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Yinrui Zhao 1, Buxiong Qi, Tiaoming Niu, Zhonglei Mei, Liang Qiao, and Yaodong Zhao

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Ultra-wideband and wide-angle polarization rotator based on double W-shaped metasurface

Yinrui Zhao, Buxiong Qi, Tiaoming Niu, Zhonglei Mei, Liang Qiao, and Yaodong Zhao

AFFILIATIONS
1 School of Information Science and Engineering, Lanzhou University, Lanzhou 730000, China
2 School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
3 Science and Technology on Electronic Information Control Laboratory, Chengdu 610036, China

ABSTRACT

In this work, we design a novel polarization converter based on a metasurface with double W-shaped unit cells. The proposed polarization converter can convert linearly polarized incident waves into its cross polarized reflective counterparts in a very wide band with high efficiency. Theoretical analysis and simulation results show that the proposed polarization converter can achieve a 90° polarization rotation, while the polarization conversion ratio (PCR) is above 90% in the frequency range from 8.44 GHz to 24.96 GHz, and the relative bandwidth can be up to 99%. The measured results agree well with simulation results. The designed double W-shaped metasurface has a very simple geometry, and can realize a highly-efficient and broadband polarization rotation. Therefore, it has practical applications in wireless communication systems, imaging, radar stealth technology, and other fields.

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I. INTRODUCTION

The polarization of electromagnetic (EM) waves refers to the trace of the electric field in a plane perpendicular to the propagation direction. The effective control of the EM wave polarization states is important because of its potential applications in wireless communications, imaging, radar stealth technology, and so on. The traditional way of manipulating EM wave polarizations is often based on the birefringence effect of materials and solid or liquid crystals are often used to achieve the effect. However, these materials are usually challenging to be applied in practical systems due to their bulky size and narrow frequency response.

Recently, metamaterials (MMs), a kind of artificially designed structures possessing the extraordinary properties that can’t be found in nature, have been proposed as an alternative solution to control EM waves. So far, MMs have been widely approved effective in controlling the polarizations of EM waves due to its exotic properties.

In the past few years, full control of the polarization states of EM waves has made significant progress based on MMs. Owing to the lower profile of MMs, they are easy to integrate into ultrathin devices. Generally speaking, metamaterial polarization converters can be realized in the following two ways: one is by using chiral MMs and the other is to use anisotropic MMs. The existing literatures indicate that the former is convenient for designing transmissive polarization converters. So far, many polarization converters of asymmetric transmission have been extensively investigated based on MMs, showing outstanding potential in many fields such as beam splitters, circulators and sensor components. For example, Singh et al. realized asymmetric transmission of circularly polarized terahertz waves through planar chiral MMs. After that, Ye et al. realized a 90° polarization rotator by using a bilayer chiral metamaterial, which is independent on the incident polarization angle. The latter approach for the polarization conversion is based on the reflection (transmission) phase difference in two orthogonal polarizations. It has been proved that high-efficiency and wideband polarization converters can be achieved by tailoring the geometry of the resonators in an array.

In 2014, Gao et al. proposed a polarization converter based on double V-shaped metasurface, which can convert linearly polarized waves into cross-polarized waves in ultra-wideband from 12.4 GHz to 27.96 GHz.
proposed by Jia et al., which can realize a polarization conversion ratio higher than 90% in the frequency range of 7.8 GHz to 34.7 GHz. In addition, since the circular polarization has advantages of mitigation of multipath fading, immunity of “Faraday rotation” and the reduction of polarization mismatching, circular polarization converters have been extensively investigated. In 2015, an invertible linear-to-circular polarization converter was proposed by Li et al., which can transform a circularly polarized wave into a linearly polarized wave or a linearly polarized wave into a circularly polarized wave in transmission mode. In recent years, to improve the practical applicability of polarization converters, high-efficiency multiband polarization converter has become a research hotspot. In 2018, Lin et al. proposed a reflector based on a symmetric structure, which can realize multiband linear polarization and circular polarization conversion. In most cases, the unit cells of these metasurfaces are mainly inspired by experimentalism and intuition. However, in 2016, Sui et al. demonstrated a topology design method of ultra-wideband polarization conversion metasurfaces based on symmetry coding. Though various designs have been put forward in this area, none of them can realize the ultra-broadband, wide-angle, high-efficiency, and simple-geometry simultaneously.

