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Polarization-insensitive wide-angle-reception metasurface with simplified structure for harvesting electromagnetic energy

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This paper reports the design, fabrication, and measurement of a metasurface with wide-angle-reception and polarization-insensitive characteristics for harvesting electromagnetic energy. Unlike the metasurface unit cell with multiple vias reported in the literature, it realizes polarization-insensitive characteristics using a single via, which reduces the complexity of the structure significantly. The harvesting and absorption efficiencies at the normal and oblique incidences, energy distribution, and the surface current for different polarization angles are investigated. The simulation results show that the maximum harvesting efficiency is 88% at the center frequency of 5.8 GHz for the arbitrary polarization at the normal incidence of 0°. Within the oblique incidence range of 75°, the maximum efficiency remains higher than 77% for the random polarization. A 5×5 array has been fabricated and measured, and the good agreement with the simulated results is obtained. *Published by AIP Publishing.*
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For harvesting the electromagnetic (EM) energy and the far-distance wireless power transmission (WPT), the traditional rectenna,[1,2] consisting of the antenna and the rectifying circuit, is effective to receive the EM wave and convert it to the direct current power on the condition of the defined operation frequency, the incident angle, and the polarization direction. However, the environmental EM waves are diverse in incident angles, polarizations and operation bands. The development of a metamaterial[3] brings opportunities and challenges for harvesting EM energy. The metamaterial is fundamentally based on assembling electrically small resonators to create a media with atypical permeability or permittivity.[4] A metasurface is an array of periodically arranged metamaterial unit cells with a thin depth. As another candidate for harvesting EM energy, the metasurface has attracted people's interest because it can not only capture EM waves like a perfect absorber,[5–8] but also recycle the energy.

The concept of using the metamaterial particles as efficient collectors for harvesting the EM energy was proposed in 2012.[4] Afterwards, many different meta-surfaces for harvesting EM energy were proposed and most of them were mainly based on two typical structures: Split-Ring Resonators (SRRs)[4,9,10] and Complementary Split-Ring Resonators (CSRRs).[11–13] The reported research demonstrated various metasurfaces with the features of broadband,[9,13,14] polarization-insensitivity,[13–16] wide-angle-reception, and multi-bands.[17,18] However, those reported metasurfaces had a common problem that the polarization-dependent characteristic was usually achieved by a single via[8–12,17] while the polarization-insensitive characteristic can only be realized by multiple vias.[13–16,18,19] In this paper, a metasurface unit cell in the shape of rotating central symmetry, with only one via to achieve polarization-independent characteristic, is proposed. The metasurface could collect the EM energy effectively with a simple one-via-cell, which would make it easier for further rectifying the EM energy to the direct current.

As schematically shown in Fig. 1, our metasurface is a sandwich system consisting of a metal plate with a periodic array of a specially designed metasurface unit cell, a substrate, and a metallic ground. The unit cell is a rotating central symmetric structure whose arc has the center point of O_2 and the radius of R_1. The used substrate has the thickness of 0.787 mm, the relative dielectric constant of 2.2, and the $\tan\delta$ of 0.001. Both the top and bottom metallic planes are copper with the conductivity (σ) of 5.8×10^7 S/m and the thickness of 0.035 mm.

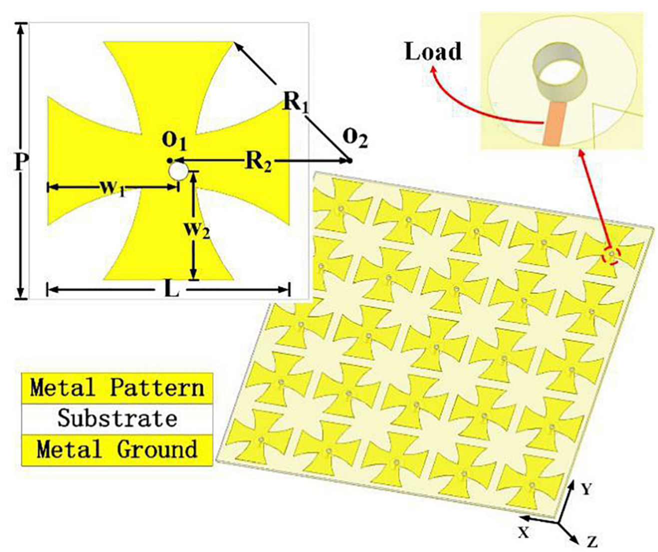

FIG. 1. Topology of the proposed metasurface and unit cell.

