Polarization dependent state to polarization independent state change in THz metamaterials

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We experimentally demonstrated a polarization dependent state to polarization independent state change in terahertz (THz) metamaterials. This is accomplished by reconfiguring the lattice structure of metamaterials from 2-fold to 4-fold rotational symmetry by using micromachined actuators. In experiment, it measures resonance frequency shift of 25.8% and 12.1% for TE and TM polarized incidence, respectively. Furthermore, single-band to dual-band switching is also demonstrated. Compared with the previous reported tunable metamaterials, lattice reconfiguration promises not only large tuning range but also changing of polarization dependent states, which can be used in photonic devices such as sensors, optical switches, and filters. © 2011 American Institute of Physics. [doi:10.1063/1.3664131]

Metamaterials are engineered materials with artificial unit cells which are typically patterned periodically with translational or rotational symmetry. With rational designs of the unit cell geometry and crystal lattice, metamaterials can have exotic optical properties such as negative refractive index, perfect absorption, and imaging with sub-wavelength resolution that may not be readily available in nature.1–4 These designable optical properties of metamaterials are essential for many practical applications such as invisible cloaking, super lens and perfect absorber, etc.5–8 However, most of the extraordinary optical properties rely on the strong resonance within or between the unit cells which leads to the narrow working band for many metamaterial-based devices.9,10

One of the solutions to circumvent the narrow-band problem is using tunable metamaterials which also have important applications in active devices such as modulators, optical switches and sensors, etc. Most of the demonstrated tunable metamaterials rely on tuning the compositing materials or changing the surrounding media11–13 which is highly dependent on the nonlinear properties of the nature materials. Although many nonlinear materials13–15 are available for laboratory experiments, the tunability and possibility for massive fabrication of the tunable metamaterials are still limited by their compositing materials. In other approaches, micromachined tunable metamaterials are reported to have reconfigurable unit cells via mechanical actuation.16–20 In this paper, we report here the active control of metamaterials by changing the lattice other than the gap within the unit cells which results in not only the resonance frequency shift but also changing the polarization dependence and switching from single band to dual band.

The terahertz (THz) metamaterials is constructed by metallic micro-rings with two dimensional (2D) rectangle-lattice array as shown in Fig. 1(a). The metallic micro-rings are chosen to be square with inner radius of 12 μm and outer radius of 18 μm. The metallic micro-rings are divided into two parts: movable rings and fixed rings which are patterned on every other line along the y-direction. The movable rings are located on the released part of the silicon frame (green) which is actuated by the comb drive actuators along the x-direction. The fixed rings are patterned on the isolated silicon islands (blue) which are anchored on the substrate (gray). The insert shows the cross view of the THz micro-ring metamaterials. In the initial state (Fig. 1(b)), the metallic micro-rings form a rectangle-lattice array with different period along x-direction and y-direction. The period along x-direction $P_x$ is 56 μm which is twice as length of the period along y-direction ($P_y = 28$ μm). The wave vector $k$ of the linear polarized incidence is perpendicular to the x-y plane (along z-direction), the polarization states of which are defined as TE (electrical field along y-direction) and TM (electric field along x-direction), respectively (Fig. 1(a)). The movable rings connected to the comb drive actuator can be actuated simultaneously from their initial position along x-direction. The displacements of the moveable rings are defined as lattice shift $S$ which is up to 28 μm (Fig. 1(c)). The lattice shift changes the surface current resonance of the metallic micro-rings and results in a shift of resonance dip frequency in transmission spectra. Figs. 1(b) and 1(c) show the contour map of the surface current intensity for TE polarized incidence at frequency 3.11 THz, which shows the surface current intensity is dependent on the lattice shift. The THz micro-ring metamaterials are designed to be purely electric16 so that the lattice changes affect the transmission spectra via changing the coupling effect of the electric dipole resonance between the adjacent micro-ring unit cells.