In this paper, we propose an ultra-broadband, wide-angle and highly efficient linear polarization converter based on double \( \omega \)-shaped metasurface. It can convert a linearly polarized incident wave into its cross polarized reflective wave. The simulation results show that it can efficiently realize polarization conversion in the frequency range from 8.44 GHz to 24.96 GHz and the PCR is above 90%. Moreover, the converter is insensitive to the incident angle, and the mean PCR is higher than 90% from 0° to 41°. The data obtained from the experiment are highly consistent with the simulations. Compared to the previous designs, the proposed polarization converter is very simple, and insensitive to incident angle, so it can be used for radar invisibility, conformal antennas etc.

II. MODEL DESIGN AND PRINCIPLE

The schematic of our polarization converter is shown in Fig. 1(a), which can convert a linearly polarized incident wave into its cross polarized reflective wave. The proposed polarization converter is composed of a top metasurface layer with double \( \omega \)-shaped unit cells, a continuous metallic background on the bottom and a dielectric substrate sandwiched between them. Figure 1(b) demonstrates detailed geometry of the unit cell structure. Obviously, the top metallic patterns are two \( \omega \)-shaped structures, which are aligned along the diagonal direction. This arrangement leads to polarization conversion when these unit cells are patterned periodically in an array. The dielectric layer is selected as F4BM-2 with the relative permittivity of 2.2 and the loss tangent of 0.001. The metasurface structures and the metallic background are made of copper film with conductivity of \( 5.8 \times 10^{7} \) S/m.

To better understand the operational principle, we analyze reflective polarization conversion by using \( u, v \) and \( z \) as the orthogonal coordinate system. As shown in Fig. 2(a), a y-polarized EM wave is demonstrated as an example. We use the \( u-v \) coordinate system to describe each polarization component, and both indicate two directions that are rotated 45° with respect to \( x \) and \( y \) directions. Obviously, the y-polarized incident EM wave can be expressed as \( \vec{E}_i = \vec{u} E_{iu} e^{j\Delta \phi} + \vec{v} E_{iv} e^{j\Delta \phi} \), and the reflected EM wave can be expressed as \( \vec{E}_r = \vec{u} r_e E_{iu} e^{j\Delta \phi} + \vec{v} r_v E_{iv} e^{j\Delta \phi} \), \( r_e \) and \( r_v \) are introduced here to describe the reflection coefficients along the \( u \) and \( v \) axes, respectively. Because of the asymmetry of the double \( \omega \)-shaped metasurface, there is a phase difference \( \Delta \phi(\Delta \phi = \phi_u - \phi_v) \) between the reflection coefficients. If \( r_e = r_v \) and \( \Delta \phi = 180° \), the vector sum for \( E_{iu} \) and \( E_{iv} \) will be along the \( x \)-direction. In other words, a 90° polarization rotation has been realized. Through extensive simulations and optimization process from a range of shapes and sizes by using commercial software, we finally obtain all parameters of the unit cell in Fig. 1(b). The corresponding simulation results are shown in Fig. 2(b). It can be seen that magnitudes of \( r_e \) and \( r_v \) are both very close to 1.0, and the phase difference is roughly 180° in the frequency range from 8.44 GHz to 24.96 GHz. The simulation results suggest that this specific design have excellent polarization conversion performance, as will be shown in the following part. The optimal geometric parameters of the unit cell are as follows: \( a = 2.2 \) mm, \( b = 2.5 \) mm, \( c = 0.3 \) mm, \( d = 0.5 \) mm, \( t = 3 \) mm, \( p = 6.5 \) mm and the thickness of copper is 30 \( \mu \)m.

