POLARIZATION SELECTIVE TUNABLE FILTER VIA TUNING OF FANO RESONANCES IN MEMS SWITCHABLE METAMATERIALS

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ABSTRACT

We experimentally demonstrated polarization selective tuning of Fano resonance in switchable metamaterials based on Microelectromechanical systems (MEMS). The transmission spectra of TE polarized incidence can be tuned while maintain those of the TM polarized incidence by continuously shifting one trapezoid of the cross-shaped unit cell. It measures a Fano resonance frequency shift of 37.9\% (low frequency region) and 25.7\% (high frequency region) for TE polarized incidence and only 0.8\% for TM polarized incidence. Compared with the previous efforts on tunable metamaterials, the switchable metamaterials promises unprecedented tunability, such as single to dual band tuning, polarization selective tuning.

INTRODUCTION

Fano resonance is named after Ugo Fano who suggested the first theoretical explanation of the sharp asymmetric absorption spectra in atoms [1]. Nowadays, Fano resonances have been revealed in many classic and quantum systems [2-4] among which metamaterial is one of the best platforms to generate Fano resonances [4-6]. With rational designs of the unit cell geometry and crystal lattice, tunable metamaterials has merits, such as flexible working frequency band and large tuning range etc. [7, 8]. Furthermore, Fano resonances are asymmetric resonances which is possible to have a very sharp steepening in frequency spectra. Therefore, Fano resonances in tunable metamaterials have promising applications in high resolution sensors, optical switches and other active photonic devices.

However, Most of the demonstrated tunable metamaterials are tuned by changing the refractive index of the compositing materials or the surrounding media [9-11] which is highly dependent on the optical nonlinearity of the nature materials. Although many nonlinear materials [11-13] are available for laboratory experiments, the tuning range and possibility for massive fabrication of the tunable metamaterials are still limited by their compositing materials. Furthermore, changing the surrounding refractive index affects all the resonance modes in the tunable metamaterials simultaneously. Thus, it is not easy to selectively tuning the targeting resonance modes while maintain the rest. In our recent works, micromachined tunable metamaterials are reported to have reconfigurable unit cells via mechanical actuation [14, 15] which can tune the geometry of the unit cells without breaking the symmetry of the unit cell along the actuation direction. In this paper, we report here the active control of metamaterials by continuously shifting one trapezoid of the cross-shaped unit cell which results in selectively tuning of the Fano resonance modes.
The tunable metamaterial is constructed by cross-shaped unit cells with two dimensional (2D) square-lattice array (Fig. 1(a)). The cross-shaped unit cell structure consists of four trapezoid metal strips with the height $h = 11\, \mu\text{m}$, the longer parallel side $L_1 = 4\, \mu\text{m}$ and the shorter parallel side $L_2 = 1\, \mu\text{m}$ (Fig. 1(b~d)). The period of the square lattice $P$ is 28 $\mu\text{m}$. One of the trapezoid metal strips in each unit cell is supported by movable silicon frames (green) and driven by two MEMS comb drive actuators. The rest of the unit cell are located on the isolated islands (blue) fixed on the substrate. The movable trapezoid can be actuated along the y-direction with the shift distance $S$ ranging from 0 $\mu\text{m}$ to 5 $\mu\text{m}$. The incidence wave vector $k$ is perpendicular to the surface of the 2D square lattice array (normal incidence). The polarization state of the incidence is defined according to the orientation of the incidence electric field. TE and TM refer to the polarization states when the electric field is along (y-direction) and perpendicular to (x-direction) the actuation direction respectively. Insert shows the cross view of the unit cell. Fig. 1(b), Fig. 1(c) and Fig. 1(d) show the evolution of the unit cell when the movable trapezoid is shifted with the distance $S = 0\, \mu\text{m}$ (initial state), $S = 2.5\, \mu\text{m}$ (middle state) and $S = 5\, \mu\text{m}$ (final state) respectively.

Figure 2: Transmission spectra (derived numerically using CST microwave studio) of the MEMS tunable metamaterial for TE (red solid line) and TM (blue dotted line) polarized incidences when the shift distance is (a) 0 $\mu\text{m}$, (b) 2.5 $\mu\text{m}$ and (c) 5 $\mu\text{m}$.

Finite integration technology (FIT) is applied to simulate the transmission spectra of the tunable metamaterial under different shift distance which are shown in Fig. 2 for both TE (red solid line) and TM (blue dotted line) polarized incidence. Fig. 2(a) shows that the transmission spectra of both TE and TM polarized incidence are identical which is due to the 4-fold rotational symmetry of the cross-shaped unit cell at initial state. The Fano resonance dip for both TE and TM polarized incidence is at 2.45 THz. However, there are two Fano resonance dips for TE polarized incidence when the unit cell is changed to middle state (Fig. 2(b)) and final state (Fig. 2(c)). The Fano resonance dips at the middle state for TE polarized light are 2.70 THz (low frequency region) and 4.50 THz (high frequency region). The Fano resonance dip shift to 2.00 THz (low frequency region) and 4.21 THz (high frequency region) when the unit cell is changed to the final state.

