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<td>Song, Qing Hua; Zhu, W. M.; Wu, P. C.; Zhang, Wu; Wu, Q. Y. S.; Teng, J. H.; Shen, Zhongxiang; Chong, P. H. J.; Liang, Q. X.; Yang, Z. C.; Tsai, D. P.; Bourouina, T.; Leprince-Wang, Y.; Liu, Ai Qun</td>
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<tr>
<td><strong>Citation</strong></td>
<td>Song, Q. H., Zhu, W. M., Wu, P. C., Zhang, W., Wu, Q. Y. S., Teng, J. H., et al. (2017). Liquid-metal-based metasurface for terahertz absorption material: Frequency-agile and wide-angle. APL Materials, 5(6), 066103-.</td>
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<td><strong>Date</strong></td>
<td>2017</td>
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<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/43691">http://hdl.handle.net/10220/43691</a></td>
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Liquid-metal-based metasurface for terahertz absorption material: Frequency-agile and wide-angle

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(Received 21 January 2017; accepted 29 May 2017; published online 9 June 2017)

Terahertz metasurface absorption materials, which absorb terahertz wave through subwavelength artificial structures, play a key role in terahertz wave shielding and stealth technology, etc. However, most of the metasurface absorption materials in terahertz suffer from limited tuning range and narrow incident angle characteristics. Here, we demonstrate a liquid-metal-based metasurface through microfluidic technology, which functions as a terahertz absorption material with broadband tunability and wide-angle features. The proposed terahertz metasurface absorption material exhibits an experimental tuning range from 0.246 THz to 0.415 THz (the tuning range of central frequency reaches 51.1%), and the tuning range maintains at high level with wide-angle response up to 60°. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license ([http://creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/)). [http://dx.doi.org/10.1063/1.4985288]

Terahertz absorption materials play a key role in applications such as terahertz wave shielding and stealth technology, etc. Recently, metasurfaces have inspired a burgeoning interest in the design of terahertz absorption materials by using a dielectric layer sandwiched between a metallic structure layer and a metal ground layer, matching the impedance to the free space and blocking all of the transmissions, respectively.2–6 By tailoring the top metallic structure layer, the spaced dielectric layer, and the bottom metallic film, various absorption performances can be realized.7–10 In general, these proposed metasurface absorption materials usually rely on the electric and magnetic responses of top metallic structures, as well as the magnetic response induced by the inductive coupling between the metallic structures and the ground plane. The magnetic responses play an important role in the realization of impedance matching.11 However, the magnetic dipole moments induced by the top metallic structures are usually perpendicular to the incident magnetic field, leading to a weak interaction between the induced magnetic dipole and the incident magnetic field. A vertical split-ring resonator12,13 is therefore developed to provide an alternative method to enhance the magnetic response by erecting the split-ring resonators up along the propagating direction, resulting in a strong magnetic response between the incident magnetic field and the induced magnetic dipole. Such a design paradigm can be exploited to realize high absorption.

In addition, it is desirable to have terahertz absorption materials with frequency-agile and wide-angle functionalities.14–16 Recent progress in terahertz metasurface absorption materials has led to
the realization of frequency-agile functionality that is provided by using liquid crystal, graphene, microelectromechanical systems actuator, etc. However, these proposed tunable absorption materials usually have limited tuning range with narrow incident angle. Although much effort has been made to develop wide-angle absorption materials, the absorption frequency cannot cover in a broad range. Some other works show that the wide-angle characteristics can work only in a certain frequency. A wide-angle absorption material with broadband tuning range is still lagging behind.

Here, we report a proof-of-principle demonstration of a frequency-agile and wide-angle absorption material based on a liquid-metal-based metasurface, where the liquid-metal-pillar array can be continuously controlled in the vertical direction using microfluidic technology. The resonant structure demonstrated here is liquid-metal-pillars whose height can be tuned in the propagation direction, which breaks the tuning limitation in the 2D plane and provides a broadband tuning range of absorption frequency. In addition, such a liquid-metal-based metasurface induces magnetic dipoles that are parallel to the incident magnetic field, resulting in a strong interaction between the induced magnetic dipoles and the incident magnetic field. The magnetic resonance strongly confines and absorbs the terahertz wave in the metasurface. Furthermore, the absorption will not be deteriorated under oblique incidence, which promises the realization of a wide-angle absorption material.

