Active control of electromagnetically induced transparency with dual dark mode excitation pathways using MEMS based tri-atomic metamolecules

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We report experimental results of the active switching of electromagnetically induced transparency (EIT) analogue by controlling the dark mode excitation pathways in a microelectromechanical system based tri-atomic metamolecule, operating in the terahertz spectral region. The tri-atomic metamolecule consists of two bright cut wire resonators (CWRs) on either side of the dark split ring resonators (SRRs). Each of the CWRs can independently excite the dark inductive-capacitive resonance mode of the SRRs through inductive coupling, and this allows for the dual pathways of dark mode excitation. The CWRs are made movable along the out-of-plane direction and electrically isolated to achieve selective reconfiguration. Hence, by controlling the physical position of these CWRs, the excitation pathways can be actively reconfigured. This enables the strong excitation of EIT analogue at 0.65 THz, only when one of the pathways is made accessible. Moreover, the transparency peak is completely modulated when both pathways are made either inaccessible or equally accessible. The proposed approach of realizing independent control of constituent resonators in a multi-resonator coupled system, enables the realization of efficient slow light devices and tunable high-Q resonators in terahertz spectral region. *Published by AIP Publishing.*
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Humans have always been fascinated with light and have explored various means to interact with and manipulate it, in terms of its intensity, phase, frequency, and velocity. This has enabled numerous disruptive technologies that have transformed human lives in unimaginable ways. One of such key advancement was the slowing down of light using cold atoms.[1–3] Controlling the velocity of light at desired spectral region and at room temperature would be a key technological milestone for the realization of next generation high-speed wireless communication systems operating at sub-terahertz frequencies.[4] Artificially engineered materials termed as "metamaterials," whose electromagnetic properties are primarily determined by their unit cell geometry, have greatly enabled research progress in the field of THz wave interaction and manipulation. The unparalleled advantage of metamaterial comes from its extreme scalability and ultrathin feature. Metamaterials have led to the demonstration of even exotic THz properties such as artificial magnetism,[5] negative refractive index,[6] unnaturally large refractive index,[7] wavelength selective absorption,[8] chirality,[9] and classical analogue of electromagnetically induced transparency (EIT).[10–13]

Recently, the classical analogue of EIT using planar metamaterials have been reported as the access route for the realization of slow light effects in THz spectral range.[12,13] EIT in metamaterial is achieved through near-field coupling between the strongly excited bright-mode and the weakly accessible/in-accessible dark-mode in the system, resonating at the same frequency. More interestingly, active control of EIT analogue has been demonstrated, and this provides an added dimension to the design and functionalities of near-field coupled resonator system. Active control of EIT in metamaterial is reported by either integrating active materials into the unit cell geometry that are controlled by the external stimulus or through structural reconfiguration of constituent resonator geometry. The dynamic control of EIT using active materials in THz metamaterials have been reported by utilizing either optical pumping of photoconductive materials,[14–18] or thermally controlled superconductors, that are integrated as a part of the resonator geometry.[19] Alternatively, structural reconfiguration of near-field coupled metamaterial have also been reported by integrating various types of microelectromechanical systems (MEMS) based microactuators into resonator geometry.[20–25] In either of these approaches, the metamaterial is formed by a bright and dark resonator configuration and active control of EIT analogue is achieved either by altering the bright/dark mode resonance frequency or the intra-atomic coupling distance between the bright-dark resonators. Near-field coupled multi-resonator systems open-up more avenues for exploring interesting coupling dynamics between numerous resonators

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that could aid in the development of advanced THz functionalities. One such feature of multi-resonator coupled system is the multi-path access route for accessing the dark mode resonance in a single metamolecule.[26] Active control of EIT analogue could be achieved by controlling these access routes that can indirectly excite dark mode resonances purely via near-field coupling from the neighboring meta-atom. However, this requires independent control of bright resonators within each metamolecule. Conventional approaches using active materials such as optical pumping of photoconductive elements or thermally controlled superconductivity are restricted to provide more of a global control. On the other hand, the electrically controlled out-of-plane reconfigurable microcantilever approach can enable isolation of controls at the sub-resonator level. This level of control isolation in microcantilever metamaterials has been exploited earlier for independent switching of electrical and magnetic response,[27] switching of bright and dark resonators,[24] complete control of anisotropy[28] and optical logic gate.[29]

