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Active control of near-field coupling in conductively coupled microelectromechanical system metamaterial devices

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Active control of near-field coupling in conductively coupled microelectromechanical system metamaterial devices

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We experimentally report a structurally reconfigurable metamaterial for active switching of near-field coupling in conductively coupled, orthogonally twisted split ring resonators (SRRs) operating in the terahertz spectral region. Out-of-plane reconfigurable microcantilevers integrated into the dark SRR geometry are used to provide active frequency tuning of dark SRR resonance. The geometrical parameters of individual SRRs are designed to have identical inductive-capacitive resonant frequency. This allows for the excitation of classical analogue of electromagnetically induced transparency (EIT) due to the strong conductive coupling between the SRRs. When the microcantilevers are curved up, the resonant frequency of dark SRR blue-shifts and the EIT peak is completely modulated while the SRRs are still conductively connected. EIT modulation contrast of ~50% is experimentally achieved with actively switchable group delay of ~2.5 ps. Electrical control, miniaturized size, and readily integrable fabrication process of the proposed structurally reconfigurable metamaterial make it an ideal candidate for the realization of various terahertz communication devices such as electrically controllable terahertz delay lines, buffers, and tunable data-rate channels. © 2016 AIP Publishing LLC.

The ever-increasing demand for faster data rates is currently pushing the wireless communication to sub-terahertz frequencies.1,2 Slow light devices is a critical part in the development of various terahertz (THz) communication devices such as modulators, optical buffers, delay-lines, and tunable bandwidth filters. However, THz waves lie in the electronic and photonic realms of the electromagnetic spectrum and also greatly lack naturally occurring materials that would strongly interact with these waves.3

Artificially engineered materials known as metamaterials have aided in bridging the so called “THz gap” over the past decade.4–6 Interestingly, planar metamaterials have been reported to achieve classical analogue of electromagnetically induced transparency (EIT) phenomenon, which provides an access route for slow light behavior in a desired spectral region.7–12 EIT analogue in metamaterial is typically realized through the excitation of sharp radiative mode resonance in the dark resonator amid a broader absorption spectra of the bright resonator by virtue of near-field coupling. Active control of EIT analogue in metamaterial would enable tunable group-delay that is highly desirable for practical applications. One of three primary parameters in the near-field coupled metamaterials—bright mode resonance frequency, dark mode resonance frequency, or intercoupling distance between the resonators—can be altered to achieve active control of EIT bandwidth, intensity, and frequency. Earlier reports on active control of EIT analogue in metamaterials predominantly utilize optically controlled photoconductive materials that are integrated either into resonator geometry13,14 or intercoupling space15 or directly used as substrate or surrounding medium.16–19 Thermally controlled superconductors are also reported for active modulation of EIT analogue in planar metamaterials.20–22 However, the scalability of these tunable approaches are limited, owing to the frequency dependent material properties of the active materials. Also, some of these approaches demand for exotic materials that are difficult to process or require bulky experimental setup to provide control signals. Alternatively, microelectromechanical system (MEMS) based structurally reconfigurable metamaterials are proposed as the most straightforward and efficient means of achieving active control in THz metamaterials.23–31 The MEMS metamaterials are also reported for active control of EIT analogue in inductively coupled systems.32,33 The in-plane reconfigurable metamaterial is numerically studied to achieve active modulation of EIT analogue by continuously varying the intercoupling distance between the resonators,32 while the out-of-plane reconfigurable metamaterial with independent control of constituent resonators was reported to achieve both EIT modulation and spectral tuning.33 However, these reports are demonstrated for inductively coupled systems, where the resonators are coupled via near-field coupling across a small spatial gap. The strongest coupling occurs in conductively coupled resonator system,34 and active switching of conductive coupling between the resonators would enable high-performance slow light characteristics, which is critical for practical THz applications.

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In this report, active switching of near-field coupling in conductively coupled split ring resonators (SRRs) placed in orthogonally twisted fashion is experimentally demonstrated in the THz spectral region. The bright and dark SRRs are designed to have identical resonant frequency and hence enable the excitation of EIT analogue at 0.68 THz by virtue of conductive coupling of dark SRR to the bright SRR. Out-of-plane reconfigurable microcantilevers are integrated into the dark SRR geometry, which enables the active sweep of the dark mode resonant frequency. Due to the mismatch between the bright and dark resonant frequencies, the system switches from strongly coupled to uncoupled state, even when they are physically connected to each other at all times. The active switching of near-field coupling provides electrically tunable group delay, which are critical for development of THz communication devices.