FIG. 1. (a) Schematic of the liquid-metal-based metasurface consisting of the liquid-metal-pillar array embedded in silicon cavities. (b) Tuning method of the liquid-metal-based metasurface in the vertical direction by using microfluidic technology. (c) Equivalent circuit model for one element of the U-shape resonator.
The liquid-metal-based metasurface is illustrated in Fig. 1(a). The element consists of four liquid-metal-pillars embedded in penetrated silicon cavities, which are sandwiched between two polydimethylsiloxane (PDMS) layers. Such an element of four liquid-metal-pillars is patterned periodically into a square array, as shown in Fig. 1(a). The liquid metal is injected from the bottom PDMS layer through microchannel and filled into each silicon cavity, as shown in Fig. 1(b). The height of liquid-metal-pillars can be controlled by the air pressure applied from the air inlet. By applying different air pressures, the liquid-metal-pillars’ height can be increased or decreased, resulting in a reversible process for flexibly reconfiguring the U-shape resonator. In order to achieve the identical tuning of the liquid-metal-pillars, the air inlets are connected with each other in the top PDMS layer, creating a uniform air pressure.

The tunable U-shape resonator is a variant of previously demonstrated designs that exhibit a Lorentz-like resonant response described by an effective complex permittivity \( \varepsilon(\omega) = \varepsilon' + i\varepsilon'' \) and permeability \( \mu(\omega) = \mu' + i\mu'' \), where \( \varepsilon' \) and \( \varepsilon'' \) are the real and imaginary parts of the permittivity, and \( \mu' \) and \( \mu'' \) are the real and imaginary parts of the permeability, respectively.\(^{25,26}\) It can be described qualitatively in terms of its equivalent circuit, as shown in Fig. 1(c). The adjacent two liquid-metal-pillars and the bottom liquid connection form an LC circuit, where the effective capacitance, inductance, and resistance are denoted as \( C \), \( L \), and \( R \), respectively. By solving the Drude-Lorentz model, the resonant frequency of the tunable U-shape resonator can be described as:\(^{25}\)

\[
\omega = \frac{1}{2\pi \sqrt{(L + \mu_S^2 V)/C}},
\]

where \( \mu_S \) is the permeability of the substrate (silicon), \( S_0 \) is the cross-sectional area of the U-shape resonator, and \( V \) is the volume of each element, which are expressed as

\[
S_0 = Gh, \quad V = P^2 h,
\]

where \( G \) is the gap between two adjacent liquid-metal-pillars, \( h \) is the height of liquid-metal-pillars, and \( P \) is the period of the metasurface (see Fig. S1 in the supplementary material). The resonant frequency of the U-shape resonator can be obtained as

\[
\omega = \frac{1}{2\pi \sqrt{(L + \mu_S G h^2 P^2)/C}}.
\]  

When the height of the liquid-metal-pillars is changed, the corresponding equivalent capacitance \( C \) and inductance \( L \) will be controlled, leading to a tunable frequency of the U-shape resonator. For example, when the height of the liquid-metal-pillars \( h \) is increased, the effective size of the capacitor and the cross-sectional area of the inductive loop are increased, such that the effective capacitance \( C \) and inductance \( L \) become larger. Therefore, the resonant frequency \( \omega \) would shift to lower frequencies based on Eq. (3) when \( h \) is increased, and vice versa.

In the simulation, the liquid metal is mercury, which 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 permittivity \( \varepsilon_r = 11.9 \). PDMS is modeled as a lossy dielectric material.\(^{27}\) The absorption of the metasurface is characterized by the absorbance,\(^{28}\) \( A(\omega) = 1 - R(\omega) - T(\omega) \), where \( R(\omega) \) is the reflectance and \( T(\omega) \) is the transmittance that is totally suppressed to zero due to the opaque metal liquid layer. It can be derived by the scattering parameter (S-parameter) using the microwave studio of CST (Computer Simulation Technology), i.e., \( A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2 \). The polarization-insensitive feature under normal incidence is numerically calculated in Fig. 2(a) when the height of liquid-metal-pillars is 70 \( \mu \)m. The symmetric structural design with four identical liquid-metal-pillars in an element enables the polarization-insensitive characteristics of the absorption under normal incidence. The absorption spectra are completely overlapped with TE and TM mode incidence (see the definition in Fig. S1 of the supplementary material). An absorption peak is induced at 0.32 THz with a near-unity absorption of 99%. This absorption peak is attributed to the induced magnetic resonance mode, which can be examined by the magnetic field distribution as shown in Figs. 2(b) and 2(c) with TE and TM mode incidence, respectively. Different electric charges are accumulated at the surface of adjacent liquid-metal-pillars, and an LC resonance is formed in the gap.\(^{29,30}\) The current loop is induced in the U-shape resonator, which is responsible for the strong enhancement of the magnetic field in the gap.
FIG. 2. Simulation results of the tunable absorption material by using the liquid-metal-based metasurface. (a) Absorption spectra with TE mode (red line) and TM mode (blue dot) when the height of liquid-metal-pillars is $h = 70 \, \mu m$. (b) and (c) Magnetic field distribution at the peak frequency with TE mode and TM mode, respectively. (d) Absorption color map with TM mode when the height of liquid-metal-pillars is tuned from $h = 25 \, \mu m$ to $h = 100 \, \mu m$. (e) and (f) Magnetic field distribution at the peak frequency when the height of liquid-metal-pillars is 40 $\mu m$ and 90 $\mu m$, respectively.

and for the creation of a magnetic resonance. In the absorption spectrum, another absorption peak is also observed at around 0.29 THz, which is induced by the Fabry–Pérot cavity.