The structures of the THz metamaterials are fabricated in a silicon-on-insulator (SOI) wafer using the deep reactive ion etching (DRIE) processes.22 Fig. 2(a) shows the overview of the THz metamaterials using the scanning electron microscopy (SEM) technique.
microscopy (SEM). Two identical micromachined comb drive actuators driven by electrostatic force are placed on both sides of the unit cell array which is approximately 1 cm² in scale ($400^2$ to $200^2$). Each actuator provides bidirectional in-plane translation (along $x$-direction) following the actuation relationship $\Delta x = AV^2$, where $\Delta x$ is the displacement, $V$ the actuation voltage, and $A = 0.05 \, \mu m/V^2$ the actuation coefficient. The movable rings are patterned on the released part of the silicon frame which is actuated by the comb drive actuator along the $x$ direction. The fixed rings are patterned on the isolated silicon islands which are anchored on the substrate. The lattice pattern is shown in Fig. 2(b) when the lattice shift $S = 0 \, \mu m$ and $S = 28 \, \mu m$, respectively. The color represents the intensity of the surface current induced by the TE polarized light at frequency 3.11 THz.

To characterize the lattice shift effects of the fabricated THz metamaterials, the transmission at different lattice shift $S$ were measured using a Bruker Vertex 80v Fourier transform infrared (FTIR) from Bruker optics. Fig. 3 shows the transmission spectra for both TE (red solid line) and TM (blue dotted line) polarized incidence when the lattice shift is $0 \, \mu m$ (Fig. 3(a)), $14 \, \mu m$ (Fig. 3(b)), and $28 \, \mu m$ (Fig. 3(c)). Both TE and TM polarized incidence have one transmission dip when the THz metamaterials are not actuated ($S = 0 \, \mu m$). These transmission dips are caused by the coupled electric dipole resonance along the electric field ($y$-direction for TE and $x$-direction for TM) which are highly dependent on the lattice constant along the electric field. Larger lattice constant results in the lower resonance frequency. The lattice constant along $x$-direction ($56 \, \mu m$) is twice the length of that along $y$-direction ($28 \, \mu m$) which explains the transmission dip frequency for TE polarized incidence (2.48 THz) is lower than that of the TM polarized incidence (3.55 THz). When the lattice shift is $14 \, \mu m$, the lattice constant along the $x$-direction is still $56 \, \mu m$. The lattice is no longer rectangle due to the lattice shift which results in a red shift of the transmission dip (from 3.55 THz to 3.24 THz) for TM polarized light. For TE polarized light, the lattice shift results in two different consequences. First, the effective coupling distance between two adjacent micro-rings increases along the $y$-direction which results in the blue shift of the transmission dip (from 2.48 THz to 2.62 THz). Second, the couplings become nontrivial between the micro-rings from every other line which introduces another resonance dip at higher frequency region (3.38 THz). When the lattice shift is $28 \, \mu m$, the lattice constant for both TE and TM polarized light are equal to each other and results in the overlap of their transmission dips at 3.12 THz.
shows the high transmission region while the dark region shows the transmission dip. The transmission spectra of both TE and TM polarized light are numerically analyzed under the lattice shift from 0 μm to 28 μm. The transmission spectrum becomes polarization independent when the lattice shift is 28 μm which is proved by the continuity of the contour map at the interface (marked by white dashed line). The white circles represent the transmission dips measured in experimental results which show a good agreement with the simulation.

In conclusion, a polarization dependent state to polarization independent state change is experimentally demonstrated via reconfiguring the lattice of THz micro-ring metamaterials. In experiment, it measures a transmission dip shift from 2.48 THz to 3.12 THz for TE polarized light and a transmission dip shift from 3.55 to 3.12 THz for TM polarized light. It is also demonstrated a single band to dual band switching for TE polarized incidence. The micro-ring metamaterials can be switched from polarization dependent state to polarization independent state which can be potentially used in sensing, switching, and filtering at THz region.

Contour map of transmission coefficient for TE (left sided) and TM (right sided) polarized incidences is shown in Fig. 4, which illustrates the transmission dependence of the tunable metamaterial on lattice shift. The bright region shows the high transmission region while the dark region shows the transmission dip. The transmission spectra of both TE and TM polarized light are numerically analyzed under the lattice shift from 0 μm to 28 μm. The transmission spectrum becomes polarization independent when the lattice shift is 28 μm which is proved by the continuity of the contour map at the interface (marked by white dashed line). The white circles represent the transmission dips measured in experiment which show a good agreement with the simulation results.