In this paper, active switching of near-field coupling in a tri-atomic metamolecule by independently controlling the dual excitation pathways is experimentally demonstrated in the THz spectral region. The tri-atomic configuration consists of two bright cut wire resonators (CWRs) placed on either side of the dark split ring resonators (SRRs) and hence allows for dual pathway for the excitation of dark inductive-capacitive resonance (LC). The CWRs are made deformable in the out-of-plane direction under electrostatic force. Based on the physical position of the two bright CWRs, the respective access pathways to excite the dark LC resonance of SRRs can be switched. When both the pathways are closed, the EIT peak does not appear and when one of the pathways is opened, a strong EIT peak is observed. More interestingly, when both pathways are made accessible, the EIT peak again disappears. Hence, independent control of resonators in a multi-resonator coupled system provides interesting insights into coupling mechanisms and light-matter interactions in a more complex system, which enables the active control of EIT analogue in THz metamaterials. The active switching of near-field coupling will enable electrically tunable slow light and non-linear properties that are highly desirable for THz communication devices.

The MEMS tri-atomic metamolecule consists of two CWRs placed on either side of two SRRs as schematically shown in Fig. 1(a). Even though, there are four physical resonators in the metamolecule, we still term it as tri-atomic metamolecule because the two SRRs are identical and provide identical response. Here, the two SRRs are used to provide a stronger response than the single SRR case, however, the coupling mechanism remains unchanged and so we consider the two SRRs as one dark resonator system with enhanced resonance strength. The CWR to the left of the SRRs is termed as "CL" and the one to the right is termed as "CR." The SRRs are completely fixed to the substrate, while the CWRs are fixed at the center and are released along the edges from the substrate plane. The geometrical parameters of the MEMS tri-atomic metamolecule is shown in Fig. 1(b) and the resonance response of metamaterial is characterized in the transmission mode. The metamaterial is made of bilayer materials—500 nm aluminum (Al) on top of the 50 nm aluminum oxide (Al_2O_3) dielectric, fabricated on lightly doped silicon (Si) substrate using complementary metal-oxide-semiconductor (CMOS) compatible process.[30] Silicon-di-oxide (SiO_2) is used as the sacrificial layer, and the selective parts of the CWR are released by isotropically etching the SiO_2 layer by using vapor hydrofluoric acid. Upon release, the bimaterial cantilevers will curve upwards due to the residual stress between the Al and Al_2O_3 layers. This initial deformation can be engineered based on the length of the cantilever and the thickness ratio of Al and Al_2O_3 layers.[31] This additional deformation increases the air gap between the Si substrate and the released cantilevers. The fabricated MEMS tri-atomic metamaterial is shown in Fig. 2(a) and the out-of-focus from the center to the tip of CWRs can be clearly seen, thereby confirming the increased deformation of the released cantilever. Electrostatic actuation mechanism is used to achieve out-of-plane deformation of the released cantilevers, by applying voltage between the Al layer of the released cantilevers and the Si substrate.[32–34] Based on the input voltage, two states are defined as—OFF state, when no voltage is applied and ON state when the input voltage is higher than the pull-in voltage. After fabrication, the cantilevers are in OFF state and can be actively reconfigured to ON state by applying an input voltage of 30 V. The profile of the released cantilever in OFF and ON states are shown in Fig. 2(b). Furthermore, the electrical line connection to the two CWRs (CL and CR) are isolated from each other, and this allows for the independent reconfiguration of the CWRs. Hence, the MEMS tri-atomic metamaterial can be actively reconfigured to one of the three unique states: CL-OFF/CR-OFF, CL-ON/CR-OFF, CL-ON/CR-ON as shown in Figs. 2(c), 2(d), and 2(e), respectively.