In order to quantify the performance of proposed polarization converter, we define cross-polarization \( r_{xy} = |E_{xy}/E_{x0}| \) and co-polarization \( r_{yy} = |E_{yy}/E_{y0}| \) to represent the \( y \)-to-\( x \), and \( y \)-to-\( y \) reflections, where \( E_{x0}, E_{y0} \) denote the reflected electric fields along the \( x \) and \( y \) direction, and the \( E_{xy} \) represents the incident electric fields along the \( y \) direction, respectively. Figure 3(a) shows the simulation.
FIG. 2. Investigation of EM responses of the double u-shaped unit cell. (a) y- and x-polarized electric field \( E_y \) and \( E_x \) can be decomposed to two orthogonal electric field of \( E_u \) and \( E_v \). (b) The reflectance and phase difference for waves along the \( u \) and \( v \) axis, respectively.

FIG. 3. Simulation results. (a) Reflection coefficients \( r_{yy} \) and \( r_{xy} \). (b) PCR.

results about \( r_{xy} \) and \( r_{yy} \) for normally incident y-polarized wave. It is obvious that the cross-polarization \( r_{xy} \) is very high and the co-polarization \( r_{yy} \) is very low in the frequency range from 8.44 GHz to 24.96 GHz. Moreover, the magnitude of \( r_{yy} \) is extremely low at three resonance frequencies of 9.19 GHz, 15.94 GHz and 23.85 GHz, indicating that the incident EM wave (y-polarized) has been perfectly converted into the cross polarized reflected wave (x-polarized).

In addition, we define the polarization conversion ratio (PCR) to evaluate the performance for the design, which can be expressed as

\[
\text{PCR} = \frac{r_{xy}^2}{r_{xy}^2 + r_{yy}^2}.
\]

From Fig. 3(b), we can see that the PCR is above 90% in the frequency range from 8.44 GHz to 24.96 GHz, and it can even reach to 100% at the above mentioned three resonance frequencies. All of the simulation results demonstrate that we have successfully designed a polarization conversion device with the characteristics of wide band and high efficiency.

III. FABRICATION AND EXPERIMENT

As illustrated in Fig. 4, the proposed polarization converter is fabricated and measured to validate the simulation results. Figure 4(a) shows the measurement setup, which consists of two horn antennas connected to a vector network analyzer (Agilent 85071E). The photograph of the polarization conversion device is shown in Fig. 4(b). Our prototype has an overall size of 180 \( \times \) 180 mm\(^2\) and consists of 28 \( \times \) 28 unit cells arranged in two directions, and the prototype is surrounded by absorbing material, as shown in Fig. 4(a). Since the operating frequency of proposed polarization converter is at 8.44 GHz to 24.96 GHz, two pairs of standard horn antennas have been used to cover the frequency range, one pair for 8 GHz to 18 GHz and the other for 18 GHz to 26.5 GHz. Figure 5(a) shows the measured results. It is worth noting that, due to the limitations of the experimental conditions, we only measured the reflection coefficient of \( r_{yy} \), and the value of \( r_{xy} \) is calculated using \( r_{yy} \). It can be seen that the PCR is above 90% in the frequency range from 8.44 GHz to 24.96 GHz in Fig. 5(b). However, there are discrepancies between experiment and simulation results, which is mainly due to the following reasons: (1) an ideal normally incident plane wave is used in simulation. However, the measurement setup uses quasi-plane waves; (2) the experimental data come from two pairs of different antennas; (3) the simulations use a sample with infinite size, however, limited sizes are used in the experiment.

