High-Power Wideband Elliptical-Grooved Over-Mode Circular Waveguide Polarizer

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Abstract—The available polarizers either cannot afford gigawatt-class high-power microwave applications or are large in length. In this letter, a novel grooved polarizer is proposed. The grooves are proposed to be created in an over-mode circular waveguide to improve the power capacity and bandwidth. Moreover, the symmetric elliptical grooves are adopted to suppress high-order modes and realize the desired phase difference. An X-band polarizer prototype is designed and manufactured with length of 91 mm. Simulated results show that the power capacity of the polarizer is more than 1.5 GW. Measured results in accordance with simulations show that the axial ratio is less than 3 dB from 8.6 to 12.2 GHz, with relative bandwidth of 34.6%. The measured return losses are better than -12.7 dB in the same frequency range.

1. INTRODUCTION

In microwave radiation systems and reflective antenna systems [1, 2], it is necessary to use polarizer to convert linearly polarized microwave into circularly polarized microwave. The structure of a polarizer is directly related to the power capacity, bandwidth, and size of the system. The existing researches of polarizers mainly focus on the improvement of bandwidth and miniature design. The representative polarizers consist of metal screws [3], metal irises [4], metal stepped septum [5, 6], or dielectric-slab [7], which are placed into waveguide to differentiate the phase of the two orthogonally polarized components. These polarizers meet the demands of polarization conversion experiments and applications. However, they could not meet the gigawatt-class high-power microwave applications for the tiny-size inserted abrupt structures [3–6], tending to cause local electric field concentration. Moreover, dielectric-slab polarizer [7] inevitably introduces triple junction, which is prone to result in RF breakdown. With the development of high-power microwave technology, many systems need circularly polarized wideband gigawatt-class high-power microwave. The demands of polarizers with high-power capacity, compact structure, and wideband become urgent.

As known, waveguide without any insert is suitable for high-power microwave applications. Truncated or grooved waveguide might be two viable polarizers. However, the truncated polarizer [8] is large in length and difficult to process. The rectangular-grooved polarizers were proved to be suitable for the Ka-band and above [9–11]. However, the power capacity and available bandwidth of polarizers are restricted for only operating in the waveguide where the dominant mode is accessible. Besides, the rectangular grooves have mutated structure, which will excite high order modes deteriorating the bandwidth of the over-mode circular waveguide polarizers. In this letter, a novel elliptical-grooved over-mode circular waveguide polarizer is proposed. Symmetrical gradient elliptical grooves are used to suppress the high-order modes and realize the propagation constant difference between the two orthogonal components. Over-mode circular waveguide is used to improve the power capacity and bandwidth of the polarizer.

2. STRUCTURE AND OPERATING PRINCIPLE

Figure 1 illustrates the structure of the proposed polarizer. It is known that increasing the cross-sectional dimension of waveguide is one of the effective methods to improve the power capacity of the device. So the over-mode circular waveguide is proposed to be used in the structure. The gradient elliptical grooves avoiding the mutated structure can be used to suppress the high-order modes. A pair of elliptical grooves symmetrical to xoz-plane are created in waveguide wall. The TE_{11} mode linearly polarized wave oriented at $45°$ to x-axis is input at one port. The input wave E_i can be regarded as two orthogonal components, E_x and E_y, with equal magnitude. These two components propagate forward in the direction perpendicular or parallel to y-axis, respectively. Since the grooves exhibit inductivity, the propagation constant in E_y direction is larger than that in E_x direction. Moreover, the grooves can make the propagation constant difference between the two orthogonal components large, which can provide the $90°$ phase difference with a short length of the elliptical groove. So the proposed polarizer should have the performances of compact structure, high-power capacity, and wideband.
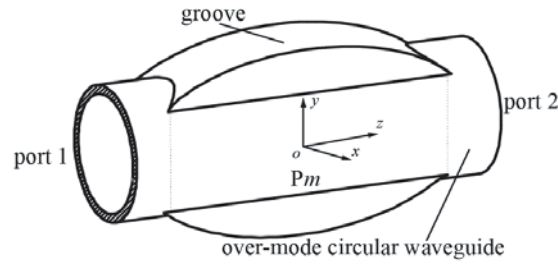

Figure 1. Structure of elliptical-grooved polarizer.