The MEMS metamaterial unit cell consists of two conductively coupled SRRs that are orthogonally twisted with respect to each other as shown in Fig. 1(a). The bright SRR is completely fixed to the substrate, while the side arms along with the tip forming split gap of the dark resonator are released from the substrate plane to provide active reconfiguration. One of the side arms of bright SRR also acts as the base of dark SRR and forms the conductive path for electrical control signal to actively reconfigure the dark SRR cantilevers. The geometrical parameters of the SRRs are shown in Fig. 1(b).

The polarization of the incident THz wave is along the gap-bearing side of the bright SRR, i.e., along x-direction and hence enables the direct excitation of fundamental inductive-capacitive (LC) mode resonance of the bright SRR. However, for this polarization of THz incidence, LC mode resonance of dark SRR is not directly accessible. In order to achieve strong coupling between the resonators, the resonant frequency of the bright and dark SRRs should be identical. In the earlier reports using inductively coupled orthogonal twisted SRRs, the same geometrical dimensions are used for both SRRs. However, in our case, the resonant frequency of SRRs will be influenced by the routing lines and shared geometry with the other SRR. Detailed finite difference time domain (FDTD) simulations were performed using Computer Software Technology (CST) Microwave studio 2009 to ensure that the resonances of individual bright and dark mode resonator are identical and to elucidate the effect of sweeping the dark mode resonance away from the bright mode in the coupled system. The SRRs are made of bilayer materials – 500 nm aluminum (Al) on top of 50 nm aluminum oxide (Al2O3) on top of silicon (Si) substrate. Al was modelled as lossy metal with conductivity of $1 \times 10^7$ S/m. Al2O3 and Si were modelled as lossless dielectric with dielectric constants of 9.5 and 11.9, respectively. In the simulation, a single unit cell of the metamaterial structure 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 unit cell from the port on the metal side, while the transmission spectrum was determined from the port placed at the other side of metamaterial.

The bright SRR is built with the following geometrical dimension of base length ($b_{L}$) = 5 µm, side arm length ($s_{L}$) = 20 µm, and split gap ($g_{b}$) = 5 µm. The simulated transmission spectra for individual bright SRR with metal line are shown in Fig. 2(a) for incident THz waves with electric field polarized along the gap of the SRR. It can be seen that there is a strong resonance dip at 0.68 THz and the circulating surface current configuration shown in the inset confirms the excitation of the LC mode resonance. The geometrical parameters of the dark mode SRR were optimized to have the base length ($b_{D}$) = 20 µm, side arm length ($s_{D}$) = 25 µm, tip length ($l_{T}$) = 3 µm, and the split gap ($g_{D}$) = 3 µm in order to achieve the same resonance frequency as the bright SRR. The THz wave was incident with E field along the y-direction, which is along the gap bearing size of the dark SRR and the simulated transmission spectrum of dark with varying release angle of the microcantilevers is shown in Fig. 2(b). It can be seen that...
It can be observed that when the lightly doped silicon (Si) substrate using complementary
transmission peak amid the absorption spectrum at 0.68 THz. The strong circulating current in the dark SRR simu-
cantilevers at normal incidence with THz electric field polar-
SRR with the bright SRR. As the angle increases, the reso-
the bright SRR at the transmission dip at 0.68 THz as shown
in Fig. 3(c) confirms the direct excitation of LC mode reso-
the bright SRR on top of 50 nm aluminum oxide (Al2O3) fabricated
in air gap between the released cantilever and Si substrate (g0) to
be 2.2 μm, which is much higher than the sacrificial layer
thickness of 100 nm. The upward curvature of the released
cantilever can be clearly seen in the optical image of the fabric-
cantilever and Si substrate increases and causes the effective ca-
Hence, the proposed MEMS metamaterial provides an effi-
Underneath these structures. The residual stress in the
bi-material layers will cause the released cantilevers to curve
up in the out-of-plane direction, thereby increasing the initial
air gap between the released cantilever and Si substrate (g0) to
be 2.2 μm, which is much higher than the sacrificial layer
thickness of 100 nm. The upward curvature of the released
cantilever can be clearly seen in the optical image of the fabri-
cantilever and Si substrate. Therefore, the position of the mi-
cantilevers towards the fixed substrate. This physical deformation gener-
etrostatic force increases sharply compared to the restoring force. Hence, after a particular value of input
voltage called the “Pull-in voltage,” the electrostatic force
will be much higher than the restoring force, thereby forcing
the microcantilever to come in physical contact with Si sub-
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. The rest
state of the cantilevers after fabrication will be the OFF state,
where there will be an airgap between the released cantilevers
and Si substrate. When the microcantilevers are reconfigured
to ON states, the cantilevers are in physical contact with the
Si substrate. The deformation profile of the microcantilevers
is characterized using Lyncee Tec. Reflection Digital
Holographic Microscope. The 3D profile of the device in OFF
state confirms the out-of-plane deformation of released canti-
levers as shown in Fig. 5. The measured phase of the curved
up cantilever in OFF state and flat cantilever in ON state is
shown as insets in Fig. 5. The negative displacement in the
ON state corresponds to the thickness of sacrificial layer of
100 nm, which is removed during the release step.

