \mu m\), and (c) the coupled MM configuration for fixed values of \(\theta = 0^\circ\), \(d = 12 \mu m\) and \(r_1 = 13 \mu m\). Electric field profiles of (d) the CSRR structures at the resonance frequency, (e) the ASRR structures at the transmission peak, and (f) the dual-band EIT MM structure at the transmission dip \(D_2\). The green arrow signifies the direction of incident polarization.](image)
peak frequency, $f = 0.62 \text{ THz}$. The transmission profile for the ASRR structures with $d = 12 \mu m$ is shown in Fig. 2(b). When the CSRR is placed concentrically to the ASRR structure, the single transparency window of the ASRR structure splits into two transparency windows with the first transparency window ranging from 0.59 THz to 0.75 THz and the second transparency window ranging from 0.82 THz to 0.93 THz. This dual-band EIT effect vanishes in the MM structure. Hence, one can switch the dual-band EIT effect to a single EIT effect in the coupled MM structure. The terahertz transmission response of the ASRR structures in the coupled MM structure. The terahertz transmission response of the MM for $\theta = 0^\circ$, $d = 12 \mu m$ and $r_1 = 13 \mu m$ is represented by the green solid line in Fig. 2(c). To further understand the coupling behavior leading to the dual-band EIT effect, we also observe the electric field profiles of the structural components of the MM structure. Figures 2(d)–2(f) represent the electric field profiles of the CSRR, the ASRR, and the coupled MM structure, respectively. Figure 2(d) describes the electric field profile for the corresponding structure at the transmission dip $D_2$ (i.e., $f = 0.79 \text{ THz}$) is shown in Fig. 2(f).

III. MODULATING THE DUAL-BAND EIT EFFECT

The transmission characteristics of the proposed MM are studied for different rotation angles of the CSRR with respect to the incident polarization. Figure 3(a) represents the dual-band EIT of the proposed MM for a fixed $r_1 = 13 \mu m$ and $d = 12 \mu m$ by varying $\theta$ from $0^\circ$ to $90^\circ$. The red solid line represents the transmission of the MM structure when $\theta = 0^\circ$. The green line represents transmission for $\theta = 20^\circ$, while the blue traces signify the transmission for $\theta = 40^\circ$. The cyan and the orange traces represent the transmission of the MM structure for $\theta = 60^\circ$ and $\theta = 90^\circ$, respectively. It is clearly evident from the figure that the dual-band EIT effect is most prominent for $\theta = 0^\circ$. The dual-band EIT effect diminishes as the inner CSRR is rotated with respect to incident polarization. When $\theta = 90^\circ$, the dual-band EIT effect vanishes in the MM structure. Hence, one can switch the dual-band EIT effect to a single EIT effect in the coupled MM structure. Modulation of the effect is further achieved by gradually varying the asymmetry of the ASRR, “$d$” from 0 $\mu m$ to 16 $\mu m$ in the MM structure. The transmission characteristics of the MM structure for different values of “$d$” with a fixed $\theta = 0^\circ$ and $r_1 = 13 \mu m$ are shown in Fig. 3(b). The orange solid line represents the transmission for $d = 0 \mu m$. The cyan traces signify the transmission for $d = 4 \mu m$. The blue and the green traces represent the transmission of the MM structure for $d = 8 \mu m$ and $d = 12 \mu m$, respectively. The red line represents the transmission of the MM structure when $d = 16 \mu m$. It is clearly observed from the figure that a single EIT effect occurs when the asymmetry parameter, $d = 0 \mu m$. However, the single EIT effect in the MM structure evolves into a dual-band EIT effect with the introduction of asymmetry (i.e., $d > 0 \mu m$). The dual-band EIT effect is further tuned by increasing the asymmetry of the ASRR in the proposed MM structure.

