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Adaptable metasurface for dynamic anomalous reflection

L. B. Yan,¹ W. M. Zhu,^{1,a)} P. C. Wu,¹ H. Cai,² Y. D. Gu,² L. K. Chin,¹ Z. X. Shen,¹
 P. H. J. Chong,³ Z. C. Yang,⁴ W. Ser,¹ D. P. Tsai,^{5,6} and A. Q. Liu^{1,4,a)}

¹School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798

²Institute of Microelectronics, A*STAR, Singapore 117686

³Department of Electrical and Electronic Engineering, Auckland University of Technology, Auckland 1142, New Zealand

⁴Institute of Microelectronics, Peking University, Beijing 100871, China

⁵Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan

⁶Department of Physics, National Taiwan University, Taipei 10617, Taiwan

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In this paper, we demonstrate an adaptable metasurface with a periodic array of liquid-metal ring-shaped resonators. Its optical properties can be dynamically controlled by individually reconfiguring the geometry (shape and orientation) of the resonators. For the proof of concept, by tailoring the phase profile of the scattered electromagnetic wave, a dynamic anomalous reflection is demonstrated, whereby the reflection angle is fixed at -45° for three different normal incident frequencies of 10.5, 12, and 14 GHz. The demonstrated adaptable metasurfaces pave a way for promising applications in multi-frequency tracking radar systems and broadband scanning systems. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4983782>]

Metasurfaces¹ are subwavelength structures designed with on demand and distinctive electromagnetic (EM) properties, which have been engineered to create vast optical components, such as flat lenses,^{2–4} holograms,^{5–7} polarizers,^{8,9} polarization beam splitters,^{10,11} waveplates,^{12–14} beam steering devices,^{15–19} and cloaking.^{20,21} One of the common drawbacks of these metasurfaces is the narrow working bandwidth, which leads to the deviation of their performance when the working frequency changes. Most of them are dispersive because of two reasons. First, the dispersion originates from the nature of the response in optical resonators. The resonance profile of most proposed metasurfaces is Lorentzian,²² leading to a resonance strength that varies strongly with the incident frequency. Second, the flat structural configuration of metasurfaces leads to different phase accumulations in free space along the propagation direction for different incident frequencies.

Mathematically, in a gradient metasurface, the reflection angle under normal incidence is $\theta_r = \sin^{-1}(\frac{c}{\xi \times f_i})$, where c is the velocity of light in free space, f_i is the frequency of the incident light beam, and ξ is the effective length which is the shortest length of the supercell to achieve the 2π phase shift of the scattered light beam. In general, a metasurface with a fixed structure has varying $\xi \times f_i$, leading to the change in the reflection angle for different incident frequencies. The phase modification implemented by metasurfaces can remain relatively constant over a certain range of frequencies, due to the overlapping and relatively broad resonances of the optical resonators.^{23,24} Recently, achromatic metasurfaces working at different wavelengths have been demonstrated using pre-designed optical resonators to compensate the dispersion of the phase accumulation such that the total phase change remains constant.³ However, it is very difficult to achieve broadband phase compensation of the optical resonators

without changing the planar geometries of the metasurfaces²⁵ because the phase compensation imposed by these metasurfaces is pre-designed and fixed for certain frequencies once the samples are fabricated. Therefore, metasurfaces adaptable to incident wavelength are highly demanded when broadband operation is required.

In this paper, we demonstrate an adaptable metasurface in which the optical response is dynamically controlled according to the incident wavelength for specific functionality. The adaptable metasurface is composed of a periodic array of liquid-metal ring-shaped resonators, whereby their geometry can be tuned individually. The adaptable metasurface for dynamic anomalous reflection is designed to deflect light of different frequencies into the same directions as illustrated in Fig. 1(a). The metasurface controls the reflection by imparting the desired abrupt phase shift into the scattered light beams. To achieve the same reflection angle at various incident frequencies, in our proposed adaptable metasurface, $\frac{1}{\xi \times f_i}$ is kept constant by tuning the value of ξ . Furthermore, different reflection angles at a specific incident frequency can also be achieved by changing ξ .

