Frequency-selective microwave polarization rotator using substrate-integrated waveguide cavities*

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A frequency selective polarization rotator that can rotate the polarization angle of an incident electromagnetic wave at the microwave frequency by 45° is presented. The polarization rotator is based on a two-dimensional periodic array of substrate integrated waveguide cavities, realizing the polarization rotation by coupling the input signal to the output wave through three metallic slots. Two layers of frequency selective surfaces are cascaded by substrate and form the polarization rotator. A vertical slot on the top layer is used to select the horizontal polarization from the incident wave, the vertical and the horizontal slots on the bottom layer are, respectively, used to obtain horizontally and vertically polarized outgoing waves. The two orthogonal outgoing waves are combined to result in the 45° polarized wave. Both full wave simulation and experimental measurement are carried out, together validating the proposed method.

Keywords: polarization rotator, substrate integrated waveguide (SIW), frequency selective surface (FSS)

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1. Introduction

Frequency and polarization controls are two important aspects in free space electromagnetic (EM) wave propagation, and may find useful applications in telecommunication and radar technology. Frequency selective surfaces (FSSs) are periodic structures which consist of one- or two-dimensional arrays of patches or slots, and can respectively exhibit bandstop or bandpass filtering performance for the spectral control of free space EM wave propagation. FSSs are widely used as antenna sub-reflectors, radomes, spatial filters of EM waves, etc.[1–3] Polarizers or polarization rotators are structures that are able to control or change the polarization direction when the EM waves propagate through them. Several structures have been proposed and successfully used in the polarization-selective technology, such as the meander-line polarizers,[4,5] ultra-wideband polarization-selective surfaces,[6] and split-ring slots FSSs.[7] A polarization rotator is a passive device that can rotate the electric field vector of an incident linearly polarized EM wave by certain degrees. In some communication systems, especially within mobile telephony, a 45° polarized wave is sometimes required, for example, associated with a dual-polarization or cross-polarization antenna. This type of polarization seems to have more advantages, such as the symmetrical propagation property compared with 0°/90° polarization.[8,9] Meanwhile, in some specific radar applications, such as collision avoidance automotive radar systems, a slot array antenna for 45° inclined linearly polarization is required to alleviate the interference coming from the opposite direction.[10]

Moreover, periodic metamaterial structures, especially chiral metamaterial structures, have been proposed to realize 90° polarization rotators.[11–14] Those 90° polarization rotators are based on an EM resonance in the metamaterial structure and therefore have a very narrow passband that can work only near a single frequency. An FSS based on the substrate integrated waveguide (SIW) technology was presented in Ref. [15]. The SIW technology has the advantages of low cost, low loss, and ease of fabrication. In a recent paper, an FSS based on the SIW technology was proposed to rotate the polarization of an incoming plane wave by 90°.[16]

In this paper, we propose a new FSS structure that has both the frequency selection and the polarization rotation abilities. We demonstrate the bandpass of the incident wave within a certain frequency band in the Ku band as well as the rotation of a linearly polarized incident wave by 45° through periodically arranged unit cells of dual-mode SIW cavities. By using two orthogonal slots on the back side of the SIW cavity, two waves can be radiated through the slots and combined to form a wave with 45° rotated polarization. Adjusting the coupling between these two orthogonal waves yields the required magnitude and phase difference and achieves the required polarization. The proposed structure exhibits a number of features, such as a dual-mode configuration, which provides a second-order resonance and therefore realizes a broader bandwidth and a flat-top transmission response as well as a high Q

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factor, a high selectivity characteristic.

2. Design of the polarization rotator

2.1. Description of the proposed structure

SIWs, synthesised on a planar substrate with periodic arrays of metallic vias, have developed rapidly over the past decade. They provide a very attractive platform to design low-cost and highly integrated microwave waveguide components, especially for filters and antennas.[17,18] The proposed frequency selective polarization rotator is based on an FSS structure utilizing an SIW configuration, which is quite compacted and easy to be fabricated with the standard printed circuit board technique. The geometry of a unit cell of the FSS in the 45° polarization rotator is shown in Fig. 1. The proposed structure comprises a square SIW cavity with one vertical slot on the top plane (solid line) and two orthogonal slots on the bottom plane (dotted line). The vertical slot on the input (top) plane is used to select the horizontally polarized wave and excite the field in the SIW cavity. The outgoing waves are coupled through the slots on the output plane. The horizontal and vertical slots on the output (bottom) plane are used to transmit vertically polarized (90° rotated cross-polarization, y-polarized) and horizontally polarized (co-polarization, x-polarized) outgoing waves, respectively. It is well known that when the phase difference between two orthogonal wave components is 0° or ±180°, they will combine to form a linearly polarized wave. If the two components are equal in amplitude, the combined wave is of 45° rotated linear polarization. If the two components with equal amplitude have a phase difference of 90°, a circularly polarized wave can be obtained.