In order to get insight into the dual-band EIT effect in the MM structure, we study the electric field profiles for various rotation angles and asymmetry parameters. Figures 4(a)–4(c) represent the electric field profiles of the MM geometry at the transmission peak $P_2$ of the second transparency window for $\theta = 0^\circ$, $40^\circ$, and $90^\circ$, with $r_1 = 13 \mu m$ and $d = 12 \mu m$ fixed. It is evident from Fig. 4(a) that the CSRR is excited by the incident terahertz radiation when $\theta = 0^\circ$. In this case, the gap of the CSRR is parallel to the direction of the incident polarization resulting in an LC resonance dip at $f = 0.82 \text{ THz}$ [see Fig. 2(a)]. The coupled MM structure exhibits a dual-band EIT effect for this configuration, due to the coupling of the resonant modes of the CSRR and the ASRR structures. However, as we rotate the CSRR with respect to incident polarization, the near field coupling behavior of the MM structure is modified. The electric field
SRR has broad dipolar resonance at a frequency close to excited by the incident electric field. The symmetric two-gap is evident from the figure that the symmetric two-gap SRR is ASRR is a symmetric two-gap split ring resonator (SRR). It which then becomes the ASRR, the dual-band EIT effect can introducing an asymmetry into the symmetric two-gap SRR, transparency EIT effect in the coupled MM structure. By CSRR, generates a transparency window leading to a single two-gap SRR, when coupled to the LC resonance of the this dipolar resonance in the CSRR. This dipolar resonance of the symmetric MM configuration is shown in Fig. 4(c). Hence, an efficient MM structure. The electric field profile for the corresponding results in the diminishing of the dual-band EIT effect in the weakly excited by the incident terahertz radiation which FIG. 4. Electric field profile of the MM structure at P_2 for different rotation parameters, i.e., (a) \( \theta = 0^\circ \), (b) \( \theta = 40^\circ \), and (d) \( \theta = 90^\circ \) for a fixed value of \( r_1 = 13 \, \mu m \) and \( d = 12 \, \mu m \). Electric field profile of the MM structure at P_1 for different asymmetry parameters i.e., (d) \( d = 0 \, \mu m \), (e) \( d = 8 \, \mu m \), and (f) \( d = 16 \, \mu m \) for a fixed value of \( r_1 = 13 \, \mu m \) and \( \theta = 0^\circ \). The incident electric field is along the direction of the green arrow.

profile for \( \theta = 40^\circ \) is shown in Fig. 4(b). The CSRR is weakly excited by the incident terahertz radiation which results in the diminishing of the dual-band EIT effect in the MM structure. Finally, for \( \theta = 90^\circ \), i.e., when the gap of the CSRR is perpendicular to the incident polarization, the LC resonance in the CSRR is no longer excited. With this right-angled rotation, an on-to-off resonance of the CSRR is created in the MM structure. For this configuration, the dual-band EIT effect reduces to a single EIT effect in the coupled MM structure. The electric field profile for the corresponding MM configuration is shown in Fig. 4(c). Hence, an efficient tuning of the dual band EIT effect is achieved as a result of this on-to-off resonance of the CSRR. Figures 4(d)–4(f) represent the electric field profiles of the MM structure at the transmission peak \( P_1 \) of the first transparency window for \( d = 0 \, \mu m \), 8 \( \mu m \), and 16 \( \mu m \) with a fixed value of \( r_1 = 13 \, \mu m \) and \( \theta = 0^\circ \). The electric field profile, at \( P_1 \), corresponding to \( d = 0 \, \mu m \) is shown in Fig. 4(d). For \( d = 0 \, \mu m \), the outer ASRR is a symmetric two-gap split ring resonator (SRR). It is evident from the figure that the symmetric two-gap SRR is excited by the incident electric field. The symmetric two-gap SRR has broad dipolar resonance at a frequency close to that of the CSRR. This dipolar resonance of the symmetric two-gap SRR, when coupled to the LC resonance of the CSRR, generates a transparency window leading to a single transparency EIT effect in the coupled MM structure. By introducing an asymmetry into the symmetric two-gap SRR, which then becomes the ASRR, the dual-band EIT effect can be realized in the coupled MM structure. The symmetry breaking in the MM structure causes a difference in the resonance frequencies of the two metallic arms giving rise to an EIT response for the ASRR structures. Figure 4(e) represents the electric field profile corresponding to \( d = 8 \, \mu m \). In this case, the ASRR structures exhibit an EIT like response due to the breaking of symmetry in the resonant mode. Consequently, the coupling of the ASRR with the CSRR structure leads to the realization of a dual-band EIT effect in the coupled MM structure. The effect can be further tuned by increasing the asymmetry of the ASRR structure. The electric field profile corresponding to \( d = 16 \, \mu m \) is shown in Fig. 4(f). It is observed that the dual-band EIT effect in the coupled MM structure is most pronounced for this configuration. Therefore, an effective tuning of the dual-band EIT effect is achieved in the MM structure.