THz time domain spectroscopy (THz-TDS) is used to
characterize the THz transmission response of the fabricated
metamaterial in different reconfiguration states. THz wave at
normal incidence interacts with the sample with predetermined

FIG. 3. (a) Simulated transmission response of conductively coupled MEMS metamaterial with varying release angle (θ) of dark SRR cantilevers. Simulated surface current at 0.68 THz for the conductively coupled MEMS metamaterial in (b) ON state and (c) OFF state, respectively.

FIG. 4. (a) Optical microscope (OM) image of the conductively coupled MEMS metamaterial with curved up cantilevers and (b) zoomed in OM image of conductively coupled MEMS metamaterial unit cell.
polarization (x-polarization). The released metamaterial chip is bonded to a printed circuit board with a hole of 1 cm x 1 cm in center. The bonded sample is then placed in the nitrogen-filled chamber of the THz-TDS setup. The dark SRR microcantilever is biased with positive potential, while Si substrate is kept as ground terminal. The measured transmission through fabricated MEMS metamaterial is then normalized with transmission through bare Si substrate of same thickness as the samples. The measured transmission spectrum at ON and OFF states of dark SRR is shown in Fig. 6(a). It can be observed that in the ON state, the EIT peak occurs at 0.69 THz which is completely modulated in comparison to the microcantilevers in the OFF state. The measured transmission spectra in ON and OFF states match quite well with the simulated data. EIT modulation of ~50% is experimentally achieved at 0.68 THz. The active modulation of the transmission properties of the coupled system is used to demonstrate the active control of the slow light behavior in the conductively coupled systems. The group delay for the pulses is given by \( \tau_g = -\frac{d\phi}{d\omega} \), where \( \phi \) is the phase and \( \omega \) is the angular frequency of the pulse. Fig. 6(b) shows experimentally measured group delay of the THz pulses propagating through the MEMS metamaterial in ON and OFF states, which depict the group delay of the THz pulse in the system. It can be seen that in the ON state, due to excitation of EIT, the group delay of ~2.5 ps is achieved, which disappears when the cantilevers are switched to OFF state. The delay band width product (DBP) defined as the product of maximum group delay and the spectrum bandwidth (DBP = \( \tau_g \times \Delta \omega \)) is calculated for the proposed samples. DBP is a figure of merit to determine the efficiency of the devices for telecommunication channels, where the maximum DBP implies that the device is more efficient to store and transmit the information through the signal channel. The measured DBP for the sample in the ON state is calculated to be 0.117 and for the OFF state the system shows complete absorption leading to the losses in the transmission channel. Thus, the information carrying bandwidth of a transmission network could be actively controlled that would enable an accurate control/modulation of the amount of information/bit volume through the telecom channel. Thus, the proposed MEMS metamaterial can be used as an active switch of DBP through the transmission line. This strong electro-optic performance achieved through active reconfiguration of conductively coupled resonators aids in the realization of efficient THz slow light devices. Furthermore, conductively coupled SRRs are proposed as a path to achieve high \( Q \) systems, and the proposed MEMS approach can be readily integrated into these metamaterials to provide tunable high \( Q \) factor devices, as well.

In summary, a structurally reconfigurable metamaterial is experimentally demonstrated for active switching of near-field coupling in conductively coupled resonators system. Complete modulation of EIT analogue was achieved through active sweeping of the dark mode resonance relative to the bright mode resonance. Electrically tunable group delay of 2.5 ps and active switching of delay bandwidth product is experimentally achieved. The proposed metamaterial is electrically controlled, highly miniaturized, and can be easily integrated with integrated circuits to provide active control signals. This makes the proposed MEMS metamaterial to be the ideal candidate for the realization of wide range of miniaturized slow light THz devices such as modulators, buffers, and optical delays.

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