TUNABLE METAMATERIALS FOR TERAHERTZ ULTRA-BROADBAND ABSORPTION DRIVEN BY MICROFLUIDICS

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ABSTRACT

A THz ultra-broadband absorber is realized using tunable metamaterials driven by a microfluidic system. In this work, a new technology is developed to precisely and continuously control the height of micro liquid pillars. Based on this technology, a proof-of-principle demonstration of tunable THz absorber is shown to have absorption frequency tuning from 0.245 THz to 0.415 THz with a tuning range of 51.5%. It creates a new paradigm for active metadevices based on tunable metamaterials with promising applications in detectors, sensors, imaging systems and stealth.

INTRODUCTION

Metamaterials, or rationally designed artificial materials with sub-wavelength scale elements, offer a fantastic platform to control and manipulate the electromagnetic (EM) waves. The sub-wavelength elements, typically metallic patterns, can respond to both the electric and the magnetic fields. Many extraordinary physical phenomena are then induced, such as negative index [1], cloaking [2], zero epsilon [3], giant chirality [4], or exotic and useful hyperbolic dispersion anisotropy [5]. Furthermore, since the metamaterial responded frequency highly depends on the size of the sub-wavelength elements, the EM wave of different frequencies can be effectively modulated. Compared to natural materials, metamaterial also has the advantage of real-time dynamically tunable for EM wave modulation. Tunable metamaterials are widely studied using micro electro mechanical system (MEMS) [6-8], phase changing materials [9] and liquid crystals [10].

In the previous tunable metamaterials [11-13], the tuning flexibilities, such as the tuning range and the resonant mode switching, are highly dependent on how the sub-wavelength elements are modulated during the tuning process. Among different tuning mechanisms, changing the geometry of the metallic structure of the sub-wavelength element typically results in a dramatic change in the EM properties since the electric and magnetic responses of the metamaterial are directly dependent on the element shapes and dimensions. Previous works on MEMS tunable metamaterials [14-15] 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 which are driven by micromachined actuators. However, the intrinsic dimensions of the resonant structures are not changed and it is difficult to reshape the metal structures once they are forged, which significantly restricts the tuning range of the metamaterial properties.

Liquid metals with sub-wavelength feature size are recently utilized to construct tunable metamaterials due to their flexibility on reshaping the geometry [16-17]. This pioneer work used a complex microfluidic system for the tuning function. Although it offers individual sub-wavelength element tuning without any metallic electrode contact that can potentially spoil the EM properties of the metamaterials and introduce extra losses, it still suffers many drawbacks due to the complexity of the system and limited tuning speed. Here, an alternative technique is applied to tune the heights of metal liquid for the THz wave absorption. Based on this technique, a tunable absorber is designed with simple fabrication processes and control systems.

DESIGN AND THEORY

The tunable absorber based on microfluidic metamaterial consists of four closed mercury pillars (Figure 1a) whose height can be tuned simultaneously through microfluidic technique. The metamaterial chip consists of three layers. A 100-µm thick silicon layer with penetrated holes is sandwiched between two polydimethylsiloxane (PDMS) layers. The liquid reservoir and air control channel are designed separately in the top and bottom PDMS layers. The mercury in the reservoir functions as a metal mirror, which will block all the transmission of the THz light. The reservoir also offers a buffer for mercury to be sucked into the silicon holes by expelling air from the top PDMS layer (300-µm height) such that the mercury pillars will be formed (Figure 1c). Since the mercury pillars are connected with each other by the reservoir, the heights of the mercury pillars will be kept at the same level due to the principle of the communicating vessels. The heights of the mercury pillars can be tuned by injecting air from the top PDMS layer (Figure 1d). By applying different air pressures, the height of the mercury pillars can be tuned at will.
Figure 1: (a) Schematic of tunable absorber based on microfluidic metamaterials. (b) Sandwiched structure of absorber. (c) Liquid metal pillars formed by injecting liquid metal. (d) Height of the pillars can be tuned by injecting different air pressures.

The fabrication of the PDMS is based on the soft lithography processes. A 6-inch silicon is cleaned using a piranha solution (H₂SO₄ + H₂O₂) and spin coated with a 50-μm SU-8 photoresist (MicroChem, SU-8 50) at 2000 rpm for 30 s using a spin coater (CEE, 200). The silicon substrate is soft baked using a hot plate at 65°C for 6 min and 95°C for 20 min. The substrate is then exposed to UV light for 30 s under the plastic mask using a mask aligner (OAI, J500-IR/VIS). The post expose bake is performed at 65°C for 1 min and 95°C for 5 min after the exposure. The SU-8 layer, which is used as the master of the PDMS channels, is developed using the SU-8 developer (MicroChem) for 6 min. The PDMS channels are fabricated using the replica molding, which is the casting of PDMS prepolymer against a master and obtaining the negative replica of the master. Two masters with different patterns are fabricated for the top and bottom PDMS layers, respectively. There are altogether two PDMS layers. One layer with microchannels patterned of fishnet-like channels for the injection of the air and one layer with a reservoir for the store of the metal liquid.