Further modulation of the dual-band EIT effect in the proposed MM structure is achieved by varying the size of the inner CSRR, \( r_1 \) from 12.5 \( \mu m \) to 14 \( \mu m \). The terahertz transmission profile for different values of \( r_1 \) with a fixed \( \theta = 0^\circ \) and \( d = 12 \, \mu m \) is shown in Fig. 5. The cyan solid line represents the transmission of the MM structure when \( r_1 = 12.5 \, \mu m \). The blue line represents transmission for \( r_1 = 13 \, \mu m \), while the green traces signify the transmission for \( r_1 = 13.5 \, \mu m \). The red traces represent the transmission of the MM structure when \( r_1 = 14 \, \mu m \). When \( r_1 = 12.5 \, \mu m \), the resonance dip of the individual CSRR structure occurs at \( f = 0.85 \, THz \). As \( r_1 \) is increased gradually, the resonance frequency of the inner CSRR decreases steadily reaching a value of 0.76 \( THz \) when \( r_1 = 14 \, \mu m \). Hence, the dip \( D_2 \) in the dual-band EIT effect experiences a red shift with the increase in \( r_1 \) in the MM configuration, resulting in the red shifting of the second transparency region as well. This further adds another degree of freedom to the tuning capability of the dual-band EIT effect in the proposed MM structure.

IV. ANALYTICAL MODEL BASED ON THE FOUR-LEVEL TRIPOD (FLT) SYSTEM

In order to validate our numerical findings and to better understand the dual-band EIT effect in the MM structure, a

FIG. 5. Terahertz transmission vs. frequency for different values of \( r_1 \) with a fixed \( \theta = 0^\circ \) and \( d = 12 \, \mu m \).
The theoretically fitted transmission transition, we can obtain a theoretical fit of the numerically simulated transmission. The four-level tripod (FLT)-system is employed.\textsuperscript{42,46} The energy level diagram for the FLT-system is illustrated in Fig. 6. In the system, the transition between $|1\rangle \rightarrow |4\rangle$, driven by the Rabi frequency, $\Omega_p$, is termed as the probe/dark transition, while the transition between $|2\rangle \rightarrow |4\rangle$, driven by the Rabi frequency, $\Omega_c$, is termed as the coupling/bright transition. The levels $|1\rangle$, $|2\rangle$, and $|4\rangle$ constitute a $\Lambda$-system exhibiting an EIT effect as a result of the destructive interference between the excitation pathways $|1\rangle \rightarrow |4\rangle$ and $|1\rangle \rightarrow |4\rangle \rightarrow |2\rangle \rightarrow |4\rangle$. With the introduction of another dark/control state $|3\rangle$, this $\Lambda$-system evolves into an FLT-system, exhibiting a dual-band EIT effect. This is because the destructive interference has changed into a constructive interference between the EIT effect of the $\Lambda$-system and the dark/control state. In our proposed MM structure, the outer symmetric two-gap SRR (corresponding to $d=0 \ \mu m$) behaves as the bright state with a broad dipolar resonance. One dark state is introduced by breaking the symmetry in the outer symmetric SRR (corresponding to $d>0 \ \mu m$), as a result of which, the outer ASRR represents a $\Lambda$-system.

Another dark state is introduced by placing the inner CSRR concentrically to the ASRR in the MM structure. The coupling between the ASRR and the CSRR structure leads to the evolution of the proposed MM structure into an analog of the FLT-system.

The energy level diagram of the FLT-system driven by three light fields $\Omega_p$, $\Omega_c$, and $\Omega_{c'}$ with the corresponding frequency detunings $\delta_p$, $\delta_c$, and $\delta_{c'}$, respectively.

FIG. 6. Energy level diagram of the FLT-system driven by three light fields $\Omega_p$, $\Omega_c$, and $\Omega_{c'}$ with the corresponding frequency detunings $\delta_p$, $\delta_c$, and $\delta_{c'}$, respectively.

The equation of motion of the FLT-system could be expressed as follows:

$$\frac{d\rho_{21}}{dt} = -\left[\gamma_{21} - i(\delta_p - \delta_c)\right]\rho_{21} + \frac{i}{2}\Omega_c^*\rho_{41},$$
$$\frac{d\rho_{31}}{dt} = -\left[\gamma_{31} - i(\delta_p - \delta_c)\right]\rho_{31} + \frac{i}{2}\Omega_c^*\rho_{41},$$
$$\frac{d\rho_{41}}{dt} = -\left[\gamma_{41} - i\delta_p\right]\rho_{41} + \frac{i}{2}(\Omega_p + \Omega_c\rho_{21} + \Omega_{c'}\rho_{31}).$$

where $\rho_{ij}$ is the off-diagonal density matrix element for the transition $|j\rangle \rightarrow |i\rangle$ (with $|j\rangle = |2\rangle$, $|3\rangle$, $|4\rangle$) and $\gamma_{ij}$ ($i,j = 2, 3, 4$) is the decay rates for the transition from $|j\rangle \rightarrow |i\rangle$. The corresponding frequency detunings are defined as $\delta_p = \omega_p - \omega_{41}$, $\delta_c = \omega_c - \omega_{21}$, and $\delta_{c'} = \omega_{c'} - \omega_{31}$, where $\omega_{21}$, $\omega_{31}$, and $\omega_{41}$ denote the energy-level transition frequencies. $\omega$ is the incident frequency and $\omega_p$, $\omega_c$, and $\omega_{c'}$ are, respectively, the resonant frequencies of the probe, the coupling, and the control fields.

