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TUNABLE THZ FILTER BASED ON RANDOM ACCESS METAMATERIAL WITH LIQUID METAL DROPLETS

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ABSTRACT

Here we report a tunable THz filter based on random access metamaterial with liquid metal droplet, which is tuned through electrical bias controlled electrowetting effects. The random access metamaterial consists of 80×80 micro droplets, which are self-assembled in micro holes array due to lotus effect. The simulation results indicate resonant dip frequency shift of about 0.01 THz induced by changing of the droplets shape via electrowetting effect and about 0.6 THz frequency shift when the droplets are connected in different forms. The random access metamaterial is realized through simple fabrication processes and can be tuned easily, which has potential application on tunable filters, tunable beam steering and flat lens.

INTRODUCTION

Metamaterials, rationally designed artificial materials with sub-wavelength scale metal elements, offers a new platform to control the electromagnetic (EM) field with designable and controllable functionalities. These sub-wavelength elements, typically with metal involved, response to the electric and magnetic field simultaneously, which result in many extraordinary physic phenomena, such as negative index [1-2], zero epsilon [3], giant chirality [4], or exotic and useful hyperbolic dispersion anisotropy [5]. Furthermore, metamaterials response to certain spectrum range depending on the size of the sub-wavelength elements, which can be engineered to function at certain frequency range, such as THz region [6, 7], where nature materials are out of choice for practical applications. Metamaterials are recently attracting wide research attentions due to enhanced nonlinear switching [8] and light emission [9, 10] performance of conventional active materials. For example, metamaterials are suitable candidate for waveform manipulation [11] and can be used for extraordinary applications such as cloaking [12, 13], wave guiding and localization of light. Driven by the promising technical prospects, tunable metamaterials are widely studied to control the EM wave using MEMS systems [14], phase change materials [15] and liquid crystals [16].

Of all the technics applied to tunable metamaterials, the tuning flexibilities, such as tuning range and the switching of the resonance modes, are highly depended on how the sub-wavelength elements are modulated during the tuning process. On the other hand, changing the geometry of the

metal part of the sub-wavelength elements typically result in a dramatic EM properties change for the tunable metamaterials since the response of the metamaterials to the incident electric and magnetic fields are directly depended on the shape of the metal structures. Previous works on MEMS tunable metamaterials [17-18] target on the change of the geometry shape of the metal elements by changing the near field coupling of the metal parts anchored on the movable islands driven by micromachined actuators. However, it is difficult to reshape the metal structures once forged.

Liquid metal with sub-wavelength feature size are recently applied to tunable metamaterials due to their flexibility on reshaping the geometry [19]. This pioneer work involves complex microfluidic system for the tuning function. Although it offers an individual sub-wavelength element tuning without any metal contact, which can potential spoil the EM properties of the metamaterials and introduce extra losses, it still suffers many drawbacks due to the complexity of the system, which limit the tuning speed. Here an alternative technics electrowetting effects is applied for the tuning of the liquid metal structures as the metamaterials elements. In this paper, we demonstrated the experimental results on the shape tuning of the metamaterial elements both simultaneously and individually. Furthermore, the changes of the EM properties of the tunable liquid metal metamaterials are analyzed in the last section of this paper.

DESIGN OF THE METAMATERIALS

Figure 1 shows the schematic of the random access metamaterials, which consists of a square lattice array formed by mercury micro droplets with the period of 300 μm . The mercury droplets were confined in the holes, which are patterned on the 2.5-cm silicon substrate. The droplets array is formed by loading the mercury liquid on a silicon substrate with pre-etched cylindrical holes, which is then covered by a crystal quartz wafer on the top and make the mercury sandwiched in between. The mercury droplets array is thus formed and assembled by lotus effect. The electrowetting effects can be induced at the contact between the substrate and the mercury droplet through electrical bias. The electrowetting effect is used to control the radius of or the connection between the liquid droplets, which results in a reconfiguration of the droplet array. Therefore, the interaction between the incident THz wave and the droplet metamaterial can be manipulated in real time which tunes the resonance of the structure.

Figure 1: Schematic of random access tunable metamaterial for filter based on liquid metal micro droplets in terahertz regime.

The schematics and microscopic view of the mercury droplets manipulated by electrowetting effect are shown in Figure 2. Fig. 2(a) and Fig. 2(c) show the schematic and graphs of the droplet at initial state. The liquid metal droplets are formed by lotus effect and the silicon substrate is pre-etched with square-lattice cylinder holes array using Deep reactive-ion etching (DRIE) method. The holes are in the size of 240- μm in diameter and 50- μm in depth. When voltage is applied as shown in Fig. 2(b), the droplet is pulled down by electric field force created by the charged substrate, which is due to the electrowetting effect. This force tend to change the contact angle θ , which simultaneously enhance the contact area between the mercury droplet and the substrate by which means the radii of the droplet is changed as shown in Fig. 2(d).