The liquid metal ring-shaped resonator of the adaptable metasurface consists of a liquid metal inlet to inject liquid metal and two air inlets to control the geometry of the resonator whereby its shape and orientation are reconfigurable as shown in Figs. 1(b) and 1(c). A supercell with eight liquid metal ring-shaped resonators whereby a 2π phase shift of the scattered light beam is achieved by simply reconfiguring the shape and orientation of the resonators is shown in Fig. 1(d). Initially, liquid metal is injected into and fills up the ring-shaped microchannel. When air is pumped into the ring-shaped microchannel through the inlet, an air gap is formed in the liquid metal, changing the shape of the resonator. The shape of the latter is defined by the angle of the air gap, which can be tuned continuously and reversibly in the range of 5° or 180° by regulating the input pressure of the air.

^{a)} Author to whom correspondence should be addressed: wmzhu@ntu.edu.sg and eaqliu@ntu.edu.sg

FIG. 1. (a) Schematic of the adaptable metasurface for dynamic anomalous reflection whereby incident light beams with different frequencies are reflected to the same angle. Liquid-metal ring-shaped resonator with the orientation of (b) 45° or (c) 315°. (d) The supercell is composed of a row of resonators, which can be individually reconfigured to tailor the scattering phase profile. (e) Adaptable metasurface is formed by periodically arrayed supercells with a pneumatic control system.

The phase shift of the cross-polarized scattered light^{12,15,26,27} changes with the shape of the resonator, and normally, a phase shift from 0 to π can be achieved with a fixed orientation, i.e., resonators α_1 – α_4 . In order to obtain a 2π phase modulation, it is essential to reconfigure the orientation of the ring-shaped resonators. The phase shift from π to 2π can be achieved by changing the air gap when the resonators orient to another perpendicular direction, i.e., resonators β_1 – β_4 . The reconfiguration of the orientation is achieved by importing air into one of the two designed air inlets, while the other air inlet is blocked. In our design, the orientation of the resonators is reconfigured in two perpendicular directions, either 45° or 315°. However, through the design of the air inlets, resonators with arbitrary orientation can be achieved. With a row of resonators, a supercell of the adaptable metasurface is formed in which we can tailor arbitrarily the phase profile of the scattered light. The adaptable metasurface is constructed using periodically arrayed supercells with a pneumatic control system^{28,29} as shown in Fig. 1(e). The metasurface is mainly composed of three layers. The top layer of the resonator array is designed to introduce a structure-dependent resonance mode in a subwavelength regime. The bottom is a perfect electric conductor (PEC) layer, which couples to the resonators via an intermediate dielectric layer suppressing transmission and enhancing reflection. Through the design of microfluidic channel's size, reconfigurable metasurfaces are applicable in a large frequency range from GHz to hundreds of THz.

The amplitude and the phase of the cross-polarized reflection as a function of the geometry of the resonator are numerically analyzed by using the microwave studio module of Computer Simulation Technology (CST) software. Figure 2(a) shows the phase and amplitude modulation of various geometries of the resonator when the incident frequency is set at 12 GHz, which are simulated using periodic boundary conditions. The blue solid line indicates the reflection amplitude, while the red solid line and dashed line represent the phase modulation when the resonator is oriented along 45° or 315°. The incident light propagates oppositely in the z -direction, which is normal to the metasurface, while the electric field of the incident light polarizes in the x -direction. By reconfiguring the geometry of the tunable ring-shaped resonator, a 2π range phase modulation is achieved. With an orientation of 315°, by tuning the air gap from 5° to 160°, a phase shift from 0 to π is obtained. By changing the orientation to 45° and tuning the air gap, a phase shift of π to 2π is obtained. As a

result, a 2π phase modulation of the cross-polarized scattered light can be achieved while the normalized amplitude of the reflection is larger than 0.82. Based on the same tuning method, a 2π phase modulation can be achieved in a broad range of frequencies. Other two specific examples of 2π phase modulation, when the incident frequency is adjusted to 10.5 GHz or 14 GHz, are shown in Fig. S1 in the [supplementary material](#).