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To collect the induced current on the metasurface unit cell, one via passing through the dielectric slab is placed near the unit cell center instead of at the central point (O_1) because the field strength is zero at the center. The diameter of the via is 1.2 mm, which is the size of the SMA's inner conductor for the experiment. The dimensions of the unit cell are chosen as $L = 14.4$, $W_1 = 7.8$, $W_2 = 6.6$, $R_1 = 12$, $R_2 = 13.5$, and $P = 16.7$, all in mm.

The effective material parameters of the metasurface unit cell were extracted from the complex scatter parameters (S_{11} and S_{21}) by the standard retrieval procedure.[20] Figures 2(a) and 2(b) show the retrieved effective permittivity and permeability. It can be observed that the real part of permeability is about -9.084 at 5.8 GHz, while that of the permittivity is -36.36. It indicates that the perfect absorption of the metasurface would originate from the atypical electromagnetic properties.

The normalized impedance to that of the free space (377 Ω) was also extracted, as shown in Fig. 2(c). It could be seen that the normalized impedance of the metasurface is (0.98–*j*0.072) at 5.8GHz. The wide angle energy harvesting characteristic comes from the good impedance match of the specially designed metasurface to the free space.[21]

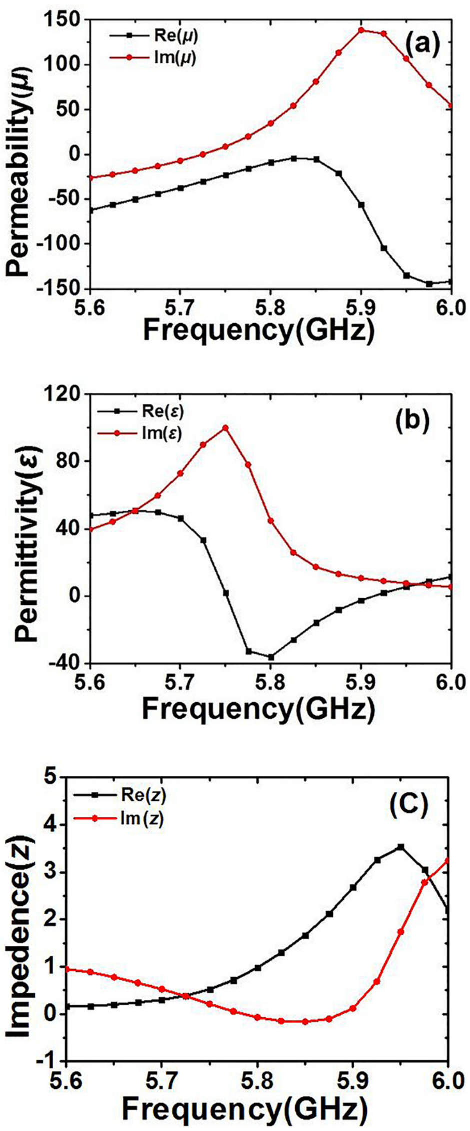

FIG. 2. Extracted effective material parameters (a) permeability, (b) permittivity, and (c) impedance.

The performances of the metasurface unit cell are analyzed using the CST simulator as done in the early works presented in the literature. The periodic boundary condition was applied to the lateral walls of the cell to numerically realize an infinite array. To provide a total incident power of 0.5 W at the footprint of a single cell, the cell was excited by the Floquet port with two modes of TE and TM polarizations at the top boundary. The two modes correspond to a plane wave with the electric component perpendicular to x-z and y-z planes, respectively.