In order to realize the dynamic control of absorption frequency, the effective length of magnetic plasmon resonance can be controlled by tuning the height of liquid-metal-pillars. The increasing height of liquid-metal-pillars results in a red shift of the magnetic resonance, as shown in Fig. 2(d). When the height of liquid-metal-pillars is 40 $\mu m$, the corresponding effective length of the magnetic resonance is decreased, as shown in Fig. 2(e), and thus, the absorption peak frequency is increased to 0.414 THz with absorption higher than 90%. When the height of liquid-metal-pillars is changed to 90 $\mu m$, the effective length of the magnetic resonance is increased, as shown in Fig. 2(f), resulting in a decreased absorption peak frequency to 0.246 THz with absorption higher than 90%. The shift of the absorption frequency induced by the change of the height of liquid-metal-pillars agrees well to
the prediction by an equivalent circuit model. The tuning range of central frequency of the absorption peak reaches 50.9% with absorption higher than 90%.

Here, we also investigate the electromagnetic response of the liquid-metal-based metasurface with oblique incidence. The absorption becomes polarization sensitive under the condition of oblique incidence. The simulation results of the absorption spectra with incident angle $\theta = 60^\circ$ are shown in Fig. S2(a) of the supplementary material. A magnetic resonance is induced with TM mode incidence, as shown in Fig. S2(b) of the supplementary material. The absorption peak maintains in a single band with 99% absorption, as shown in Fig. S2(a) (blue line) of the supplementary material. However, a higher order of magnetic response occurs with TE mode incidence, which induces another absorption peak as shown in the red line. In this paper, we focus on TM mode incidence with oblique incidence. When the incident angle is increased from 0° to 60°, the tuning range of central frequency of the absorption peak covers 27.6% from 0.25 to 0.33 THz with absorption higher than 90%, as shown in Fig. S3 of the supplementary material, which realizes a broadband tunable absorption material in the wide incident angle with TM mode. Different from conventional Fabry–Pérot that is based on light interference between two reflective surfaces, the liquid-pillar-based metasurface is based on plasmonic resonance of the U-shape resonator, which has the merit of miniaturizing the resonator thickness to the deep sub-wavelength scale. For example, when the absorption frequency is 0.33 THz

FIG. 3. Fabrication results of the liquid-metal-based metasurface. Top view of the microscopic images for a single element of the metasurface (a) without liquid metal injection and (b) with liquid metal injection. The silicon cavity and top PDMS control channel are highlighted as blue and yellow color, respectively. Confocal image for a single element of four-pillars with the height of liquid-metal-pillars at (c) $h = 25 \mu m$, (d) $h = 50 \mu m$, (e) $h = 75 \mu m$, and (f) $h = 100 \mu m$. 
(wavelength $\lambda = 910 \mu m$) with incident angle of $60^\circ$, the height of the U-shape resonator is $53 \mu m$ ($\sim \frac{1}{17}\lambda$), which is much smaller than the operating wavelength.

The liquid-metal-based metasurface consists of $70 \times 70$ elements with $300 \mu m$ period. The fabrication processes are shown in Fig. S4 of the supplementary material. The top view of the microscopic images without and with mercury injection is shown in Figs. 3(a) and 3(b), respectively. Mercury can also be replaced by other liquid metals, such as galinstan and liquid phase conducting polymers. The confocal images with different height of liquid-metal-pillars that are reconfigured by applying different air pressures are shown in Figs. 3(c)–3(f).