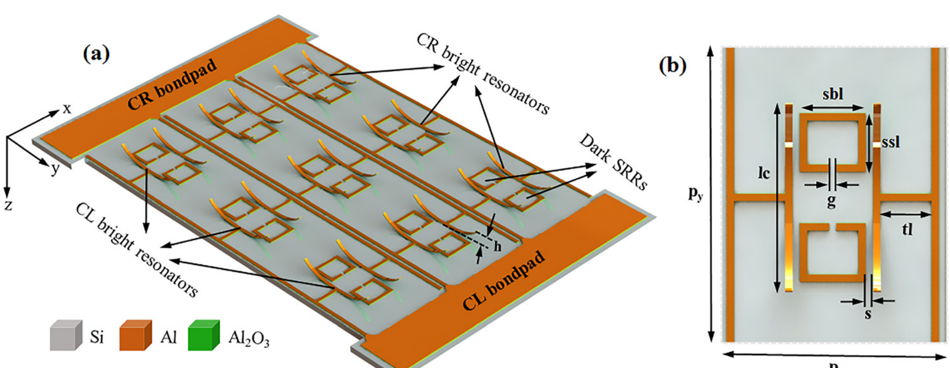

FIG. 1. Schematics of (a) MEMS tri-atomic metamaterial with selectively out-of-plane reconfigurable CL and CR bright resonators with fixed dark SRRs and (b) top view of the metamolecule with geometrical parameter definitions—Px = 100 μm, Py = 120 μm, lc = 90 μm, sbl = 29 μm, ssl = 29 μm, tl = 20 μm, s = 3 μm, g = 5 μm, and h = 4 μm, respectively.

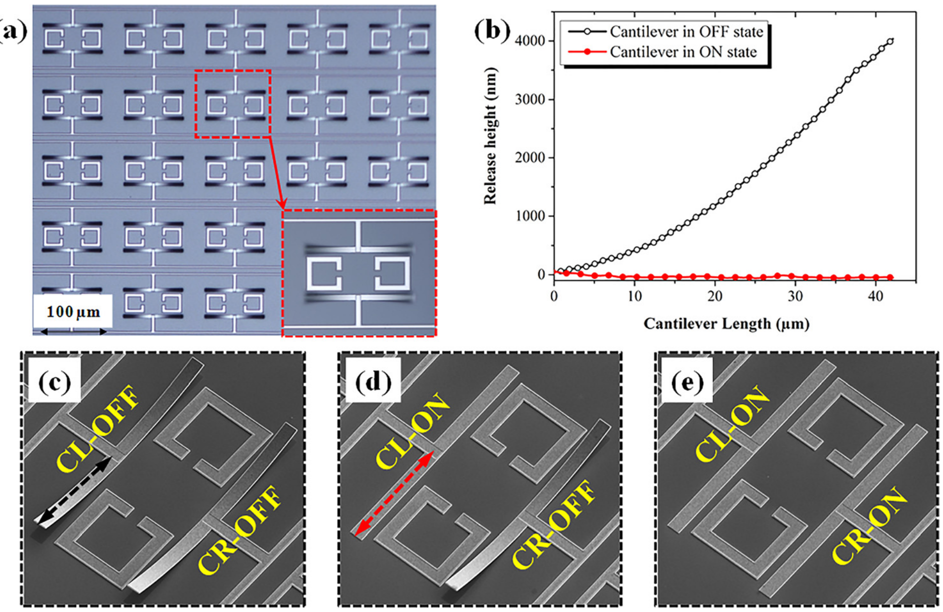

FIG. 2. (a) Optical image (OM) of the fabricated MEMS triatomic metamaterial after release step with inset showing the unit cell. The increasing out-of-focus from the center to the tip of bright resonators confirms the curving up of cantilevers upon release. (b) Measured cantilever profile of the bright resonator in OFF and ON state. Scanning electron microscope (SEM) image of the unit cell in various reconfiguration states—(c) CL-OFF/CR-OFF, (d) CL-ON/CR-OFF, and (e) CL-ON/CR-ON, respectively.