We emphasize that the work presented here is focused on maximizing the absorption efficiency and the harvesting efficiency. It is important to note the definition of the absorption and harvesting efficiencies. The absorption efficiency is evaluated by $A = 1 - |S_{11}|^2 - |S_{21}|^2$, where S_{11} is the reflection coefficient and S_{21} is the transmission coefficient. Since the bottom layer is copper laminated, the transmitted power is zero. Therefore, the absorption efficiency can be maximized by adjusting the structure for minimizing the reflection coefficient. The harvesting efficiency of the metasurface is calculated by[9] $\eta = P_{LOAD}/P_{INC}$, where P_{LOAD} is the total time-average power dissipated on the resistive loads, and P_{INC} is the total time-average power incident on the metasurface.

By sweeping the resistor value, it is found that the maximum absorption at 5.8 GHz would occur on the resistance of 50 Ω (see in Fig. 3). There are three points to emphasize. First, the load value has an influence on the impedance match between the free space and the metasurface and so the absorption efficiency. Second, there is an optimized resistance for the maximum absorption, which can be explained by the fact that the equivalent circuit will have strong resonance if the impedance of the load matches well with that of the via (output port). Third, the optimized resistance value (50 Ω) is affected by the unit cell's size and topology, the properties of substrate, and the size and position of the via.

Figure 4(a) shows that the resonance occurs at 5.8 GHz at the normal incidence, and the absorption and harvesting efficiencies are 93% and 88%, respectively. Only 5% energy is dissipated in the substrate and metal part, which provides the possibility of recycling the EM energy. The polarization directions have no obvious influence on the harvesting efficiency [see in Fig. 4(b)], which is attributed to the rotating central symmetrical structure of the cell's topology although

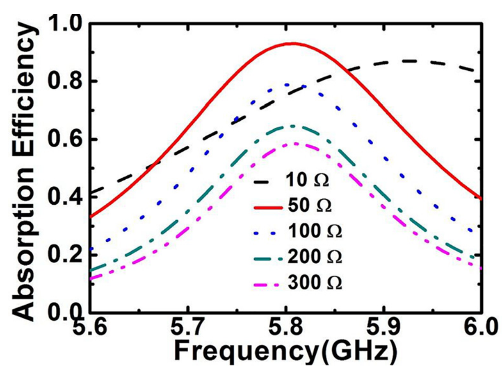

FIG. 3. Calculated absorption efficiency for various resistive loads placed at the gap between the via and the ground plane.

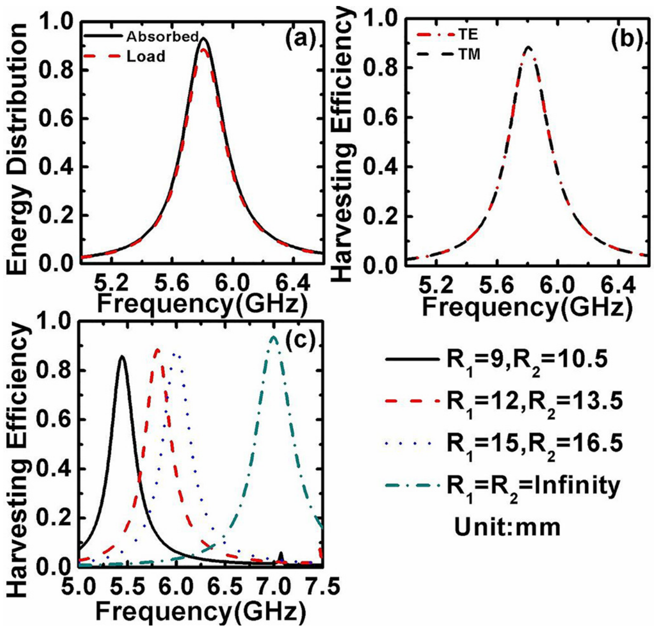

FIG. 4. (a) Energy distribution efficiency, (b) harvesting efficiency of TE and TM polarized incident waves, and (c) simulated harvesting efficiency with the changes of R_1 and R_2, at the normal incidence.