IV. ANALYSIS AND DISCUSSION

A. Effect of incident angle on the polarization conversion

In order to get the polarization rotation properties of proposed polarization converter for oblique incidence, we simulated the PCR
under obliquely incident waves with the TE and TM polarizations. Here the TE and TM polarizations mean that the y- and x-polarized plane waves illuminate the structure, respectively. At the TE mode, the direction of the incidence and the magnetic field direction, rotate at various angles, whereas the E-field direction stays at the same (y axis). In the case of the TM polarization, the direction of the incident waves, as well as the electric field direction changes at arbitrary angles, whereas the H-field direction keeps still at the direction of the x axis. Figures 6(a) and 6(b) show the simulation results of PCR under different incident angles at different frequencies with the TE and TM polarizations, respectively. The angle resolution is 1° in the simulation results. It is obvious that the values of PCR are always higher than 90% when the incident angle is under 30° in the frequency range from 8.44 GHz to 24.96 GHz. We can see that the bandwidth of proposed polarization converter is gradually reduced with the further increment of the incident angle, which is attributed to the destructive interference at the surface of the metamaterial under oblique incidence. In order to quantify the conversion efficiency more obviously, Figure 6(c) shows the results of mean values of PCR with TE polarization (PCR(θ)\(=1/N \sum_{i=1}^{N}\)PCR(f_i, θ_j)), where f_i, N represent the discrete frequency points and the number of discrete points within the frequency range of 8.44 GHz to 24.96 GHz for each angle θ_j, respectively). It is obvious that the mean PCRs are higher than 90% within the range from 0° to 41°. The mean PCRs remain as high as 80% when the angle of incidence increases to 50°. Similarly, Figure 6(d) represents mean values of PCR(f_i) of M incident angles in the incidence range from 0° to 50° for the fixed frequency point f_i (PCR(f_i)=1/M \sum_{j=1}^{M}PCR(f_i, θ_j), where θ_j, M represent the discrete angle points and the number of discrete points within the angle range of 0° to 50° for each frequency f_i, respectively). The simulation results show that almost all of mean PCRs are higher than 90% within the frequency range from 8.44 GHz to 24.96 GHz when the incident angle varies from 0° to 50°. All of above results indicate that broadband and highly-efficient performance of double w-shaped converter is sustained over a wide incidence angle range.

B. Effect of geometry parameter on the polarization conversion

Geometrical parameters of the unit cell shown in Fig. 1(b) play an important role in the polarization conversion, and they are

![Image](image_url)
FIG. 7. The phase responses with the variation of the geometry parameters of the unit cell shown in Fig. 1(b). (a)-(e) demonstrate the corresponding simulation results when $a$, $b$, $c$, $d$ and $p$ varies while other parameters remain unchanged, respectively.

The phase responses for different values of $a$, $b$, $c$, $d$ and $p$. It’s obvious that the change of $c$, $d$ and $p$ has a weak influence on the phase response. However, the parameters of $a$ and $b$ are crucial for obtaining 180° phase difference, as

FIG. 8. When incident angle is fixed at 30°, PCR spectra with the variation of the geometry parameters of the unit cell shown in Fig. 1(b). (a)-(e) demonstrate the corresponding simulation results when $a$, $b$, $c$, $d$ and $p$ varies while other parameters remain unchanged, respectively.
are shown in Fig. 9. When \(u\)- and \(v\)-polarized waves irradiate the converter, additional phase difference will be generated for the reflected waves due to the metasurface. As shown in Fig. 9, it is obvious that phase variation trend of \(\phi_u\) is almost the same as that of \(\phi_v\). In other words, the phase difference is a constant value about 180° within the frequency range from 8.44 GHz to 24.96 GHz. Furthermore, since the loss of dielectric substance is very small, the amplitude of the reflectance is close to 1. As a result, when the converter is illuminated with a \(y\)-polarized wave, which can be decomposed into \(u\)- and \(v\)-polarized ones with equal amplitude, since the phase difference is about 180° and the reflection amplitude is close to 1, the polarization of the total reflected wave will be rotated 90° relative to the incident polarization. In other words, the \(y\)-polarized wave is converted to \(x\)-polarized wave within the frequency range from 8.44 GHz to 24.96 GHz. In addition, the superposition of multiple resonances also broadens the bandwidth, which will be discussed in part D.