Based on $\theta_r = \sin^{-1}(\frac{c}{\xi \cdot f_i})$, to achieve the same cross-polarized reflection angle at various incident frequencies, in our adaptable metasurface, $\frac{1}{\xi \cdot f_i}$ is kept constant by tuning the value of ξ . The adaptability of the metasurface is demonstrated with three incident frequencies f_i ($i = 1, 2, 3$), i.e., 10.5, 12, and 14 GHz. In such a case, the effective length of the supercell is changed from 40 mm and 35 mm to 30 mm, respectively. Table S1 in the [supplementary material](#) shows the configurations $C_{10.5}$, C_{12} , and C_{14} of the resonators in the supercell for each incident frequency, where the subscripts represent the corresponding incident frequencies in GHz. By individually tuning the gap opening and orientation of the resonators, the wavefront of the scattered light can be tailored for different incident frequencies. As an example to verify the phase profile control of the scattered light, Figs. 2(b)–2(d) show the cross-polarized scattered electric field of the individual resonator composing the supercell in the adaptable metasurface. The wavefront of the scattered light is tuned to be the same for all three incident frequencies, leading to the same reflection angle being set at -45° as shown by the cross-polarized scattered E-field distribution in Fig. S2 in the [supplementary material](#). Other reflection angles can also be obtained by properly tuning the configuration of the adaptable metasurface.

In the fabrications, the ring-shaped microfluidic channels were imprinted into the 2 mm thick polydimethylsiloxane (PDMS, $\epsilon_r = 2.69$) layer by soft-lithography as shown in Fig. S3 ([supplementary material](#)). To avoid the deformation of the microfluidic channels, we bonded the PDMS layer with a 1 mm thick dielectric layer of poly(methyl methacrylate) (PMMA, $\epsilon_r = 2.57$). To enhance the bonding strength, the PMMA layer was coated with a thin film of PDMS. A gold mirror was put at the bottom as the PEC layer to suppress the transmission and enhance the reflection. Non-toxic galinstan is chosen to build the liquid-metal ring-shaped resonator, which is in the liquid phase at room temperature.^{30,31} Galinstan is characterized by high electrical conductivity (3.46×10^6 S/m), which is only one order of magnitude

FIG. 2. (a) Simulation results of the reflected amplitude and phase as a function of the air gap and the orientation of the liquid-metal ring-shaped resonator in the adaptable metasurface at 12 GHz. Simulated scattered electric field for individual resonators composed of the supercell for different configurations of the metasurface $C_{10.5}$, C_{12} , and C_{14} , designed for (b) 10.5 GHz, (c) 12 GHz, and (d) 14 GHz, respectively. The white solid and dashed lines refer to the wavefront of the scattered light and effective length, respectively.

lower than that of copper (5.96×10^7 S/m). We used a binary pneumatic control system (see the detailed design in Fig. S4 in the [supplementary material](#)) to partially fill galinstan into the ring-shaped microchannels and then form different geometries of the liquid-metal ring-shaped resonators. The control system can accurately select and subjectively reconfigure the geometry of each liquid-metal ring-shaped resonator. The pressure of the air inlet channel is controlled by a pump in order to accurately tune the air gap of the liquid-metal ring-shaped resonator. The gap size change is 0.438% per degree due to the thermal effect, which is two orders of magnitude smaller than the control of the pneumatic valves. The well-defined resonator array forms a 60×60 lattice by combining nine 20×20 resonator arrays with a periodic spacing of 5 mm, and the total footprint of the metasurface is $300 \text{ mm} \times 300 \text{ mm}$, as shown in Fig. 3(a). The width and the radius of the resonator are 0.4 and 2 mm, respectively. The thickness of the ring-shaped microchannel is 0.1 mm. Each 20×20 array is independently fabricated by soft-lithography and controlled using a pneumatic control system. First, we used the pneumatic control system to select the specific resonator. Then, the hydrochloric vapor is pumped into one of the air inlets, which expelled the galinstan away and formed an air gap of 120° as shown in Fig. 3(b). The air gap restored to 5° when the pressure of the air inlet is reduced as shown in Fig. 3(c).