For a steady state, Eq. (1) reduces to

$$\rho_{21} = \frac{\Omega_p^*\rho_{41}}{2[\gamma_{21} - i(\delta_p - \delta_c)]},$$
$$\rho_{31} = \frac{\Omega_c^*\rho_{41}}{2[\gamma_{31} - i(\delta_p - \delta_c)]},$$
$$\rho_{41} = \frac{i(\Omega_p + \Omega_c\rho_{21} + \Omega_{c'}\rho_{31})}{2[\gamma_{41} - i\delta_p]}.$$  

Then from Eq. (2), one can obtain the exact solution of $\rho_{41}$ as

$$\rho_{41} = \frac{-\Omega_p}{2i(\gamma_{41} - i\delta_p) - \frac{|\Omega_p|^2}{2(\gamma_{21} + \delta_p - \delta_c)} - \frac{|\Omega_c|^2}{2(\gamma_{31} + \delta_p + \delta_{c'})}}.$$  

The transmission amplitude for the FLT-system is given by the expression, $t(\omega) = 1 - Im(\rho_{41})$ as

$$t(\omega) = 1 - Im\left(\frac{\Omega_p}{2[\gamma_{21} + \delta_p - \delta_c]} + \frac{|\Omega_c|^2}{2[\gamma_{31} + \delta_p + \delta_{c'}]} - \frac{2i(\gamma_{41} - i\delta_p)}{2|\gamma_{41} - i\delta_p|}\right).$$

Using the expression given by Eq. (4) and through carefully tuning the Rabi frequencies and the decay rates of each transition, we can obtain a theoretical fit of the numerically simulated transmission. The theoretically fitted transmission for the FLT-system, shown in Fig. 7, is in good agreement with our numerical results represented in Fig. 3. When $d>0 \ \mu m$, the ASRR structure behaves as an analog of a $\Lambda$-system. In this case, the rotation of the CSRR structure acts as the dark/control field giving rise to the dual-band EIT effect in the FLT-system. This control field evolves due to the in-plane rotation of the CSRR in the MM structure which in turn modifies the coupling behavior in the FLT-system. This results in the diminishing of the dual-band EIT-like effect in the MM structure. Finally, for an orthogonal rotation of the CSRR, the dual-band EIT effect reduces into a single EIT effect [as represented by the orange line in Fig. 7(a)]
in our proposed MM. For this configuration, the FLT-system behaves as if the dark/control state is absent, reducing to a $\Lambda$-system. On the other hand, the $\Lambda$-system evolves into a FLT-system when the asymmetry in the ASRR is varied. The asymmetry parameter, in this case, acts as the dark/control state of the system when the asymmetry in the ASRR is varied. The asymmetry parameter intuitively explains the coupling behavior in the proposed MM structure.

**V. CONCLUSION**

The dual-band EIT effect in a terahertz metamaterial (MM) comprising an inner circular split ring resonator (CSRR) concentrically coupled to an outer asymmetric two-gap split ring resonator (ASRR) is numerically and theoretically analyzed. The proposed MM structure exhibits the effect as a result of coupling between the resonant mode of the CSRR and the EIT response of the ASRR. The coupling behavior in the MM is modified through an in-plane rotation of the CSRR structures. A gradual orthogonal rotation of the CSRR leads to the vanishing of the dual-band EIT effect in the MM. Modulation of the effect is further achieved by gradually varying the asymmetry of the outer ASRR as well as the size of the inner CSRR. A theoretical model based on a Four Level Tripod system intuitively explains the coupling behavior in the proposed MM geometry. Our study may be significant in realizing multi-band slow light devices, narrowband absorbers, switches, etc. in the terahertz regime.

**ACKNOWLEDGMENTS**

G.K. gratefully acknowledges the financial support from the Board of Research in Nuclear Sciences (BRNS), India (No. 34/20/17/2015/BRNS). D.R.C. gratefully acknowledges the financial support from the SERB, Department of Science and Technology, India (No. EMR/2015/001339). K.M.D. would like to thank MHRD, Government of India for a research fellowship.