The liquid-metal-based metasurface is experimentally characterized using THz time-domain spectroscopy (THz-TDS). The amplitude of the THz-TDS signal reflected from a metal mirror is measured as the reference, which is denoted as $r_{\text{ref}}(\omega)$. The measured THz-TDS signal reflected from the metasurface sample is denoted as $r_{\text{sam}}(\omega)$. Since the transmission is totally blocked by the metal liquid layer, the absorbance is normalized as $A(\omega) = 1 - R(\omega) = 1 - \left[ r_{\text{sam}}(\omega)/r_{\text{ref}}(\omega) \right]^2$. The measured results with normal incidence when the height of liquid-metal-pillars keeps at $70 \mu m$ are shown in Fig. 4(a). An absorption peak occurs at 0.32 THz with the absorption close to nearly unity, which agrees with the simulation results, as shown in Fig. 2(a). There is a slight difference

![Image](image_url)

**FIG. 4.** Experimental results of the tunable absorption material with normal incidence by using the liquid-metal-based metasurface. (a) Absorption spectra with TE mode (red line) and TM mode (blue dot) when the height of liquid-metal-pillars is $h = 70 \mu m$. (b) Absorption color map with TM mode when the height of the liquid-metal-pillars is tuned from $h = 30 \mu m$ to $h = 90 \mu m$. 
of the bandwidth of absorption between the simulation and experimental results, which is caused by the fabrication errors. All liquid-metal-pillars are not perfectly uniform due to the inhomogeneous pressure in the silicon cavity. These non-monodispersed liquid-metal-pillars will affect the bandwidth of absorption. The absorption spectra with TE mode and TM mode are almost overlapped, which verify the polarization-insensitive feature of absorption under normal incidence. By applying different air pressures, the height of liquid-metal-pillars can be changed from 0 to 100 µm. Figure 4(b) shows the absorption color map when the height of liquid-metal-pillars is increased from 30 to 90 µm. The absorption peak frequency is tuned from 0.246 to 0.415 THz with a tuning range of central frequency 51.1% and absorption higher than 90%.

Figure 5(a) shows the experimental results of absorption spectra with different incident angles (TM mode) when the height of liquid-metal-pillars is 50 µm. The absorption peak frequency slightly red shifts when the incident angle is increasing as shown in Fig. 5(b) and the absorption maintains at nearly 99%. Such a frequency shift caused by the change of the incident angle will restrict its potential applications in electromagnetic wave shielding, etc. The red shift can be compensated by decreasing the height of liquid-metal-pillars, which realizes broadband absorption with wide incident angle. The experimental results of the wide-angle absorption material tuned by different heights of liquid-metal-pillars are shown in Fig. 6. We demonstrate three absorption frequencies that are fixed.
FIG. 6. Experimental results of the wide-angle tunable absorption material in broad bandwidth with TM incidence when the incident angle is 0° (black line), 15° (red line), 30° (green line), 45° (blue line), and 60° (dark yellow line). By tuning the height of liquid-metal-pillars, the absorption peak frequency can be fixed at (a) 0.25 THz, (b) 0.28 THz, and (c) 0.33 THz. The tuning range of central frequency reaches 27.6%.

at 0.25 THz [Fig. 6(a)], 0.28 THz [Fig. 6(b)], and 0.33 THz [Fig. 5(c)] when the incident angle is changed from 0° to 60°. By continuously tuning the height of liquid-metal-pillars, the wide-angle absorption can cover all the frequencies from 0.25 THz to 0.33 THz with a tuning range of central frequency 27.6%. The absorption outside the central frequency stays as high as 60%, which is caused by the top lossy PDMS layer. It can be suppressed by using low loss dielectric materials in the terahertz regime. Suppose the top dielectric layer is lossless (the imaginary part of the permittivity is zero), the absorption outside the central frequency is suppressed to near zero, as shown in Fig. S5 of the supplementary material.

In conclusion, a liquid-metal-based metasurface with frequency-agile and wide-angle broadband absorption working in terahertz has been demonstrated experimentally based on microfluidic technology. By controlling the height of the liquid-metal-pillar array in the vertical direction, the absorption frequency of the liquid-metal-based metasurface can be controlled from 0.246 THz to 0.415 THz with a tuning range of central frequency 51.1% and the absorbance higher than 90%. Finally, a wide-angle absorption material working from 0.25 THz to 0.33 THz with a tuning range of central frequency 27.6% is experimentally demonstrated when the incident angle is changed from 0° to 60°. Such a terahertz absorption material has potential applications in terahertz wave shielding and stealth technology, etc.
See supplementary material for the complete electronic structure of the simulation results with oblique incidence and fabrication processes.

The authors acknowledge F. Capasso for the useful discussions and valuable suggestions.

The work is mainly supported by National Research Foundation, Singapore under the Environmental & Water Technologies Strategic Research Programme (1102-IRIS-05-01) administered by PUB, and under the Competitive Research Program (NRF-CRP13-2014-01). D. P. Tsai acknowledges support from Ministry of Science and Technology, Taiwan (Grant No. MOST-105-2745-M-002-005-ASP) and Academia Sinica (Grant No. AS-103-TP-A06).

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