Ultrabroadband reflective polarization convertor for terahertz waves

Yong Zhi Cheng,1,2 Withawat Withayachumnankul,1,3,a) Aditi Upadhyay,3 Daniel Headland,1 Yen Nie,2 Rong Zhou Gong,2 Madhu Bhaskaran,3 Sharath Sriram,3,b) and Derek Abbott1

1School of Electrical and Electronic Engineering, The University of Adelaide, Adelaide, South Australia 5005, Australia
2School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
3Functional Materials and Microsystems Research Group, School of Electrical and Computer Engineering, RMIT University, Melbourne, Victoria 3001, Australia

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We design and experimentally demonstrate an ultrathin, ultrabroadband, and highly efficient reflective linear polarization convertor or half-wave retarder operating at terahertz frequencies. The metamaterial-inspired convertor is composed of metallic disks and split-ring resonators placed over a ground plane. The structure exhibits three neighboring resonances, by which the linear polarization of incident waves can be converted to its orthogonal counterpart upon reflection. For an optimal design, a measured polarization conversion ratio for normal incidence is greater than 80% in the range of 0.65–1.45 THz, equivalent to 76% relative bandwidth. The mechanism for polarization conversion is explained via decomposed electric field components that couple with different resonance modes of the structure. The proposed metamaterial design for enhancing efficiency of polarization conversion has potential applications in the area of terahertz spectroscopy, imaging, and communications. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4901272]

Terahertz science and technology have seen rapid development, underpinned by many promising applications in imaging, sensing, and communications.1 Towards these applications, high-performance terahertz components become essential for manipulating terahertz waves. One important group of components is related to polarization manipulation, including polarizers, wave retarders, and polarization rotators. In particular, conventional wave retarders can be achieved by using waveplates made of natural birefringent materials with a retardation effect.2,3 Those wave plates require a relatively long propagation distance to obtain sufficient phase accumulation, despite the limited operation bandwidth and availability. Thus, more convenient and flexible approaches are desirable to fully manipulate the polarization state of electromagnetic waves.

Over the past decade, metamaterials as artificial composite materials have attracted great attention due to their exotic electromagnetic properties unavailable to natural materials.4 Such unique properties open up significant opportunities, including an alternative approach to manipulating the polarization of electromagnetic waves.5–9 Several high-efficiency wave retarders have been demonstrated through different metamaterial microstructure designs, and these polarization wave retarders were demonstrated for conversion between different polarization states, such as linear to linear,10–14 linear to circular,15,16 and circular to circular polarization.17 Compared with the traditional wave plates, these metamaterial-based wave retarders have advantages including subwavelength thickness, high conversion efficiency, angular tolerance, and scalability. In most of the existing wave retarders, the polarization states are manipulated in the transmission mode with a limited number of designs operating in the reflection mode.11,12,15,18 For most retarders in the reflection mode, the undesirable high co-polarization reflection severely limits the polarization conversion efficiency and the bandwidth. To extend the functionality, broadband reflective polarization convertors or retarders with high performance are highly desirable.

Here, we present design, fabrication, and characterization of an ultrathin and highly efficient half-wave retarder operating in the reflection mode at terahertz frequencies. Based on the concept of metamaterials, the retarder comprises an array of split-ring resonators (SRRs) and disk resonators (together henceforth referred to as DSRRs), which in conjunction can rotate the linear polarization by 90° with an extended operation bandwidth. An underlying physical mechanism of the observed polarization conversion is investigated through decomposed electric field components that interact with the DSRRs.

A schematic of the proposed reflective linear polarization convertor is shown in Fig. 1. A unit cell of the DSRR is composed of a metallic disk and split-ring resonator placed near to the ground plane and separated by a 30-μm thick

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*a)Electronic mail: withawat@eleceng.adelaide.edu.au
b)Electronic mail: sharath.sriram@gmail.com

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FIG. 1. Schematic of the proposed polarization convertor: (a) A DSRR array and (b) a unit cell structure. The dimensions are as follows: \( p_x = p_y = 110 \mu m, t_b = 30 \mu m, r_i = 28 \mu m, r_o = 48 \mu m, w = 12 \mu m, s = 6.8°\), and \( \theta = 41.6°\).
polydimethylsiloxane (PDMS) dielectric spacer. Specifically, the top metallic layer and the ground plane are made of 200 nm thick gold and platinum layers, respectively, to provide etch selectivity during microfabrication. The structure is periodic along the \( x \) and \( y \) axes with periods \( p_x \) and \( p_y \) of 110 \( \mu m \) to avoid diffraction at the normal incidence for frequencies up to 2.7 THz. As shown in Fig. 1(a), the DSRR orientation is such that incident waves with the polarization along the \( x \) or \( y \) axis is rotated by 90° to their orthogonal polarization state after reflecting off the structure.

