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TUNABLE META-FLUIDIC-MATERIALS BASE ON MULTILAYERED MICROFLUIDIC SYSTEM

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ABSTRACT

We demonstrate a multilayered microfluidic system with a flexible substrate, which has tunable optical chirality within THz spectrum range. The optical properties of the multilayered microfluidic system can be tuned by either changing the liquid pumped into each layer or stretching the flexible substrate. In experiment, the polarization rotation angle is tuned from zero (non-chiral structure) to 16.9° (strong-chiral structure). Furthermore, the tuning resolution can be well controlled due to the fine refractive index change of the liquid with different concentrations. It is feasible for the multilayered microfluidic structure to be integrated to an optofluidic system, where strong or tunable optical chirality are needed, which not only can be used as traditional optical components such as THz polarizers and filters but also has potential applications on imaging and sensor of bio-materials.

INTRODUCTION

The concept of artificial materials, such as metamaterials and photonic crystals, has created a platform of new functionalities of devices, which can manipulate light across the entire electromagnetic spectrum. The extraordinary optical properties of artificial materials, such as negative index [1-3], zero epsilon [4] and giant chirality [5] arise from their sub-wavelength elements, which are both designable and controllable for different applications. Artificial materials, such as metamaterials, are now widely studied for the enhanced nonlinear switching [6, 7] and light emission performance over conventional active materials. Furthermore, the possibilities on waveform manipulation and cloaking have promising potential in vast applications, which cannot be realized using materials already existed in nature. Those thrilling technological prospects have stimulated a wide search for developing artificial materials with tunable and switchable properties using MEMS, phase change media, liquid crystal, magnetic media and superconductors [8-12]. However, the tunabilities of the artificial materials are still limited by the nature materials, which are used to fabricate the sub-wavelength elements. Previous works on structural reconfigurable metamaterials, manage to gain the tunabilities from varying the near field coupling of the metal structures [13-16]. However, the tuning range is still limited since the metal structure cannot be changed once fabricated.

Microfluidics systems have been intensively studied for inkjet print heads, DNA chips, lab-on-a-chip technology and micro-propulsion applications. The

concept of digital microfluidics, the formation and control of nano litter droplets, offers great opportunities in particle Lab-on-a-chip applications, such as bio-imaging, sensor and particle sorting. Although the demands for new functional materials of above mentioned applications are increasing, the possibilities of developing functional materials using microfluidics systems have never been explored, which is mainly due to the low contrast ratio of the fluidics refractive index. The liquid metal, on the other hand, can be used to construct functional materials when patterned and controlled by using the microfluidic systems. Different from the solid state metal structures, the geometry of the sub-wavelength liquid metal elements can be redefined by the valves and pumps via microfluidic channels, which offers more flexibility in the dynamic control of the functional materials properties.

MICROFLUIDIC SYSTEM DESIGN

Figure 1: Schematics of the microfluidic system. (a) the working principle of the tunable optical chirality of the multilayered microfluidic system. (b) the polarization rotation due to the change of the liquid in the micro channels (purple).

Figure 1 shows the schematic and working principle of the microfluidic system, which consists of two layers of “S” shaped microfluidic channels separated by a 100- μm Polydimethylsiloxane (PDMS) layer. This microfluidic system is designed as a THz chiral material with tunable polarization rotator function. The microfluidic channels are all connected together at the inlet and outlet points, where the liquid can be pumped in and out, respectively. A via hole can be used to connect the outlet of the top layer and inlet of the bottom layer if both layers are designed to be pumped with identical liquid, as shown in Fig. 1(a). In this paper, we don’t use the via hole since only the liquid in the top layer need to be changed during the tuning of the polarization rotator. The S-shaped microchannels on the top layer and the bottom layer are identical but perpendicular to each other. Once pumped with liquid metal, each single layer of the microfluidic systems are planar metamaterials, which cannot be superimposed on its in-plane mirror image. However, these planar metamaterials still possess mirror symmetry for the mirror parallel to the plane and require tilted incidence to achieve the chiroptical effects.

Figure 2: Photographs of microfluidic systems. (a) The over view graph of the microfluidic system with flexible substrate. (b) and (c) The SEM graph of the over view and cross section of the system. (b) shows the overview SEM graph of the top layer microfluidic channels. (c) shows the cross section of the bi-layer microfluidic system (d) and (e) the microscope graph of the polarizer taken at different focus distance F . (d) shows the top layer graph ($F = 175 \mu\text{m}$). (e) shows the bottom layer graph ($F = 375 \mu\text{m}$).