The incoming THz wave at normal incidence illuminates the metamaterial surface with the electric field polarization, along the length of the bright CWRs, i.e., along y-direction. This enables the direct excitation of dipolar mode resonance of the CL and CR resonators and hence are the bright mode resonators. But, for this polarization of THz incidence, the LC mode resonance of SRRs is not directly accessible and so acts as the dark mode resonance. However, the bright CWR can excite the dark LC mode resonance of the SRR by virtue of inductive coupling, thereby enabling the EIT peak to appear.[35] It is also important to note that the EIT excitation can be achieved only when the dipolar resonance frequency of CWRs matches with the LC resonance frequency of the SRRs. Systematic investigation of the coupling dynamics between the tri-resonator system was carried out through finite difference time domain (FDTD) simulations using Computer Software Technology (CST) Microwave studio. Al was modeled as a lossy metal with conductivity of 1×10^7 S/m, while Al_2O_3 and Si were modelled as lossless dielectric with dielectric constants of 9.5 and 11.9, respectively. In the simulation, a single metamaterial unit cell was simulated with periodic boundary conditions employed in axial directions orthogonal to the incident waves. The perfectly matched layers are applied along the propagation of the electromagnetic waves. Plane waves were incident onto the metamolecule from the port on the metal side, while the transmission spectrum was determined from the port placed at the other side of metamaterial. Firstly, the CWRs and SRRs are simulated independently. The dipolar resonance of single CWR (CL or CR) occurs at 0.67 THz for E_y incidence as shown in Fig. 3(a). The LC mode resonance of the SRRs was also designed to be at 0.67 THz for E_x incidence. The E_x scattering field was simulated to study the coupling mechanism when SRRs are placed at the two ends of the CWR. It can be seen that the E_x scattered field for CL resonator is negative at the top region and positive at the bottom region, where SRRs will be placed as shown in Fig. 3(b). However, the scattered E_x field for CR resonator is positive at the top and negative at the bottom as shown in Fig. 3(c). Following this, the coupled mode resonators consisting of single bright CWR (CL and CR) with SRRs were simulated separately. The simulated THz transmission responses were identical, when the SRRs were coupled with either CL or CR bright resonator as shown in Fig. 3(a). EIT peak is clearly observed at 0.63 THz and the surface current at this frequency reveals strong circulating currents in the SRRs for both CL and CR coupled cases as shown in Figs. 2(d) and 2(e), respectively. However, it is important to note that the direction of current induced in the SRRs for CL and CR bright resonators are totally out-of-phase. The circulating current in the SRRs are in anti-clockwise direction when excited with CL resonator, while the circulating current in

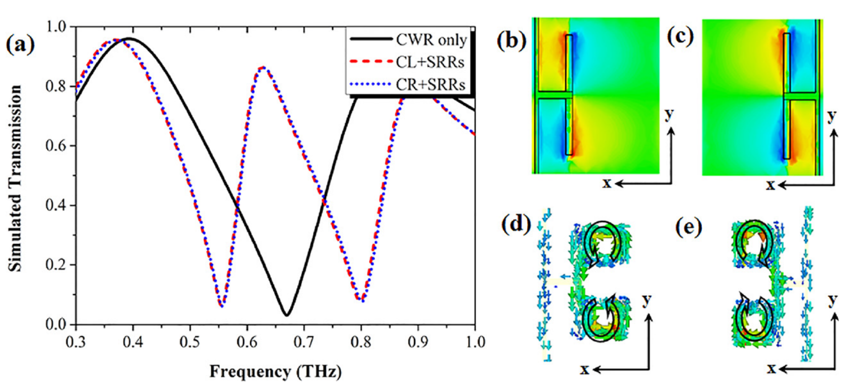

FIG. 3. (a) Simulated transmission response for Ey THz incidence of single cut-wire resonator (black-solid curve), CL resonator coupled with dark SRRs (red-dash curve) and CR resonator coupled with dark SRRs (blue-dot curve). Simulated Ex scattered field at 0.67 THz for (c) CL resonator and (d) CR resonance, respectively. Simulated circulating current in the SRRs at 0.63 THz showing the near-field excitation of dark LC resonance by the bright (d) CL resonator and (e) CR resonator, respectively.

the CR resonator excited SRRs are in clockwise direction. This is caused due to the difference in the phase of E_x scattered field of the CL and CR resonators that in turn excites the SRRs.