Figure 3: Contour map of surface current under the excitation of different incidence frequency. The light color shows the high density of surface current and the arrows show the surface current flux direction. The initial, middle and final states are shown in (a) to (d) (first row), (e) to (h) (second row) and (i) to (l) (last row) respectively. The first and second columns show the Fano resonances under TE excitation. The third column shows the Fano resonances under TM excitation while the last column shows the coupled oscillators analogue of each state.

The contour maps of the surface current under the Fano resonance dip frequencies are calculated to further explain the origin of the Fano resonances of the tunable metamaterials. The light color shows the high density of surface current and the arrows show the surface current flux direction. The initial, middle and final states are shown in (a) to (d) (first row), (e) to (h) (second row) and (i) to (l) (last row) respectively. The first and second columns show the Fano resonances under TE excitation. The third column shows the Fano resonances under TM excitation.
excitation while the last column shows the coupled oscillators analogue of each state. In the initial state, the incidences excite the two trapezoid metal strips oriented along the E field (Fig. 3(a) and Fig. 3(c)). The coupled oscillators analogue is shown in Fig. 3(d) where each trapezoid is represent by one classic oscillator. The resonance is directly generated along the direction of the periodical forces (E field). The excited resonance modes can couple to the other two trapezoid strips and generated two dark modes which are out of phase to each other and results in zero net effect. The Fano resonance dips only appear at low frequency region since the two excited trapezoid is connected with each other and form a large resonator. At middle state, the two trapezoid strips along y direction are disconnected with each other which results in a blue shift of Fano resonance dip (Fig. 3(e)). Furthermore, TE polarized light also induces a dark mode resonance within the trapezoid along the x direction. The second Fano resonances arise at high frequency region (4.50 THz) due to the interference between the dark mode and the bright mode (Fig. 3(f)). At finial state, the movable trapezoid strip attached the rest of the unit cell from backside. The large metal strip results in a red shift of the Fano resonance in low frequency region for TE polarized incidence (Fig. 3(i)). Similarly, the resonance frequency of the bright mode is red shifted and results in the red shift of the Fano resonance at high frequency region. The shifting of the movable trapezoid has minor effects on the resonance induced by TM polarized incidence which results in similar Fano resonances along the x direction (Fig. 3(c), Fig. 3(g) and Fig. 3(k)).

EXPERIMENTAL RESULTS

Figure 4: Scanning electron microscopy (SEM) graph of the MEMS tunable metamaterial. (a) overview of the unit cells array and comb drive. (b) zoomed-in view of the cross unit cell (The metal part is highlighted with false color). (c) Folded flexure springs for the suspension of the released frame.

The structures of the tunable metamaterial are etched onto a silicon-on-insulator (SOI) wafer using the deep reactive ion etching (DRIE) process. Fig. 4(a) shows the overview of the MEMS tunable metamaterial using the scanning electron 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 × 400). Each actuator provides bidirectional in-plane translation (along x direction) following the actuation relationship, where Δx is the displacement, V the actuation voltage and A = 0.05 μm/V² the actuation coefficient. Fig. 4(b) shows a close-up view of the unit cells. The micro-ring unit cells are formed by patterning a 0.5-μm thick evaporated aluminum layer on the top of SOI wafer. The movable split rings are patterned on the central frame, which consists of many crossed narrow beams (3-μm width). The fixed split rings are patterned on the isolated anchors. Since each anchor encloses a larger area of underlying oxide layer than the frame, it needs much longer time to remove all the oxide under the anchor than that under the frame. The supporting frame is fully released and becomes freely movable while the anchor remains fixed on the substrate by controlling the release time.

Figure 5: Measured transmission spectra for TE (first column) and TM (second column) polarized incidence. The initial, middle and final states are shown in the first, second and last rows respectively.

To characterize the lattice shift effects of the fabricated tunable metamaterial, the transmission at different shift distance are measured using a Bruker Vertex 80v Fourier transform infrared (FTIR). Fig. 5

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shows the measured transmission spectra for TE (first column) and TM (second column) polarized incidence. The initial, middle and final states are shown in the first, second and last rows respectively. The inserts shows the schematic of the unit cells at different states. At initial state, the Fano resonance dip is measured to be 2.42 THz and 2.41 THz for TE and TM polarized incidence respectively (Fig. 5(a) and Fig. 5(b)). At middle state the measured Fano resonance dip are 2.65 THz (low frequency region) and 4.17 THz (high frequency region) under TE polarized incidence and 1.94 THz (low frequency region) and 4.17 THz (high frequency region), both of which are red shifted compared with the middle state (Fig. 5(e)). The variation of Fano resonance dip is within 0.02 THz (0.08% of resonance frequency region), both of which are red shifted compared with the middle state (Fig. 5(e)). The variation of Fano resonance dip is within 0.02 THz (0.08% of resonance frequency 2.39 THz) for TM polarized incidence.

CONCLUSIONS
In conclusion, a tunable metamaterial for polarization selective tuning of Fano resonance is designed, fabricated and experimentally demonstrated. In experiment, it measures a Fano resonance frequency shift of 37.9% (low frequency region) and 25.7% (high frequency region) for TE polarized incidence and only 0.8% for TM polarized incidence. It is also demonstrated a single band to dual band switching for TE polarized incidence. The tunable metamaterial can be switched from polarization dependent state to polarization independent state which can be potentially used in sensing, switching, and filtering at THz region.

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