The DSRR design shown in Fig. 1(a) has been fabricated with photolithography and metallization process steps. A ground plane made of a 200 nm platinum layer with a 20 nm thick titanium adhesion layer is deposited on a standard silicon substrate. The PDMS is subsequently prepared in a 1:10 ratio of curing agent to pre-polymer and spin-coated onto the platinum surface and cured. A spin speed of 1900 rpm with acceleration of 1000 rpm/s\(^2 \) and spin duration of 30 s are used. Then, a 200 nm gold layer with a 20 nm chromium adhesion layer is deposited. This metal bilayer is patterned to define the DSRR structure by photolithography and wet etching. The sample is then cleaned with solvents to strip residual photoresist in preparation for terahertz measurements. The sample is then cleaned with solvents to strip residual photoresist in preparation for terahertz measurements. The sample measures 50 \( \times \) 50 mm\(^2 \) and is made up of 207,025 identical DSRRs with periodic arrangement. Figure 2 shows the microscopic images that reveal the details of a small area and a unit cell of the sample. Subsequent characterization of the sample with a surface/stylus profilometer shows that the actual PDMS thickness, \( t_{PDMS} \), is 45 \( \mu m \), as opposed to the target of 30 \( \mu m \).

The measurement utilizes a fiber-coupled terahertz time-domain spectrometer (THz-TDS), Tera K15 manufactured by Menlo Systems GmbH. For normal incidence, as shown in Fig. 3(a), a linearly polarized terahertz beam from an emitting Menlo Systems GmbH. For normal incidence, as shown in Fig. 1(a), the DSRR orientation is such that incident waves with the polarization along the \( x \) or \( y \) axis is rotated by 90° to their orthogonal polarization state after reflecting off the structure.

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PCR of the optimal structure in Fig. 4(c) is roughly above 80% from 0.65 to 1.45 THz. Hence, the bandwidth relative to the center frequency is 76%. This achieved bandwidth is nearly twice as broad as that obtained from L-shaped antennas in the infrared regime. For this optimal design, the PCR is greater than 95% at the three resonance frequencies, where nearly perfect polarization conversion takes place.

The broadband operation mainly originates from the superposition of multiple resonance modes. As for the fabricated non-optimal structure in Fig. 4(d), the PCR is degraded but can still be maintained over 50% from 0.53 to 1.36 THz. This reasonable performance demonstrates the robustness of the design to fabrication tolerances, particularly where the PDMS thickness is deviated by up to 150%.

Figure 5 shows the magnitude of the reflection coefficients of the non-optimal structure at 45° oblique incidence in the x-z plane with the TM and TE polarizations. The experimental and numerical results are in good agreement in general. For both of the polarizations, the measured magnitude of the cross-polarization reflection coefficients \( r_{yx} \) and \( r_{xy} \) is greater than 50% from 0.52 to 1.3 THz, while the co-polarization reflection coefficients \( r_{xx} \) and \( r_{yy} \) are less than 50%. The corresponding PCRs are greater than 75% at most points in this band as shown in Figs. 5(c) and 5(d). Those sharp spectral features are not resolved in the experiment because of the limited spectral resolution. It is clear that the bandwidth of the convertor can be reasonably sustained at a wide range of incidence angles.

The mechanism of the polarization convertor can be understood from resolved current distributions in relation to decomposed incident electric fields along the \( u \) and \( v \) axes, as shown in Fig. 6(d). At the lowest resonance frequency of 0.71 THz, each arc that constitutes the SRR behaves as a dipole resonator that couples with the \( E_v \) component, as shown in Fig. 6(a) and imparts a zero phase shift in reflection. At this frequency, the structure does not resonate with the \( E_u \) component, and hence a \(-\pi\) phase shift is imparted on this component by the ground plane. At the second resonance, as shown in Fig. 6(b), the \( E_u \) component excites a set of shorter dipoles, which induces a 0° phase shift similarly to the first case. Since the \( E_u \) component is in this case reflected off by the ground plane, the phase difference between the two orthogonal components is equal to \( \pi \). At the highest resonance, as shown in Fig. 6(c), both the disk and SRR are coupled with the \( E_v \) component, which is reflected off with a zero phase change, whilst the ground plane imparts the \( E_u \)
component with an $-\pi$ phase change. Therefore, at these resonance frequencies, the absolute phase difference between the reflected $E_u$ and $E_v$ components is always equal to $\pi$, which causes polarization rotation by 90° for the incident $E_v$. This underlying mechanism for the phase difference is confirmed through the simulation with $E_u$ and $E_v$ excitations on the structure (not shown).

In conclusion, we have numerically and experimentally demonstrated an array of the DSRRs that functions as a broadband half-wave plate to convert the linear polarization of terahertz waves into its orthogonal polarization. The reflection-mode operation at terahertz frequencies offers an alternative to existing converters operating in transmission. For the optimal design, the polarization conversion ratio is greater than 80% in the frequency range between 0.65 and 1.45 THz, equivalent to 76% bandwidth. This high polarization conversion efficiency is ascribed to the three resonances that can be tuned via the DSRR geometry. Furthermore, the results show that this converter can tolerate the oblique incidence with an angle at least 45° for both the TE and TM polarizations. The proposed design can also be used to invert the handedness of the elliptically or circularly polarized waves and can be scaled to operation at other frequency ranges.

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