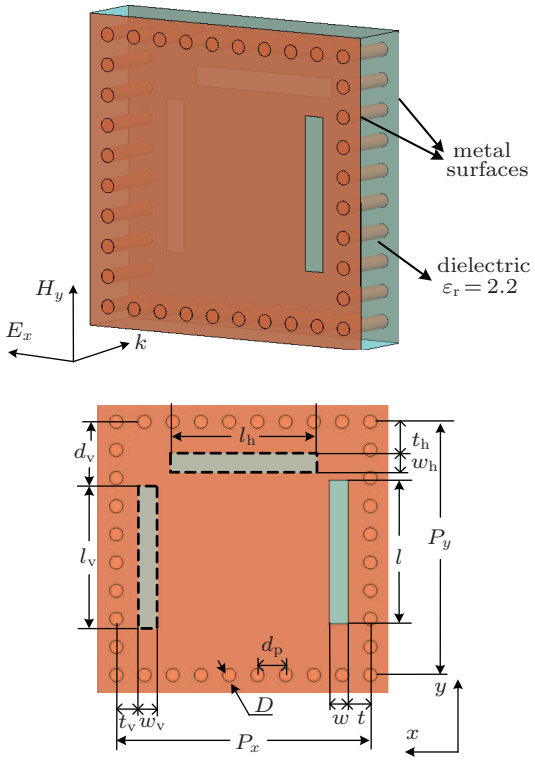


Fig. 1. (color online) Geometry of a unit-cell of the proposed 45° polarization rotator.

2.2. Operating principle

As is well known, the conventional FSS consisting of periodic slots in a metallic surface leads to a bandpass performance. In Ref. [19], the SIW technique was first applied to a bandpass FSS, in which the unit cell was made of an SIW cavity with the same slots on the top and the bottom surfaces. Two different resonance modes can be excited by a plane wave in the SIW cavity. The combination of the SIW cavity with slotted FSS sheets results in two different resonances and hence provides a highly selective bandpass response. Based on this, FSSs with the SIW technique were presented to provide a quasi-elliptical bandpass response.[20,21] A compact FSS with a quasi-elliptic bandpass response, realized by vertically cascading three SIW cavities with different slots on the surface, was presented in Ref. [22].

To take advantage of this, the proposed structure is composed of a periodic SIW cavity with different slots on the top and the bottom surfaces. The operating principle of the proposed polarization rotator can be understood by considering a virtual decomposition of the unit cell into two structures, as shown in Fig. 2. With respect to the polarization direction of the incident wave, one structure transmits its cross-polarized wave and the other transmits its co-polarized wave.

The signal can couple into or emit from the cavity only when the E-field vectors are orthogonally aligned with the slots. The electric field vector of the incident wave is perpendicular to the vertical slot on the top surface, hence the horizontally or x-polarized waves can couple into the SIW cavity through the input slot. The y-polarized waves can be transmitted through the horizontal output slot and the x-polarized waves can be transmitted through the vertical output slot in the bottom surface.

Figure 2(a) illustrates an example of an x-directed co-polarization wave transmitter, which consists of two parallel slots: one on the top plane and the other on the bottom plane. The slot on the top is used to select the horizontal polarization from the incident wave and the parallel slot on the bottom is used to realize an outgoing wave with the same (co-) polarization. When the backside slot is horizontally or orthogonally placed, it becomes a y-directed 90° polarization rotator as shown in Fig. 2(b). The cross-polarized signal is transmitted from the slot on the bottom, and produces an outgoing wave of rotated polarization 90° compared with the incident wave. It should be mentioned that the simulated results in Fig. 2 are obtained from a full-wave EM numerical simulation utilizing the commercial software Ansoft HFSS.

