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Cavity-based high-efficiency and wideband 90° polarization rotator

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We present a high-efficiency wideband 90° polarization rotator based on 2D array of substrate integrated waveguide cavities etched with three twisted slots, which can rotate a horizontally polarized incident wave into an outgoing vertically polarized wave. The twisted slots etched on the surface of the cavity are utilized to couple the wave into and out of the cavity with the polarization direction rotated. As a proof-of-concept, a prototype of the proposed rotator is fabricated and measured in the microwave regime. The proposed 90° polarization rotator features a low insertion loss of about 0.5 dB in the pass band with a fractional bandwidth of 28.6%, as well as high polarization rotation efficiency of over 90%. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4964855>]

Polarization is an essential nature of electromagnetic (EM) waves, which carries the information about microscopic anisotropy, chiral feature, and spin orientation. Hence, it plays a central role when the waves interact with matter.^{1,2} Controlling the polarization state of an incident wave shows extreme importance for a variety of applications and has been extensively explored from microwave to optical frequencies.^{3–5} Among the polarization-selective devices, linear polarizers^{6,7} are used to select a wanted direction of linearly polarized (LP) wave from the mixed-polarization waves, while circular polarizers^{8,9} are utilized to transmit a circularly polarized wave of a specific handedness. Different from polarizers, polarization converters¹⁰ can realize conversion between linear and circular polarizations. Nevertheless, with the fast development of wireless communication systems and photonic integrated circuits, polarization rotators, especially 90° polarization rotators,^{11–26} are being developed, which can rotate the polarization plane of an LP wave by 90° without changing its LP nature.

Conventional 90° polarization rotators are designed using mode coupling with bulky plasmonic waveguide made by silicon-on-insulator.^{15–18} This configuration cannot be easily integrated in a compact system. For this reason, chiral metamaterials (CMMs) were recently explored and proposed to realize 90° polarization rotators with compact, planar, and easily integrated structures,^{19–22} which can obtain the polarization rotation within a subwavelength thickness. Due to their extremely thin profile and subwavelength resonant nature, the CMM polarization rotators are inherently narrow-banded. Although broadband polarization rotators have been realized in metasurface using localized surface plasmon,²⁵ their transmission loss is quite large, which means that only part of the energy can pass through the polarization rotators. To overcome this shortcoming, cavity-based structures^{7,26} have been recently proposed to rotate the polarization direction of an incident LP wave, while their operating band may be further improved.

In this Letter, we demonstrate that a high-efficiency wideband 90° polarization rotator can be realized based on a 2D periodic array of cavities etched with three twisted slots, which can rotate the polarization direction of an LP wave by 90°. The fundamental mode in the cavity is carefully investigated to understand the polarization rotation mechanism. After that, the polarization rotational characteristic of the proposed rotator is verified through both numerical simulations and experimental measurements. Results demonstrate that an extremely flat and high cross-transmittance of 0.9 as well as high polarization rotation efficiency (PRE) of over 90% can be obtained over a wide frequency band. Furthermore, a detailed comparison of typical 90° polarization rotators is made to demonstrate the superior performance of the proposed rotator.

The proposed 90° polarization rotator is depicted in Fig. 1(a). It is constructed by a 2D periodic array of double-layer substrate integrated waveguide cavities, with three twisted slots etched on the front, middle, and back metal surfaces, respectively. The three slots are twisted 45° with respect to each other. An x -polarized wave propagating along the z -direction strikes normally onto the rotator, and a y -polarized wave is subsequently transmitted out on the other side of the rotator without much attenuation. The structural details of a unit cell of the proposed rotator are shown in Fig. 1(b). It is clear that the unit cell consists of two square cavities formed by three metallic interfaces with two thin substrates. Specifically, the vertical walls of the cavity are implemented through the use of four rows of metallized cylindrical vias. The metallized via-holes have the diameter of D and period of P along x - and y -directions, respectively; their values should be properly chosen to make sure that a cavity of vertical walls can be formed.⁷ The side width and thickness of the square cavity are marked as W and t , respectively. The y -directed slot etched at the center of the front surface is used to couple the x -polarized incident wave into the cavity, while the x -directed slot at the center of the bottom surface is utilized to couple the field out so that the transmitted wave is y -polarized. More importantly, the slot tilted 45° is introduced at the center of the middle surface,

