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Tunable Meta-Liquid-Crystal Based on Mercury Microdroplets

Q. H. Song\textsuperscript{1,2}, W. M. Zhu\textsuperscript{2}, W. Zhang\textsuperscript{2}, E. M. Chia\textsuperscript{3} and A. Q. Liu\textsuperscript{1,2}†

\textsuperscript{1}School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, China
\textsuperscript{2}School of Electrical and Electronic Engineering, Nanyang Technological University
50 Nanyang Avenue, Singapore 639798
\textsuperscript{3}School of Physical and Mathematical Sciences, Nanyang Technological University
50 Nanyang Avenue, Singapore 637371

Abstract

Here we report a tunable Meta-Liquid-Crystal based on liquid metal droplet, the optical properties of which is tuned by controlled electrowetting effects. The Meta-Liquid-Crystal consists of 80 × 80 micro droplets, which are formed and self-assembled by lotus effect on silicon substrate with micro holes array. In experiment, it measures a 0.01-THz frequency shift of the dipole resonance spectrum induced by changing of the droplets shape via electrowetting effect. The Meta-Liquid-Crystal is flexible in tuning and easy in fabrication, which has potential application on tunable filters, controllable beam steering and flat lens.

1. Introduction

Tunable metamaterials with active and switchable \[1-2\] optical properties are, at the very beginning, proposed to compensate for the drawbacks of the metamaterials such as high absorption loss and narrow working bandwidth, which are typically due to the strong resonance nature of the metamolecules. Now, exciting and technologically important capabilities of tunable metamaterials range from tunable optical charity [3], controllable magnetic resonance [4] to dynamic quantum effects, with applications across science and engineering from active photonic devices to biological sensors and imaging systems. Most tunable metamaterials researches targeting on nanophotonic circuits are limited by the availability of fast and highly responsive nonlinear media that react to the control signals by phase changing or refractive index variation. It is difficult to deliver in nanoscale devices using electronic or molecular nonlinearities, where the tuning range and speed are often limited by the saturation effects of the chosen nonlinear media and the sub-wavelength scale optical paths. On the other hand, the concept of structural reconfigurable metamaterials was demonstrated with low switching speed of several Hertz and large metamolecules sizes of millimeter scale five years ago, which has metamolecules now been minimized to submicron scale with tuning speed up to megahertz. Although the structural reconfigurable metamaterials based on micromachined actuators [5-6] or other tuning methods can be possible alternatives of active metamaterials with the help of quick and widespread proliferation of new nanofabrication techniques, the capabilities of structural reconfiguration are always limited by the solid-based metal patterns, which cannot be changed once fabricated.

Here we report a tunable functional material realized by combining the concept of metamaterials with the technology of optofluidics. The pure liquid based functional materials, which is named as Meta-Liquid-Crystals, are feasible to manipulate light with engineered sub-wavelength structures based on fluids, which has much more freedom in structural reconfiguration than those of tunable metamaterials based on solid metal patterns. We demonstrated the realization of the Meta-Liquid-Crystals.

2. Design of the Meta-Liquid-Crystal

![Figure 1: Schematic and working principle of tunable Meta-Liquid-Crystal in terahertz regime (a) and (c) Overview of the Meta-Fluidic-Crystal without and with applied voltages. (b) and (d) show how the voltage is applied to the microdroplets.](image)
Figure 1 shows the schematic of the Meta-Fluidic-Crystal, which consists of a square lattice array formed by mercury micro droplets with the period of 300 µm. The THz incident wave is reflected by the dipole resonance of the droplets and the transmission spectrum is therefore can be controlled by the radii of the metal droplets. Fig. 1(b) and Fig. 1(c) shows the schematic of the droplets with uncharged and charged substrate, respectively. It shows that the radii of the droplets can be controlled by the electrowetting effect.

Figure 2: The radii of the microdroplets as the function of applied voltage. Blue dot represents measured major radii of metal droplet manipulated by EWOD when different voltage applied. Red curve shows the fitting curve based on the discrete point. Insert graphs show surface current on single unit cell with different major radii.

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

\[ \cos \theta = \cos \theta_0 + \frac{C}{2\gamma} V^2 \]  

(1)

Where \( \theta_0 \) is the contact angle between mercury and the substrate at initial state, \( \theta \) is the contact angle when voltage applied, \( \gamma \) is the surface tension of the mercury, \( C \) is the areal capacitance of the substrate and \( V \) is the applied voltage.

The radius of each droplet when different voltages are applied is shown at Fig. 2. The blue dot shows the experimental results and the solid line is the fitting curve. The radii of mercury droplet become larger when the applied voltage becomes higher. The insert graphs show the surface current on each mercury droplet with different radii, which shows the dipole resonance induced by the incident wave with the frequency of 0.34 THz. The liquid metal droplets are formed by lotus effect by placing the liquid metal between the silicon substrate and the quartz wafer. The silicon substrate is pre-etched with square-lattice cylinder holes array using Deep reactive-ion etching (DRIE) method.

3. Results and discussions

Figure 3: The Meta-Liquid-Crystal with the radii of microdroplets tuned by applied voltage. (a), (b), (c) and (d) shows the tuning of the radii from 100 µm to 120 µm. The applied voltages from Fig. 3(a) to (d) are 25 V, 28 V, 38 V and 50 V, respectively.

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 µm ((b), (c)) and 120 µm ((d), (e)).
Figure 4(a) shows the numerical analysis of the transmission spectra at different radii of the mercury droplets. The absorption frequency due to the dipole resonances 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 $r = 80 \, \mu m$ and an ellipse for $r = 120 \, \mu m$ 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.

### 4. Conclusions

In conclusion, a THz Meta-Liquid-Crystal based on mercury droplets is designed, fabricated and experimentally demonstrated. In the experiment, the radii of each droplet are tuned from 80 $\mu m$ to 120 $\mu m$ while the dip frequency is tuned from 0.342 THz to 0.349 THz, which has potential application on tunable filters, controllable beam steering and flat lens.

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### References