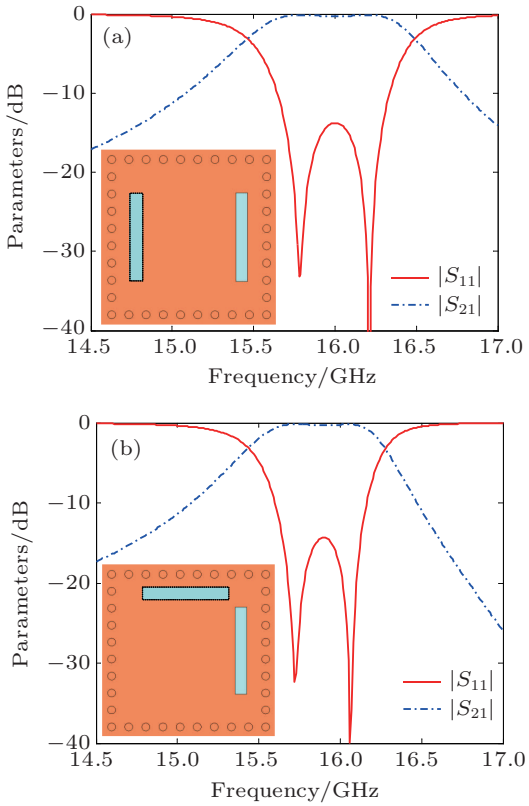


Fig. 2. (color online) Simulated frequency responses of the two separate polarization rotators. (a) Co-polarization transmitter ($l_v = 7.7$ mm, $t = t_v = 2.8$ mm), (b) Cross-polarization rotator ($l_h = 7.75$ mm, $t = t_h = 2.35$ mm), the other parameters are $P_x = P_y = 13.5$ mm, $D = 1$ mm, $d_p = 1.5$ mm, $h = 3.175$ mm, $l = 7.7$ mm, $w = w_v = 1$ mm.

Figure 2 shows that the incident signals are well coupled at the resonant frequency, and the pass bands of the two examples are almost identical around 16 GHz. Combining the two examples together yields a structure with one slot on the input plane and two orthogonal slots on the output plane, as shown in Fig. 1, which results in the transmission of two orthogonally polarized signals. The dimensions of the structure are slightly adjusted, and the optimized dimensions of one design example of the 45° polarization rotator are shown in Table 1.

Table 1. Dimensions of one design example of the polarization rotator (in units of mm).

P_x, P_y	D	d_p	h	l_s	w_s	t_s
13.5	1	1.5	3.175	7.7	1	2.94
l_h	w_h	t_h	l_v	w_v	t_v	d_v
7.75	1	2.94	7.6	1	2.94	5.03

Figure 3 shows the simulated results of the proposed polarization rotator. Two orthogonal signals are transmitted in the passband with nearly equal amplitude (an insertion loss of 3 dB as shown in Fig. 3(a)). A phase difference of 180° exists between the two outgoing signals (as shown in Fig. 3(b)), which results in rotating the polarization by 45° when combined. A 3-dB bandwidth for $|S_{21}| \geq -6$ dB is about 5.6% (15.47–16.37 GHz). To demonstrate the polarization quality, the axial ratio (AR), the amplitude ratio E_{cross}/E_{co}, and the phase difference between the E_{cross} and E_{co} components have been calculated and shown in Fig. 4. It can be seen that the AR exceeds 50, with a peak of 450 at 15.8 GHz. The amplitude ratio is close to 1, and the phase difference approaches 180° in the passband. The reflection leakage (reflection in cross-polarization) is well below −50 dB.

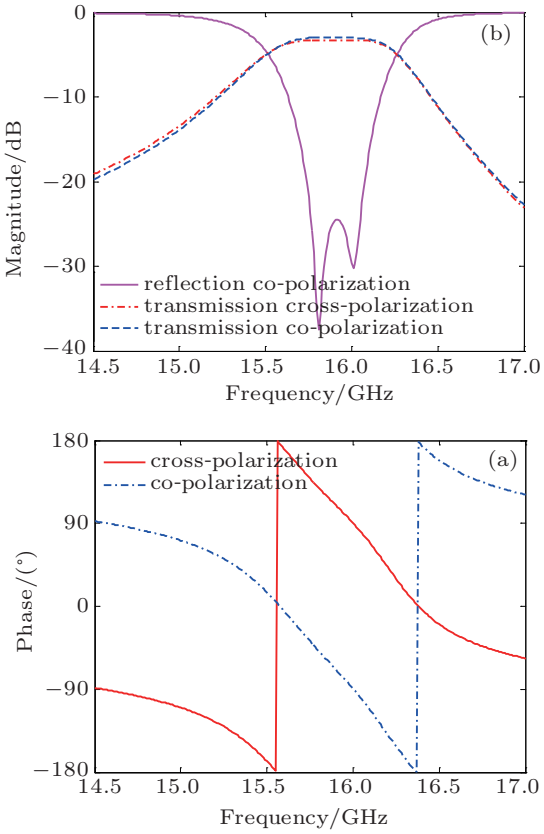


Fig. 3. (color online) Simulated (a) magnitude and (b) phase of the reflection and transmission coefficients of the proposed structure.