3. INNER MODES OF POLARIZER

As described, the waveguide is designed in over-mode circular waveguide. In this case, the high-order modes disturbing the performance of polarizer might be introduced in the waveguide. The inner modes of the polarizer should be analyzed firstly. Based on the full-wave simulation method, the magnitudes of the modes are analyzed with different waveguide radii R, and the results are shown in Fig. 2. There are only two orthogonal TE_{11} modes at the output port of the polarizer. The transmission coefficients of both orthogonal TE_{11} modes are equal to 0.707. No high-order modes appear. Fig. 3 shows the
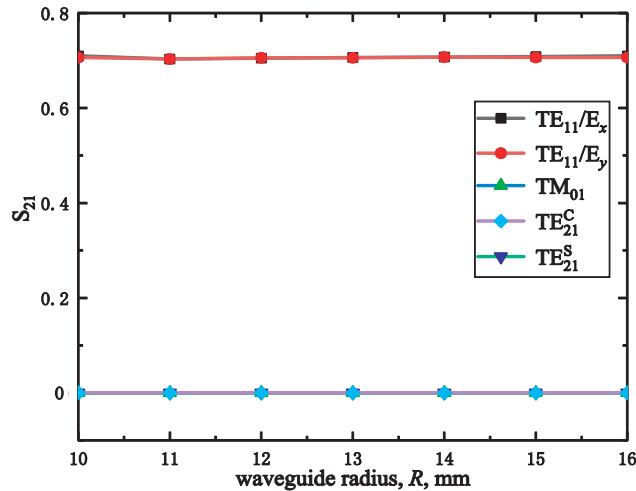

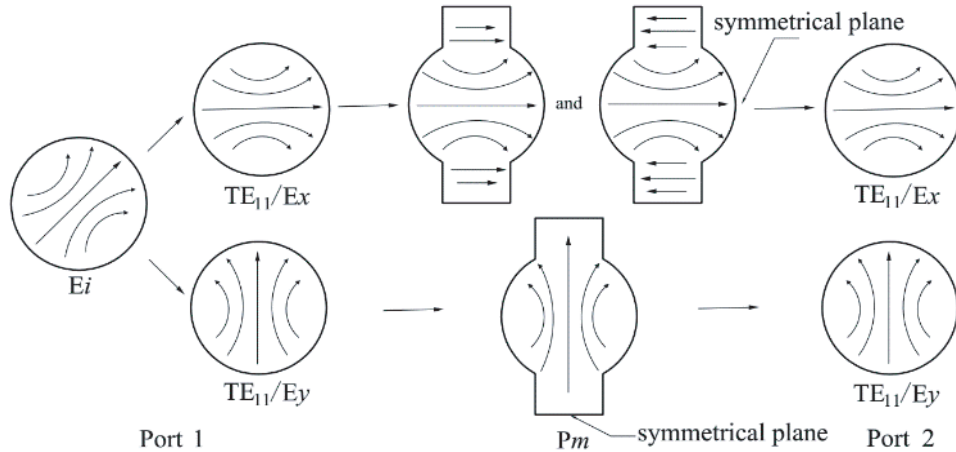**Figure 2.** Influence of R on on inner modes.

Figure 3. Cross sections and corresponding E-field patterns of polarizer.

cross sections and corresponding E-field patterns of the elliptical-grooved polarizer. The grooves can be regarded as a short-circuit rectangular waveguide. There will be mode-coupling between the modes having same symmetry plane with respect to all geometries. Inside the polarizer, the TE_{11} mode components in x-axis and y-axis directions keep in even function modes, and the elliptical grooves have a gradual structure, so almost all of the input energy will be transferred to output port in TE_{11} mode. In addition, with the length of semi-major, semi-minor axes, and the width of the elliptical grooves changed, no high-order modes appear in the elliptical-grooved polarizer.