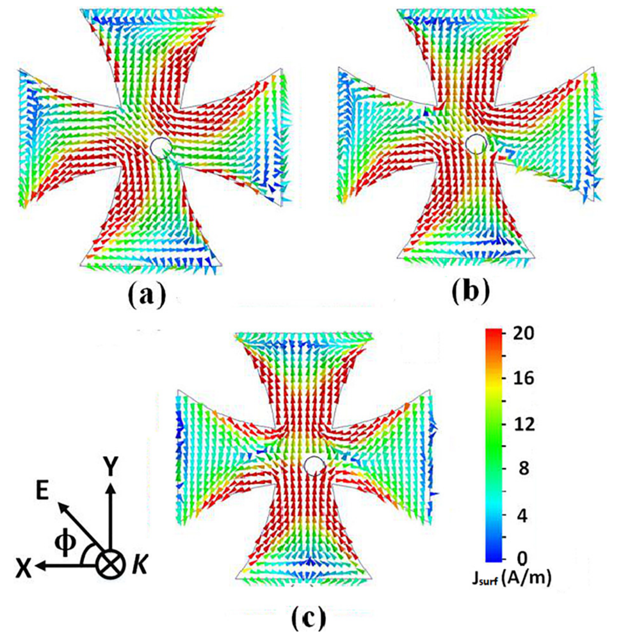

FIG. 5. Surface current within the unit cell at the normal incidence for (a) $\varphi = 45°$, (b) $\varphi = 60°$, and (c) $\varphi = 90°$.

the via is not located at the center. By decomposing the electric field vector, a similar efficiency will be achieved for arbitrary polarization at the normal incidence.

By adjusting the radius (R_1) and the position (R_2) of the auxiliary circle (O_2), we make the following observations in Fig. 4(c). First, R_1 and R_2 influence the resonant frequency effectively, which is caused by the different lengths of surface current, so tuning the frequency is flexible. Second, the maximum harvesting efficiency changes very slightly when the resonant frequency alters. It is necessary to highlight that the resistor value always equals 50 Ω while tuning the dimensional sizes.

In order to obtain an insight into the physical operation mechanism of the structure, we investigate the metasurface unit cell's surface current. From Fig. 5, the current direction is consistent with the polarization angle at the normal incidence. For different polarization angles, there is always current passing into the via, which shows that the via is always near the hot part of current. Therefore, compared with the metasurface unit cell reported in the literature,[8–17] this unit cell can concentrate energy using a single via for arbitrary polarization at the normal incidence, which means that it is easy to collect the EM energy for further rectifying it into the direct current.

Finally, the metasurface is studied at different oblique incidences for TE and TM polarizations, and the results are shown in Fig. 6. For the TE polarization wave [see in Figs. 6(a)], the resonant frequency has nearly no shift and the HPBW (Half Power Band-Width) decreases gradually when the incident angle increases from 0° to 75°. The HPBWs are 5.5%, 5.3%, 5%, 4.4%, 3.8%, and 2.9% at the incident angle of 0°, 15°, 30°, 45°, 60°, and 75°, respectively. The little decline of bandwidths can be explained by the decrease in the effective electric resonance, which is caused by the drop of the wave vector's normal component. For the TM polarization wave [see in Figs. 6(b)], the resonant frequency shifts a little high with the incident angle increasing from 0° to 75° while the HPBW has nearly no change due to the combined effect of the electric resonance and the magnetic resonance. Specifically, the electric resonance drops and the magnetic resonance rises when the incident angle increases, and both of them maintain the HPBW value constant.

To validate the EM energy harvesting efficiency of this metasurface, we fabricate a 5 × 5 array, which is shown in Fig. 7. The array is illuminated by the incident field generated by a horn antenna, which is excited by an Agilent E8257D signal generator. The metasurface is placed at the far field of the standard horn with a distance of R to ensure the illumination of plane waves. The far field distance of R is defined according to the aperture of the horn. The power is delivered to the central unit cell and is measured using an Agilent E4416A power meter.