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FIG. 1. Schematic diagram of the proposed 90° polarization rotator. (a) 3D view of the cavity-based polarization rotator and its function. (b) Expanded view of the structural details of a unit cell, where the dashed lines indicate that there is no distance between each other.

which artfully extradites the energy from the front cavity to the back one. The lengths and widths of three slots are denoted by l_1 , l_2 , l_3 , w_1 , w_2 , and w_3 , respectively, as manifested in Fig. 1(b). The performance of the proposed 90° polarization rotator is simulated by the full-wave EM simulation software ANSYS HFSS. Moreover, periodic boundary conditions are employed along the x - and y -directions to characterize the infinitely large structure. Furthermore, the polarization of the incident wave is x -polarized in our simulations.

As a cavity resonator, it is of importance to investigate the operating mode inside the cavity. Generally, a cavity of very low profile only supports TM_{mn0} modes,²⁶ which indicates that the fields in the cavity are uniform along the z -direction. In addition, due to the fact that the electric current on the lateral side walls can flow only in the z -direction along the metallized vias, TE modes cannot exist in the cavity. In this design, the fundamental TM_{110} mode is utilized as the operating mode of the cavity, which results in a smaller size for the unit cell and more stable performance under oblique incidence. Besides, this fundamental mode features relatively low quality factor when the cavity has centrally cut slots compared to higher-order modes and this leads to a broader operating band, as demonstrated later. Its resonant frequency f can be estimated from the physical dimension as follows:⁷

$$f = \frac{c_0}{\sqrt{2\mu_r\epsilon_r W_{eff}}}, \quad (1)$$

where c_0 is the speed of light in vacuum, ϵ_r and μ_r are the relative permeability and permittivity of the substrate, respectively, and $W_{eff} = W - D^2/(0.95P)$ is the effective width of the conventional metallic cavity.

To gain insight into the polarization rotation mechanism, the electric field inside the cavity and electric current distributions of the TM_{110} mode are carefully investigated using HFSS Eigenmode Calculator, as shown in Figs. 2(a) and 2(b). It is worth mentioning that the simulated quality factor of the pure cavity is 770. It can be clearly seen that the field is well confined in the via-surrounded cavity, which suggests that a good cavity is obtained by utilizing the metallized vias to act as vertical walls of the cavity. Moreover, both numbers of extremes in the cavity are one along the x - and y -directions, which indicate that the mode of operation in the cavity is indeed the TM_{110} mode. Again, there is

no variation along the z -direction, as illustrated in Fig. 2(a). Furthermore, the electric current distribution in Fig. 2(b) is directing toward to the surface's center of the cavity, which corresponds to the electric field distribution. In this design, we employ slot coupling to excite the cavity on its both front and back surfaces. The initial length of the slot is equal to half a guided wavelength $c_0/(2f\sqrt{(\epsilon_r + 1)/2})$.

Based on the analysis of field distributions, it is easy to think of directly using two perpendicular slots etched on the front and back surfaces of a cavity, respectively, to achieve 90° polarization rotation, as shown in the inset of Fig. 3(a). Unfortunately, the behavior of this simple design is not satisfactory because the electric current on the back surface will be distributed along the x -direction under the influence of the y -directed slot. In this case, the backside x -directed slot cannot cut the current flow, and thus, no y -polarized wave can be coupled out from the cavity, which is demonstrated by the cross-transmittance T_{yx} shown in Fig. 3(a). However, high co-transmittance T_{xx} of 0.65 is observed, and this is due to the wide slots used to facilitate the wave going through the cavity from one side to the other. In order to achieve the polarization rotation, a tilted slot is introduced on the backside of the cavity. It is noted that the tilt angle of the tilted slot should be less than 45°, so that the tilted slot can effectively cut the currents and then radiate the wave with the polarization direction perpendiculars to the slot. In other words, one layer cavity etched with two twisted slots can realize arbitrary polarization rotation from 0° to 45°. Therefore, one can utilize N -layer cavities etched with $N + 1$ twisted slots, with twisted angle of $90^\circ/N$ ($N \geq 2$) to realize a 90° polarization rotator. Although the bandwidth and efficiency of the rotator can be slightly enhanced with increasing number of layers, the structure will become more complicated, resulting in high