We also analyze the reflection phase and amplitude when the incident angle changes. As shown in Fig. 10(a), the amplitude of the reflectance along the \(u\) axis are close to 1 except for a few points when the incident angle increases to 30°. However, for reflected waves along the \(v\) axis, the amplitude is almost 1 in the frequency range from 8.44 GHz to 24.96 GHz. Besides, the phase difference is also shown in Fig. 10(c), and it is obvious that the values are roughly 180° when the incident angle increases to 30° in the frequency range from 8.44 GHz to 24.96 GHz. Again, these two factors will ensure a polarization conversion for a wide incident angle and broad bandwidth. As for the lower reflections in Fig. 10(a), they are mainly due to the destructive interference between the reflected waves at the metasurface. When EM waves illuminate on the \(w\)-shaped meta-surface, the first reflection from the top surface and other reflections from the bottom (PEC ground) will interfere on the upper surface.
For a fixed incident angle, the destructive interference will only happen on some specific frequencies (while for a fixed frequency, it only happens at a specific incident angle), where the phase difference between these two waves are exactly 180°. Even at these lower reflections, the overall polarization conversion is still very good, as has been shown in Fig. 8. Therefore, the proposed polarization converter has a good performance in a wide spectrum and wide angle.

D. Surface current distribution for normal incidence

Furthermore, to get an insight into the polarization conversion of the proposed converter, we then simulated the surface current distributions on the top metasurface and bottom layer at these resonant frequencies of 9.19 GHz, 15.94 GHz and 23.85 GHz, respectively, as shown in Figs. 11(a)–(f). As the EM wave propagates to the converter, it is observed that surface currents can be generated at the top and bottom layer. At the resonant frequency of 9.19 GHz, the surface currents flow along the two arms of the w-shaped resonator without changing direction, which make the double w-shaped resonator equivalent to a cut-wire resonator along the -u axial direction, as shown in Fig. 12. The cut-wire resonator forms an equivalent current $i$, which is antiparallel to the current flowing on the metallic ground. Namely, they are forming current loops in the intermediate dielectric substrate, known as a magnetic resonance, which results in an equivalent artificial magnetic moment. Similarly, for the resonance frequency of 23.85 GHz, the surface currents of double w-shaped resonator (also equivalent to a cut-wire resonator) are parallel to those induced on the ground sheet, as shown in Figs. 11(c) and 11(f). Hence, the electric resonance is formed. For Fig. 11(b), the situation is a little complicated, which involves both electric and magnetic resonances. As shown in Figs. 11(b) and 11(e), the surface currents are perpendicular with each other. However, they can be decomposed into two components, as indicated by the green and purple arrows in Figs. 11(b) and 11(e). For the currents represented by green arrows, they indicate magnetic resonance due to the antiparallel direction; while for the currents represented by purple arrows, they form electric resonance since their directions are the same. Based on Fig. 11, the physical mechanism behind the three PCR peaks can be clearly understood.

Compared to previous designs, our design has a simple geometry but can realize a high-efficiency and broadband polarization rotation. Table I compares the key characteristics of the proposed polarization converter with other reported devices based on single-layer metasurface in the microwave frequency range. The comparison indicates that our design has an ultra-wide band in which the PCR is greater than 90%, meaning excellent performance.
V. CONCLUSION

In conclusion, an ultra-broadband and wide-angle polarization converter based on double \(\omega\)-shaped metasurface is proposed. The polarization converter can realize a broadband polarization conversion in the microwave frequency. Both the numerical simulation and experimental results show that the PCR of the proposed polarization converter is above 90% in the frequency range from 8.44 GHz to 24.96 GHz and the relative bandwidth reaches 99%. In addition, the polarization converter is insensitive to the incident angle, the mean PCR remains more than 80% even when the incident angle increases to 50\(^\circ\). Since the proposed polarizer has features like wide bandwidth, high PCR and incident angle insensitivity, it has many wide applications in novel polarization-control devices.

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