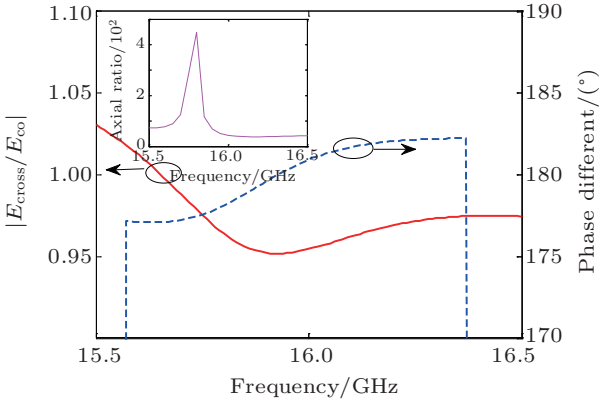


Fig. 4. (color online) Axial ratio (inset), amplitude ratio, and phase difference between two orthogonal electric field components E_{cross} and E_{co}.

2.3. Mode analysis and design guidelines

In general, an SIW cavity only supports TM_{mn0} modes ($m = 1, 2, 3, \ldots$ and $n = 1, 2, 3, \ldots$). Based on the above slot

arrangement, TM_{mn0} and a dual-mode configuration combining TM_{n10} and TM_{1n0} ($n \geq 1$) modes are allowed in the cavity.

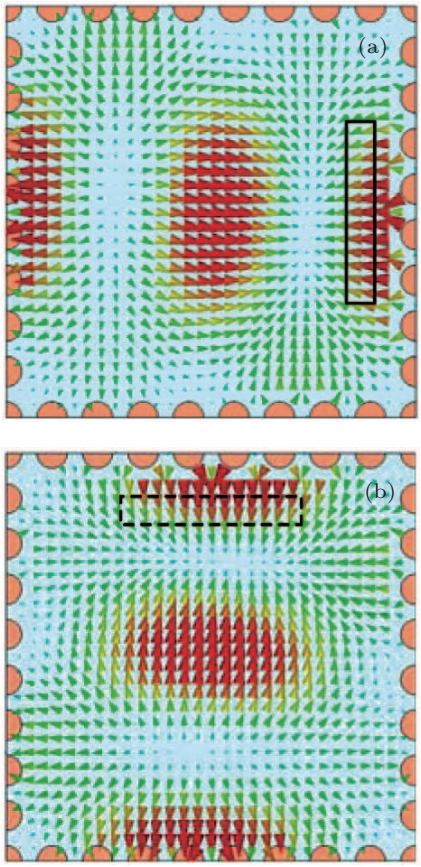


Fig. 5. (color online) Electric field distributions of (a) the TM_{210} mode (input coupling) and (b) the TM_{120} mode (output coupling) in the SIW cavity.

For the TM_{110} mode, the required slot length is almost equal to the size of the cavity, whereby the slot would be too long for the cavity, and therefore this mode is not chosen in our design. The TM_{210} and TM_{120} modes, as shown in Fig. 5, are also suitable for the configuration. These two degenerate modes co-exist in the SIW cavity. The TM_{210} mode can be strongly excited through the coupling between the incident wave and the vertical slot on the top surface, and then the TM_{210} mode would be coupled to the TM_{120} mode inside the cavity. The outgoing wave is coupled with the slot on the bottom surface through the TM_{210} mode in the case of Fig. 2(a) and through the TM_{120} mode in the case of Fig. 2(b). For TM_{310} and TM_{130} modes or other dual-mode configurations such as TM_{n10} and TM_{1n0} ($n > 3$) modes, the coupling with the incident wave is weaker and the performance is degraded, which is not preferred in the design. Hence, based on the dimension and arrangement considerations, the TM_{210}/TM_{120} dual-mode configuration performs best in this design.