For the tri-atomic metamolecule configuration, the CL and CR bright resonators are placed on either side of the SRRs. The simulated transmission response of the tri-atomic metamaterial in various reconfiguration states is shown in Fig. 4(a). In the CL-OFF/CR-OFF state, a resonance dip is observed at 1.1 THz in the transmission spectrum. The simulated surface current at 1.1 THz, reveals the excitation of dipolar mode resonance in the CL and CR resonators in OFF state, as shown in Fig. 4(c). In the OFF state, the CL and CR cantilevers are released with an air gap between them and the Si substrate. This causes the effective out-of-plane capacitance of resonators to decrease. This decrease in effective capacitance, will therefore lead to the blue shift of resonance frequency for the CL and CR resonators.[36] Hence, in the OFF state, the dipolar resonance is blue-shifted to 1.1 THz from the ON state dipolar resonance frequency of 0.67 THz. Due to large mismatch between the bright dipolar resonance of the CL and CR resonators in OFF state, i.e., 1.1 THz and the LC resonance of SRR at 0.67 THz, the system is primarily in the uncoupled state. Hence, both the pathways for the excitation of dark resonance is inaccessible and so no EIT peak is observed for CL-OFF/CR-OFF state of the MEMS tri-atomic metamaterial. When one of the bright CWR resonators is switched, the metamaterial will be in CL-ON/CR-OFF or CL-OFF/CR-ON configuration. However, due to the mirror symmetry in both states, same response will be achieved, and hence is considered as the same reconfiguration state. When CL is selectively switched to ON state, while retaining CR in the OFF state, the respective dipolar resonances will be at 0.67 THz and 1.1 THz, respectively. Furthermore, the ON state dipolar resonance frequency of CL resonator matches with the dark LC resonance of SRRs and the pathway for exciting the dark resonance is opened. This leads to the transparency peak at 0.63 THz as shown in Fig. 4(a). The excitation of dark LC resonance of the SRR is evident from the induced circulating current in the SRRs at 0.63 THz as shown in Fig. 4(d). While, at 1.1 THz, the transmission dip is caused due to the direct excitation of the dipolar resonance in the OFF-state CR resonator and is clearly seen from the induced current along the CR resonator shown in Fig. 4(e). Similarly, the dark resonance can also be excited by the CR resonator in ON state, while the CL resonator is retained in OFF state. This allows for the dual pathway excitation of the dark resonance through near-field coupling to selective bright resonators. Finally, when both the CL and CR resonators are switched to ON state, the metamaterial will be in the CL-ON/CR-ON state. The dipolar resonance of CL and CR resonators in ON state is at 0.67 THz, which is identical to the LC resonance of the SRRs. However, a broad transmission dip is observed at 0.8 THz with no obvious transparency peak in the spectral region of interest. The simulated current configuration shows the strong excitation of dipole mode resonance in both the CL and CR resonators. In this state, both pathways for exciting the dark resonance have been made accessible. However, when both CL and CR resonators excites the dark LC resonance in SRRs, they are completely out-of-phase. Hence, the excitation of dark LC resonance by CL resonator will be totally cancelled by the excitation of same dark resonance by CR resonators. Hence, the EIT peak can be actively controlled based on switching the excitation pathways rather than the resonances itself.

THz time domain spectroscopy (THz-TDS) is used to characterize the THz transmission response of the fabricated metamaterial in different reconfiguration states. THz wave is incident normally on the sample with predetermined polarization (y-polarization). The measured transmission spectrum of the MEMS tri-atomic metamaterial at various reconfiguration states is shown in Fig. 4(b). In the CL-OFF/CR-OFF state of the metamaterial, a resonance dip is observed at 1.1 THz. When the CL resonator is selectively switched to