Figure 2 shows the photograph of the microfluidic metamaterial based tunable absorber. Figure 2a shows the top view of the PDMS layer, which is fabricated by the soft lithography as stated before. The structure of the top PDMS layer is designed as fishnet-like structure, which will connect all the silicon holes together. The width of the fishnet-like air channel is 25 μm, which allows air to flow and restrict the mercury to be injected inside. Figure 2b shows the top view of silicon layer. The penetrated silicon holes are fabricated by using the deep reactive ion etching processes. The original thickness of the silicon wafer is 725 μm. By using the deep reactive ion etching processes, a periodic hole with 150 μm depth are etched. Then, by using Backgrinder machine, the silicon wafer is grinded to 100-μm in thickness, such that the silicon holes are penetrated. The radii of the silicon holes are 50 μm. Finally, the silicon layer and the two PDMS layers are bonded together by using plasma bonding as shown in Figure 2c.

RESULTS AND DISCUSSION

In the simulation(CST Microwave Studio™), mercury is modeled with high electrical conductivity $\sigma = 1.04 \times 10^6$ S/m. Silicon is modeled as a loss free dielectric with the real part of the permittivity $\varepsilon_r = 11.9$. PDMS is modeled as a lossy dielectric, whose real and imaginary part of complex permittivity can be derived from the reference [18].

In the design, each unit cell consists of four individual metal pillars. The adjacent pillars allow the surface current to flow and create magnetic plasmon resonance. In order to realize the dynamic control of absorption frequency, we manage to tune the effective length of the magnetic plasmon resonance by tuning the heights of the pillars. The fishnet-like structures of the control channels allow all the mercury pillars connect to each other by air, which ensure identical pressure exerts on the top of the mercury pillars and the height of the mercury pillars will be tuned identically. The tuning process has been discussed in Figure 1. By applying different air pressures, the height of the mercury pillars will be changed from 0 μm to 100 μm, subsequently, the effective length of the magnetic plasmon resonance will be changed. In this way, one can realize a wide tuning range of the absorption peak frequency.
Simulation and experimental results give the absorption at the peak frequency with $h = 20\, \mu m$. The simulation results of the magnetic absorption at $h = 20\, \mu m$ to $68\, \mu m$ are in good agreement with the experimental results. Figure 3 shows the polarization independent feature of the tunable absorber based on microfluidic techniques, which mainly due to the in-plane rotation symmetry of the metamaterial. Figure 3a shows the absorption spectra with the TE mode (left figure) and TM mode (right figure) when the height of the pillars remained at $50\, \mu m$. The red lines and blue dots represent the simulation and experimental results, respectively, which have an absorption peak at $0.325\, THz$ and both results are in good agreement. Figure 3b shows the magnetic field distribution at the absorption peak frequency of $0.325\, THz$. The positive and negative signs indicate the electric charge distribution on the top of the liquid metal pillars. The adjacent liquid metal pillars will form an LC resonance along the height of the pillars between the gap. Therefore, a strong magnetic hot spot appears in the gap, which gives rise to high absorption of the EM wave.

Figure 4 shows the broadband tunability of the tunable absorber based on microfluidic metamaterials. Figure 4a shows the experimental results of the absorption spectra. Different colors of lines indicate the spectrum at different pillar’s height. The height of the metal pillars can be tuned by air pump from the top PDMS layer. When the height of the pillars is tuned from $20\, \mu m$ to $68\, \mu m$, the absorption frequency can be tuned from $0.245\, THz$ to $0.415\, THz$. The tuning range of the central frequency can be reached to $51.52\%$. The simulation results of the magnetic distribution when the height of the pillars keeps at $20\, \mu m$ are shown in Figure 4b. Compared to the magnetic distribution in Figure 3b, it is shown that the effective length of the magnetic plasmon resonance is decreased, and the magnetic hot spot become smaller.

**CONCLUSIONS**

In conclusion, a polarization independent and ultra-broadband tunable absorber with wide incident angle based on microfluidic metamaterial in THz is designed, fabricated and experimentally demonstrated. In the experimental results, the height of the mercury pillars can be tuned from $0\, \mu m$ to $100\, \mu m$ by air pump tuning method, while the absorption peak frequency can be tuned from $0.245\, THz$ to $0.415\, THz$ with over $90\%$ absorption efficiency. The tuning range of the central frequency reaches to $51.5\%$. This work shows a new way to innovate meta-devices with sophisticated tunability for applications in detector, sensor, imaging system and stealth, just to name a few.

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REFERENCES


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