There are two points to emphasize in this experiment. First, by the input power P_{IN} at the horn and the horn gain values G provided by the antenna company, the incident power intensity $\boldsymbol{S}$ at the distance of R from the horn is calculated using[12]

$$\vec{S} = \hat{r}\,\frac{GP_{IN}}{4\pi R^2}. \quad (1)$$

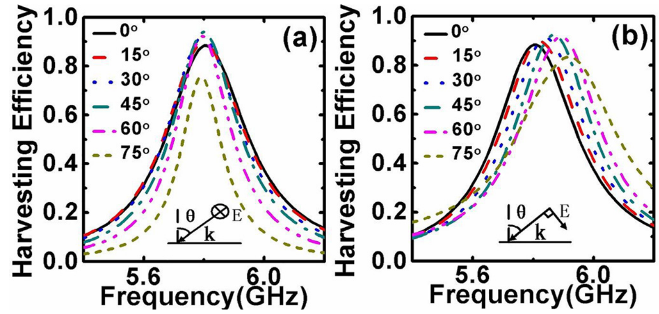

FIG. 6. Simulated harvesting efficiency of the infinite metasurface at different incident angles for (a) TE and (b) TM polarized incident waves.

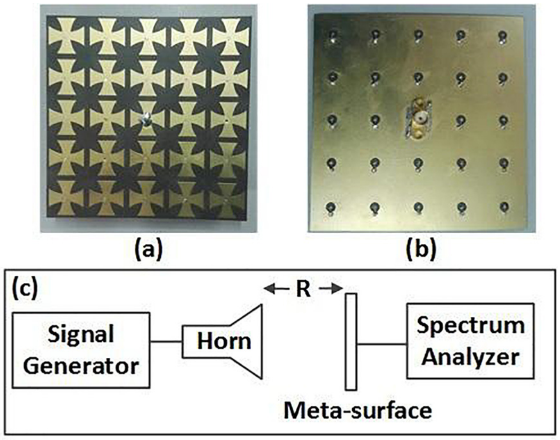

FIG. 7. A photograph of the 5×5 array (a) top view and (b) bottom view. (c) The measurement setup used in the experiment.

The incident power available at the surface of the central unit cell is calculated by multiplying the incident power intensity by the physical area of the central unit cell. The reason for choosing the central unit cell to measure is that it is close to the simulated one in terms of the infinite array. Second, in order to achieve a similar electromagnetic coupling environment to the simulation, the ports of the other unit cell in the array are terminated by resistor of 50 Ω [see in Figs. 7(b)]. The experimental setup is shown in Figs. 7(c).

To adjust the incident angle in experiments, we rotate the metasurface while remaining the transmitting horn being fixed. The center point of the metasurface is aligned to that of the horn plane. The measured harvesting efficiency of the fabricated metasurface is shown in Fig. 8. At the normal incidence, the measured maximum harvesting efficiency is 80% at the resonance frequency of 5.91 GHz, which is a slight shift of 1.9% to the simulated 5.8 GHz. The result shows that the maximum harvesting efficiency remains higher than 68% with the oblique incident angle increasing from 0° to 75° for TE and TM polarization.

The differences between the simulated and measured results come from three factors. First, the fabricated metasurface array is 5×5 while the simulated one is an infinite array. The finite array has the edge effect, which will influence the central cell's performance. Second, the CST simulation software imitates the infinite array by setting the period boundary condition around the unit cell, which might cause a difference with the actual infinite array. Third, the fabrication tolerances might also induce errors. The measured results are in reasonable agreement with the simulated ones, which indicates that this metasurface exhibits the characteristics of polarization-insensitive and wide-angle-reception.

A metasurface with the simplified unit cell structure for harvesting the EM energy effectively has been demonstrated

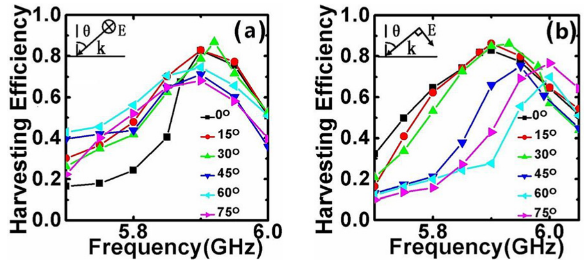

FIG. 8. Measured harvesting efficiency at the different incidence angles for (a) TE and (b) TM polarized incident waves.

in this work. Through the numerical full-wave analysis and laboratory measurement, the metasurface, consisting of the specially designed metasurface unit cell using a single via, has the characteristics of polarization-insensitive and wide-angle-reception. The simplified metasurface unit cell would make it easier to further rectifying the EM energy into the direct current to replace batteries of the low-power-consumption electronic devices.

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