Although the out-of-plane mirror symmetry can be broken by adding a substrate to the microfluidic system, the achieved chirality is inevitably low in these metamaterials due to the weak magnetic responses. Therefore, another layer of microfluidic channels is added to the system to achieve strong chiroptical effects with the out-of-plane mirror symmetry broken by the 90-degree rotated microchannels at different layers. However, the microfluidic system is a non-chiral structure with plain mirror symmetry when pumped with identical liquid. The symmetry can be broken by pumping the top and bottom layers with different liquid. Furthermore, the out-of-plane symmetry of the microfluidic system can be changed by pumping the liquid with different refractive indexes to the front layer, which can be used for the tuning of the optical chirality.

The fabrication of the microfluidic system is based on the polymer soft lithography technique. The designs of the microfluidic channels of each PDMS layers are drawn using a computer-aided design (CAD) program (L-Edit). A dark field clear feature plastic mask is fabricated based on the CAD drawing. A 6-inch silicon is cleaned using a piranha solution ($\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$) and spin coated with a 50- μm SU-8 photoresist (MicroChem, SU-8 50), which is achieved by spinning coat the photoresist at 2000 rpm for 30 s using the spin coater (CEE, 200). The silicon substrate is soft baked using a hot plate at 65°C for 6 mins and 95°C for 20 mins after the spin coating. Then, the substrate is exposed to UV light for 30 s under the plastic mask using the mask aligner (OAI, J500-IR/VIS). The post expose bake is performed at 65°C for 1 min and 95°C for 5 mins 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 mins. The PDMS channels is fabricated using the replica molding, which is the casting of PDMS prepolymer against a master and obtaining the negative replica of the master. Three masters with different patterns are fabricated for metamolecules array layer, air pumping channels layer and the control panel layer, respectively. There are altogether 3 PDMS layers. Two layers with microchannels and one layer without any pattern as the substrate. The microfluidic system is fabricated by plasma bonding the three PDMS layers.

Figure 2 shows the graphs of the multilayered microfluidic system with flexible substrate. The micro channels are 20- μm wide and the total thickness of the microfluidic system is approximately 500 μm while the foot print of the microchannels region is 1 cm $\times$ 1 cm. Fig. 2(b) and Fig. 2(c) show the SEM graphs of top view and cross section of the microfluidic system, respectively. The cross section view is taken by cutting the microfluidic system into two pieces from the microchannel region. The microchannels are highlighted with pink color. The channel spacing within and between the layers is 250 μm and 200 μm , respectively, as shown in Fig. 2(c). Photographs of the microfluidic system with different focus lengths show that the top and bottom layer are perpendicular to each other. Fig. 2(d) and 2(e) shows the graph of the top and bottom layer, which are 175 μm and 375 μm from a reference plane. Therefore, the vertical spacing is approximately 200 μm between the top and bottom PDMS channels.

RESULTS AND DISCUSSIONS

Figure 3: Numerical simulation of the transmittance phase delay under different polarization states. The insert shows the electric field concentration at the top and bottom layers of the multilayered metamaterial, which shows the polarization rotation due to the rotation of the resonance modes.

Figure 3 shows the numerical analysis of the transmittance phase delay under different polarization states for the microfluidic system. The magenta and navy blue lines represent the phase delay of right and left circular polarized lights, respectively, which show large difference at 2.56 THz.

The optical activity is defined as polarization azimuth rotation of elliptically polarized light

$$\theta = (\Phi_L - \Phi_R)/2 \quad (1)$$

where Φ_L and Φ_R are the phase change of the left and right circular transmittance, respectively.

The insert shows the electric field distribution at the top and bottom layers of the microfluidic system when the microchannels of the top and bottom layer are filled with air and mercury, respectively. The rotation of the resonance modes indicates the rotation of the polarization states.

Figure 4: Experimental results showing the change of the rotation angle due to the pumping of different liquid into the micro channels of the top layer of the metamaterial. The polarization rotation decreases when the concentration of the sodium chloride solution is increasing.

The circular transmittance, Φ_L and Φ_R , is difficult to measure due to the lack of corresponding polarizer in THz region. In experiment the phase and amplitude of linear polarized light are measured using TeraView Spectra 3000 and the results are converted to the circular polarized light using the method as shown in [17]. Dry air is supplied in the measuring chamber to dispel water in atmosphere, which has large absorption in terahertz regime.

Figure 4 shows the experimental results of the rotation angle θ as the function of the concentration of sodium chloride solution within the top layer. The left circular polarized incident light is at 2.56 THz. The bottom layer is pumped with mercury. The polarization rotation angle is tuned from 16.9° to 0°.

CONCLUSIONS

In conclusion, a microfluidic system with tunable optical chirality is designed, fabricated and demonstrated. The microfluidic system is 500 μm in thickness, which is approximately 2.5 times of the working wavelength. In experiment, it measures a large tunability in optical chirality, which has potential applications not only on traditional optic components such as THz polarizers and filters but also on imaging devices and sensor of bio-materials.

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