FIG. 2. Perspective view of (a) electric field and (b) surface electric current distributions of TM_{110} mode.

FIG. 3. Simulated transmission characteristics of structures etched with (a) orthogonal and (b) twisted 45° slots. ($W = 4.2$ mm, $l_1 = l_2 = 4$ mm, and $w_1 = w_2 = 2$ mm.)

fabrication costs. To simplify the structure of the rotator, the tilt angle of 45° is considered in this Letter, as shown in the inset of Fig. 3(b). It can be seen that both T_{yx} and T_{xx} have a relatively high value around 0.7, which indicates that the wave can pass through the cavity with its polarization direction rotated by 45° . Consequently, we can use two cavities etched with three twisted slots to realize the proposed 90° polarization rotator, as shown in Fig. 1.

To verify the functionality of the proposed configuration, a sample of a 42 mm $\times$ 42 mm containing an array of 10×10 unit cells is fabricated using the standard printed circuit board and plated through-hole technology. The photograph of our fabricated sample is shown in Fig. 4. The substrate used is RT/Duroid 3003 with $\epsilon_r = 3 + i0.002$, which has a smaller imaginary part of its complex permittivity and hence absorbs less energy. In addition, this substrate has a metal thickness

FIG. 4. Perspective view of the fabricated rotator.

of 0.017 mm, which is much greater than the penetration depth of gold at microwave frequencies, and therefore, the metal is considered to be a perfect electrical conductor. The optimized physical dimensions of the proposed 90° polarization rotator are designed as $D = 0.3$ mm, $P = 0.525$ mm, $W = 4.2$ mm, $t = 0.76$ mm, $l_1 = 4.1$ mm, $l_2 = 3.6$ mm, $l_3 = 3.8$ mm, $w_1 = 2.05$ mm, $w_2 = 1.8$ mm, and $w_3 = 1.9$ mm.

The fabricated sample is measured by the free-space method using two horn antennas and a vector network analyzer (VNA). In our experiment, the two horn antennas are separated by a distance of 300 mm so as to meet the far-field region condition. The incident wave is polarized along the x -direction and normally impinging onto the sample, and the corresponding reflection and transmission coefficients of x - and y -polarized waves are then measured by rotating the polarization direction of the receiving horn. It should be pointed out that since the highest frequency of our VNA is 43.5 GHz, we can only provide measured data for the frequency up to 43.5 GHz. Figure 5 shows the performance of the proposed 90° polarization rotator under normal incidence with the excitation of an x -polarized wave. All measured results show good agreement with simulated ones, while some small differences are attributed to the manufacturing and experimental errors. It is clear in Fig. 5(a) that both co- (R_{xx}) and cross- (R_{yx}) reflections are below 0.3 from 30 to 40 GHz, representing a fractional bandwidth of 28.6% at the center frequency of 35 GHz. Moreover, three reflection poles can be observed in the R_{xx} curve. To understand these reflection poles, the slot and cavity modes of the proposed structure are carefully investigated through the Eigenmode Calculator. Figure 5(b) plots the quality factors of resonant modes and their corresponding frequency variations by changing the slot width. It is obvious that the two modes with the lower and higher quality factors are representing the slot and cavity resonances, respectively. It can be seen that the quality factors of slot modes are relatively stable under different slot widths. However, the loaded quality factors of the cavity mode are drastically reduced with the increase in the slot width. When the slot width is very small, the two cavity modes are very close. By increasing the slot width, the separation between these modes becomes more and more obvious, which leads to different distinct resonant frequencies. It should also be mentioned that the resonant frequencies of one slot mode and one cavity mode are very close to each other, which result in a merged resonant frequency. Therefore, three resonant frequencies are noticed in R_{xx} , as shown in Fig. 5(a).