The dimensions of the SIW cavity can be determined from

$$f_{r,TM_{mn0}} = \frac{c_0}{2\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{P_{xeff}}\right)^2 + \left(\frac{n}{P_{yeff}}\right)^2}, \quad (1)$$

with $P_{eff} = P - D^2/0.95d_p$, which is valid for $d_p < \lambda_0\sqrt{\varepsilon_r}/2$ and $d_p < 4D$. Here P_x and P_y represent the size of the SIW cavity and ε_r is the dielectric constant of the material. The integers m and n are the mode indices, D is the diameter of the via holes, and d_p is the distance between the centers of two adjacent via holes.

The narrow slot resonates at the specified frequency when the slot length l is approximately equal to half of the wavelength. Hence the slot length can be approximately obtained from

$$l = \frac{c_0}{2f_{rs}\sqrt{\varepsilon_{eff}}}, \quad (2)$$

where the effective dielectric constant is $\varepsilon_{eff} = \sqrt{(\varepsilon_r + 1)/2}$, and f_{rs} is the resonant frequency of the slot, which needs to be close to the resonant frequency of the SIW cavity so that a coupled incident wave can determine the excitation of the cavity mode.

Generally speaking, a substrate material with a lower dielectric constant increases the bandwidth of the bandpass structure. Moreover, the thickness of the substrate affects the effective permittivity as well as the field caused by the slot, therefore influencing the bandwidth. With a thicker substrate, the perturbation in the cavity is enhanced and the bandwidth increases. Hence, a Rogers 5880 substrate with a dielectric constant of 2.2 and a thickness of 3.175 mm is used in the design example.

With the designed resonant frequency of 16 GHz as an example, employing the substrate with a dielectric constant of 2.2 and using the TM_{210}/TM_{120} dual-mode configuration, we obtain the size of the SIW cavity from Eq. (1) as $P_x = P_y =$ 13.5 mm. The slot length can be calculated from Eq. (2) to be $l = 7.7$ mm. The slot is set with a width nearly $l/8$ and a slot position close to the cavity edge at $t = 2.94$ mm.

The resonant frequency of the modes in the cavity is defined mainly by the unit-cell size P. Varying the size of the slots (length l and width w) affects the frequency, which needs to be close to the cavity resonant frequency. Moreover, a larger P and a smaller l result in less perturbation and a narrower bandwidth.

3. Experimental results

Figures 6(a) and 6(b) show the photographs of the fabricated polarization rotator. It has 14 × 15 unit cells, with outer dimensions of 210 mm× 223 mm. The measurement is conducted in an anechoic chamber. Two linearly polarized Ku band horn antennas, which have a focusing dielectric lens mounted on the aperture, are employed as the emitter and the

receiver for the EM waves, as shown in Fig. 6(c). The distance between the lens antennas and the FSS is kept to the focal length to make sure the focus is located on the FSS. A number of thru-reflect line (TRL) calibration steps are carried out first, whereby the transmission in the empty chamber and the reflection by conducting plates are taken into account as references. The reflection for an *x*-polarized wave (co-polarization) is measured by receiving a reflected horizontally polarized wave with an incident wave of horizontal polarization. The transmission (including magnitude and phase) in *x*-polarization or *y*-polarization is measured by receiving transmitted horizontally or vertically polarized waves (with the receiving antenna rotated by 90°), respectively, with a horizontally polarized incident wave.