Figure 2: Schematics of the mercury droplets manipulated by electrowetting effect with (a) uncharged, (b) charged substrate, respectively. Corresponding graphs of the mercury droplets (c) at initial state, and (d) controlled by means of electrowetting effect when voltage applied, respectively.

Figure 3: Top view of four mercury droplets connected with each other to form different type which was called (a) “::” type, (b) “||” type, (c) “L” type, and (d) “C” type. Numerical results of electrical field distribution with different type of connection (e-h).

The phenomenon of Electrowetting can be interpreted by Young-Lippmann equation [20]:

$$\cos \theta = \cos \theta_0 + \frac{C}{2\gamma} V^2 \quad (1)$$

where θ_0 is the initial contact angle, θ is the contact angle when voltage V applied, γ is the mercury surface tension, C is the areal capacitance of the substrate.

The resonant frequency can be effectively tuned through the droplet radius control, while the tuning range is limited. Therefore, we further explore an alternative approach which realizes a large frequency tuning through the droplet manipulation as shown in Fig. 3. The silicon holes are etched with the size of 80- μm in diameter and 20- μm in depth. In this case the droplets are shaped in cylinders and can be connected as “::” type (Fig. 3(a)), “||” type (Fig. 3(b)), “L” type (Fig. 3(c)), and “C” type (Fig. 3(d)). The corresponding electrical field distribution are shown in Fig. 3 (e)-(h).

ANALYSIS OF THE EM RESPONSE

Figure 4(a) shows the numerical analysis of the transmission spectra at different radii of the mercury droplets. The resonant dip frequency is observed in the THz regime and shifts to the higher frequency region when the radii of the mercury droplets are increasing. The electrical field intensity of the structure is numerically investigated using CST microwave studio as shown in Fig. 4 (b-e). The droplet is modeled as a sphere for $r = 80 \mu\text{m}$ and an ellipsoid for $r = 90, 100, 110$ and $120 \mu\text{m}$ with the same volume. For comparison, electrical field intensity at non-resonant frequency (Fig. 4 (b) and (d)) and resonant frequency (Fig. 4(c) and (e)) are both plotted. Common dipole resonance is observed on the droplet at the non-resonant frequency, which is simply due to the incident linear electrical field. On the other hand, strong electrical field energy is confined in the space between the droplet and the substrate, which forms a resonant cavity and induces the absorption peak.

Figure 4: Numerical analysis of (a) the transmission spectra at different radii of unit cell and the electric field with different resonant mode at radii of $80 \mu\text{m}$ ((b), (c)) and $120 \mu\text{m}$ ((d), (e)).

The numerical analysis of the dip frequency at different connection type is shown in Fig. 5. The dip frequency is strongly decreased when the connection length increases. This tuning method achieves a 0.6 THz frequency shift which is much larger than the tuning method of radius control. This phenomenon can be interpreted by Fig. 6(a-d), which present the surface current of different connection types. In the “:” type (Fig. 6(a)), the surface current indicates a dipole

Figure 5: Numerical results of dip frequency at different connection type.

Figure 6: Numerical results of surface current at different connection type.

resonance on each isolated droplets. The small radius of the droplets results in a high resonant frequency at 0.735 THz. When two droplets are connected (Fig. 6(b)), the “:” type droplets is reshaped into a “||” type structure. The surface current flows along the bridge between two droplets, where an electrical dipole is excited and a lower frequency at 0.35 THz is induced compared with the isolated droplets. On the other hand, the “:” type droplets can be connected into “L” type, as shown in Fig. 6(c), the surface current of which flows along the two connected bridges when interact with the linearly y -polarized incident light. The resonance frequency is then decreased to 0.185 THz. Furthermore, in the reconfigured “C” type metamaterial, the resonant frequency is decreased to 0.118 THz. Therefore, large frequency shifting is realized.

CONCLUSIONS

In conclusion, a THz random access metamaterial based on mercury droplets is designed, fabricated and experimentally demonstrated. In the experiment, the radii of each droplet are tuned from 80 μm to 120 μm , while the dip frequency is tuned from 0.342 THz to 0.349 THz. Furthermore, we also demonstrate a new tuning method by connecting the droplet, and the dip frequency is tuned from 0.75 THz to 0.118 THz, which has potential application on tunable filters, controllable beam steering and tunable flat lens.

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