Figure 5(c) gives the corresponding transmittances of x - and y -polarized waves coming from an x -polarized incident wave. Clearly, a remarkably flat and high T_{yx} around 0.9 of y -polarized wave can be obtained, from 30 to 40 GHz, which is consistent with the reflectance results. In addition, the T_{xx} shown in Fig. 5(c) is below 0.3 throughout the entire frequency band. Resultantly, the proposed polarization rotator can efficiently rotate an x -polarized incident wave into an outgoing y -polarized wave. This remarkable characteristic can also be demonstrated by the PRE, which is defined as

$$PRE = P_y / (P_y + P_x), \quad (2)$$

FIG. 5. Performance of the proposed 90° polarization rotator, where the lines with and without symbol represent the measured and simulated results, respectively. (a) Reflectance of an LP incident wave reflected by the rotator, the inset shows the configuration of a unit cell. (b) Quality factors of resonant modes and their corresponding resonant frequencies variations by changing the ratio k , $k = w_i/l_i$. (c) Transmittances of x - and y -polarized waves coming from an x -polarized wave. (d) PRE of the proposed rotator, the inset shows the simulation model and its function.

where P_x and P_y represent the power of transmitted x - and y -polarized waves, respectively. Figure 5(d) plots the PRE of the proposed 90° polarization rotator. It can be seen that the high PRE of over 90% can be obtained from 31.4 to 41.9 GHz, representing to a fractional bandwidth of 28.6%. Furthermore, it is noted that PRE decreases dramatically outside the operating band because the cavity mode cannot be excited, and the incident wave is then rejected by the structure. Therefore, both x - and y -polarized waves are very weak on the other side of the rotator. Simultaneously, the electrical field shown in the inset also clearly demonstrates the function of the proposed structure to achieve 90° polarization rotation.

In order to clearly illustrate the performance of our rotator, a detailed comparison between the proposed design and other typical 90° polarization rotators is made in Table I. It can be observed that our rotator has a low insertion loss (IL) of 0.5 dB and a thin thickness of $0.178 \lambda_0$ (λ_0 is the free-space wavelength at the center frequency), as well as a wide bandwidth of 28.6% for reflection below 0.3 and at least 90% PRE. As shown in Table I, the waveguide structure shows the largest thickness, while the design based on CMM exhibits very small thickness accompanied by an extremely narrow operating bandwidth. Although the metasurface rotator shows the broadest bandwidth for PRE, it has restricted

applications due to its extremely high IL. Compared with the previously described cavity-based designs, our proposed 90° polarization rotator has a much wider operating bandwidth for reflection below 0.3 and at least 90% PRE, which exhibits its superior performance.

In conclusion, we have experimentally demonstrated a high-efficiency and wideband 90° polarization rotator using superposition of two cavities etched with three twisted slots. The fundamental TM_{110} mode in the cavity has been analyzed in detail to reveal the polarization rotation mechanism. A prototype of the proposed rotator has been fabricated, and measured results are in close agreement to the theoretical predictions. Compared with other types of 90° polarization rotators, our rotator exhibits excellent performance, in terms of low insertion loss, broad operating band, and high PRE, as well as small thickness, which makes the proposed rotator potentially useful in many practical systems.

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TABLE I. Performance comparison of typical 90° polarization rotators.

References	Structure	IL (dB)	Bandwidth (%)		Thickness (λ_0)
			$R < 0.3$	$PRE > 0.9$	
15	Waveguide	~5	...	~10	1.61
19	CMM	0.5	1–3	1–3	0.03
23	Metal grids	1.9	...	...	0.132
25	Metasurface	12	...	46	0.33
26	Cavity-based	0.2	9.1	9.1	0.184
This work	Cavity-based	0.5	28.6	28.6	0.178

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