The measurement of the adaptable metasurface is accomplished in a microwave chamber based on the experimental setup shown in Fig. S5 ([supplementary material](#)). Two dual-polarized quadruple-ridged horns (WJ-48430) serve as the source and the receiver, respectively. The horn serving as the source (tinted in red) projects normally incident light with a broadband frequency from 2 GHz to 18 GHz onto the $300 \text{ mm} \times 300 \text{ mm}$ adaptable metasurface. On the other hand, the receiver (tinted in green) can move along an arc for angle-dependent measurements. In the experiments, we detected the far-field cross-polarized reflection amplitude from the reflection angle of 0° to -70° . Both the horns are connected to a vector network analyzer (VNA, Agilent N5230A) in order to characterize the far-field reflection properties. Figure 4(a) shows the reflection angle versus incident frequency when the adaptable metasurface is tuned in configurations $C_{10.5}$ (red line and symbol), C_{12} (green line and symbol), and C_{14} (blue line and symbol). The colored lines indicate the simulation results, while the symbols refer to the experimental results. In a particular configuration, the reflection angle changes with frequency. For example, when the adaptable metasurface is tuned in configuration C_{12} , the reflection angle changes from -58° to -35° with the incident frequency changing from 10 GHz to 15 GHz. The far-field cross-polarized scattering intensity as a function of

FIG. 3. (a) An overview photograph of the fabricated adaptable metasurface. Zoom-in view of the array of resonators where a single resonator with the air gap of (b) 120° and (c) 5° is obtained when the input pressure of hydrochloric vapor changes.

frequency and angle of reflection also shows the dispersion property in the reflection angle (Fig. S6 in the [supplementary material](#)). The same reflection angle of -45° is achieved for all three frequencies 10.5, 12, and 14 GHz with their respective configurations of $C_{10.5}$, C_{12} , and C_{14} as highlighted with a black line in Fig. 4(a). This occurs because $\frac{1}{\epsilon \times f_i}$ is kept constant for different incident frequencies f_i by specifically controlling and reconfiguring the metasurface. By tuning the adaptable metasurface into a proper configuration, other reflection angles can also be demonstrated. In Figs. 4(b)–4(d), we present the cross-polarized scattering intensity distribution at different angles when the adaptable metasurface is tuned in the configurations of $C_{10.5}$, C_{12} , and C_{14} , respectively. The blue solid lines indicate the simulation results, while the red dashed lines refer to the experimental results. In all the three configurations, the reflection angles are tuned to -45° . The diffraction efficiency drops from 50.7% to 30.5% because of the loss associated with the phase discontinuity, which changes when the working frequency changes from 10.5 to

FIG. 4. (a) Simulation (colored lines) and experimental results (colored symbols) of the reflection angle as a function of frequency from 10 to 15 GHz. Simulation (red dash line) and experimental results (blue solid line) of far-field scattering intensity as a function of the reflection angle with the normal incidence frequencies of (b) 10.5, (c) 12, and (d) 14 GHz.

14 GHz. This can be further improved by increasing the optical resonators in the supercell with optimized design. All the simulation and experimental results are in good agreement, which demonstrates that the optical properties are controlled in a wide range of frequencies through the designed metasurface.

In conclusion, we demonstrated an adaptable metasurface with real-time individual control of the ring-shaped resonator's geometry for dynamic anomalous reflection. The shape and orientation of each resonator can be tuned individually and dynamically using a microfluidic control system to control the optical response of the metasurface.

The adaptable metasurface can be used as a wavefront correction device with controllable functionalities, corresponding to the incident frequencies. It has high potential for various applications such as in multi-frequency tracking radar and broadband scanning systems.

See [supplementary material](#) for supporting content.

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