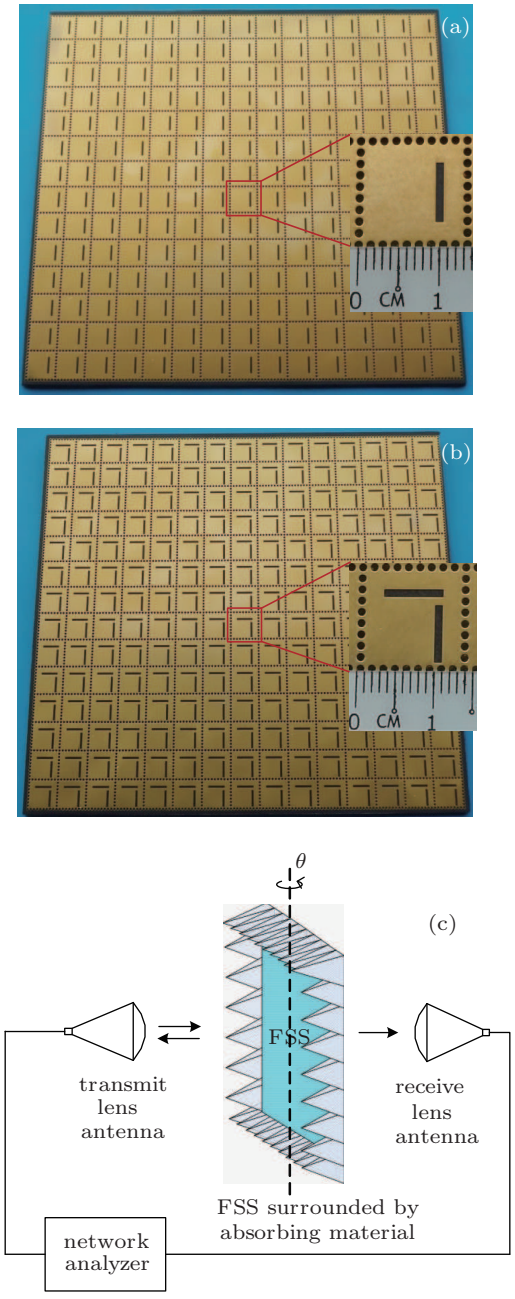


Fig. 6. (color online) Photographs of the fabricated polarization rotator ((a) front view and (b) back view), and (c) schematic of the measurement setup.

A comparison between simulated and measured results is presented in Fig. 7, showing a reasonable agreement. The second resonant frequency in Fig. 7(a) is slightly higher for the measured result, resulting in a wide measured bandwidth due to the fabrication and measured tolerance as well as losses not accounted for in the simulation. The magnitudes of the two transmitted polarized components are approximately equal and the phase difference between them is nearly 180°. The measured insertion losses of two transmission signals are nearly 4 dB, and there is a slight phase shift between simulated and measured results, which is mainly because of the tolerance in the measurement, as the phase is sensitive to the distance between two antennas and the structure. The 3-dB bandwidth is calculated to be 5.7% (15.45–16.36 GHz), which is slightly wider than that in the simulation.

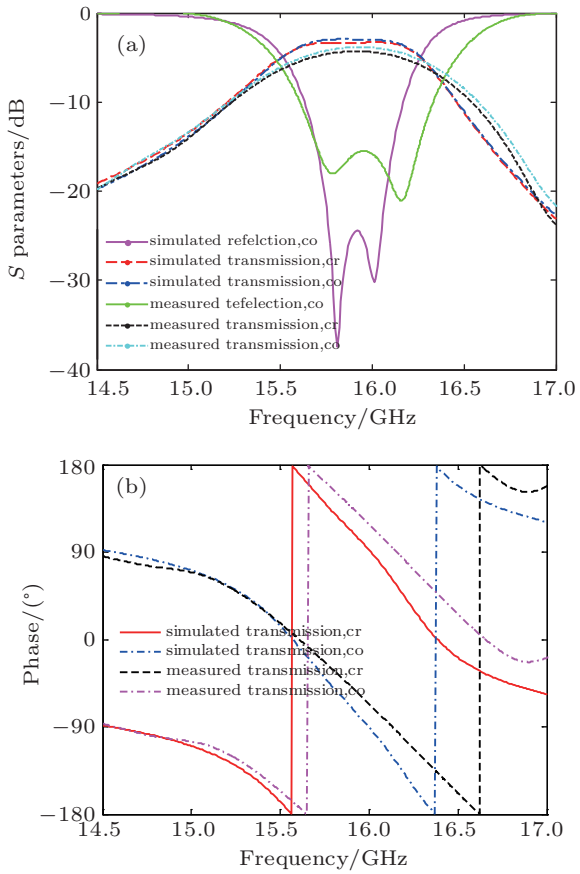


Fig. 7. (color online) Simulated and measured results of the proposed polarization rotator ((a) magnitude and (b) phase).

4. Conclusion

We propose an FSS structure based on an SIW cavity structure that can transmit an EM wave with a passband together with a 45° polarization rotation. It is made possible by the coupling of the EM wave with different slots in the SIW cavity. They enable the transmission of two orthogonal polarized signals and combine two equal-amplitude and orthogonal output signals to a 45° rotated polarized wave when there is a 180° phase difference between the two signals. To validate

the proposal, an example structure has been designed at the frequency of 16 GHz with a 3-db bandwidth of 5.6%. Measured results are in good agreement with simulated ones. By modifying the slot arrangement, a polarization convertor from linear to circular polarization or a polarization rotator for another degree may also be designed utilizing a similar structure.

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