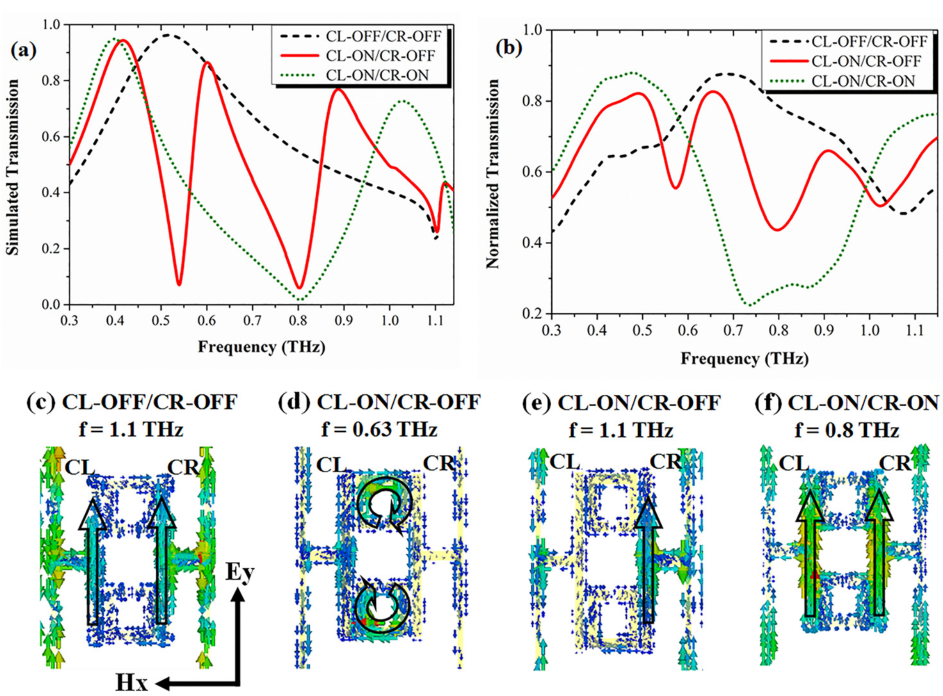

FIG. 4. (a) Simulated and (b) measured THz transmission response of the MEMS tri-atomic metamaterial in various reconfiguration states—CL-OFF/CR-OFF (black-dash curve), CL-ON/CR-OFF (red-solid curve), and CL-ON/CR-ON (green-dot curve), respectively. (c) Simulated surface current showing the excitation of OFF state dipolar resonance at 1.1 THz for CL-OFF/CR-OFF state, (d) simulated surface current at 0.63 THz for CL-ON/CR-OFF state, showing the strong excitation of dark LC resonance through near-field coupling of CL resonator, (e) Simulated surface current at 1.1 THz for CL-ON/CR-OFF state, showing the excitation of dipolar resonance in CR resonator and (f) Simulated surface current at 0.8 THz showing strong dipolar resonance in CL and CR resonators in CL-ON/CR-ON state, respectively.

ON state, an EIT peak appears at 0.65 THz, and the dipolar resonance of OFF state CR resonator is observed at 1.05 THz. Finally, when both the CL and CR resonators are switched to ON state, a broad resonance dip is observed due to overlapping of strong dipolar resonances from CL and CR resonators. The experimental results show a similar trend as the simulation results and the observed discrepancy between the simulated and measured results can be attributed to the non-uniformity of the release height of the cantilevers, undesirable substrate effects, fabrication errors, and errors due to incident polarization and the incident angle of the excitation field. The proposed approach of altering the excitation pathways provides a means of achieving active control of EIT analogue. Interestingly, the possibility of independently controlling individual resonators in a multi-resonator coupled system provides more freedom of design and advanced functionalities related to slow light effects,[12,37] non-linearity,[38] and high Q resonances[39–43] in THz spectral range.

In summary, a structurally reconfigurable tri-atomic metamaterial is experimentally demonstrated for active switching of electromagnetically induced transparency analogue by controlling the dual excitation pathways for accessing the dark resonance. EIT peak was excited at 0.65 THz, when the dark mode is accessible through only one of the pathways and was completely modulated when both the pathways were made either inaccessible or simultaneously accessible. The proposed approach provides much deeper insights into the near-field coupling dynamics between the multiple resonators in coupled systems and can be extended to high degrees of coupled resonator system. Electrical control, miniaturized size, and easier integration with ICs along with the possible versatility of resonators, make the MEMS based multi-resonator metamaterial as an ideal candidate for the realization of advanced THz functional devices.

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