4. PARAMETRIC ANALYSES

The influence of waveguide radius R on phase difference between the two orthogonal components and field intensity of polarizer is shown in Fig. 4 with all other parameters kept constant. The phase difference is calculated by the following formula:

$$Py - Px = (\beta y - \beta x) \cdot z \tag{1}$$

where βx and βy are the propagation constants in x-axis and y-axis directions, respectively, and z is the length of groove. Both the maximum E-field intensity and phase difference decrease with increasing R, which means that the length of polarizer will be increased, and the power capacity will be improved
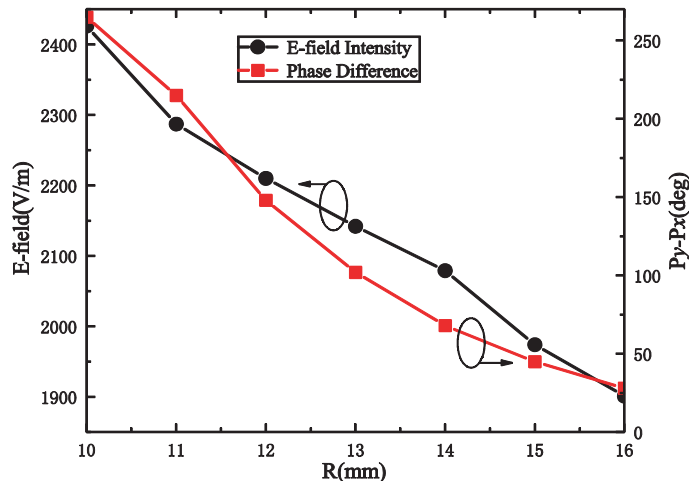

Figure 4. Influence of R on phase difference and E-field intensity.
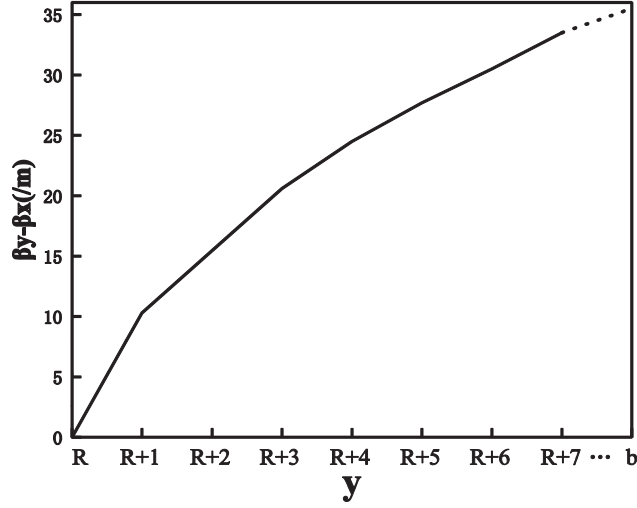
Figure 5. Influence of groove depth on wavenumber difference.

with the radius of the circular waveguide increased. Therefore, in the determination of waveguide radius R of a high-power elliptical-grooved polarizer, it is necessary to weigh the demand of power capacity and length.

Then the parameters of the elliptical groove should be analyzed. The groove can be regarded as a plurality of rectangular groove. The relationship of the wavenumber difference $\Delta\beta$ between two orthogonal components and the groove depth y is shown in Fig. 5, which can be fitted into a coordinate equation:

$$\Delta\beta = \beta y - \beta x = f(y). \tag{2}$$

From the elliptic equation and Eqs. (1)–(2), in order to achieve the phase difference of $90°$, the length of semi-major axis a and semi-minor axes b of elliptical groove should satisfy the following relation:

$$\int_0^{a\sqrt{(1-\frac{R^2}{b^2})}} \Delta\beta \cdot 2dz = \int_b^R f(y) \cdot 2a \cdot d\left(\sqrt{1 - \frac{y^2}{b^2}}\right) = \frac{\pi}{2}. \tag{3}$$

Based on the preliminary dimension of a and b, an elliptical-grooved polarizer can be designed by some parametric sweep analysis.

5. SIMULATIONS AND EXPERIMENTS

In this letter, an X-band elliptical-grooved polarizer with a central frequency of 10.4 GHz is designed to validate the method. From Fig. 4, considering the power capacity and miniature requirement of the polarizer, the waveguide radius R is selected to be 13.5 mm. According to Eq. (3), the preliminary dimension of the two semi-axis lengths, a and b, can be obtained. The formula of calculation of axial ratio is as follows [12]:

$$AR = \sqrt{\Delta A^2 + 0.0225 \times (\Delta\varphi - 90°)^2} \tag{4}$$

where ΔA and $\Delta\varphi$ are the magnitude difference (unit in dB) and phase difference (unit in deg) of the two orthogonal components, respectively. The parametric sweep of the polarizer is carried out by using the full-wave simulation software. With variables a and b, the calculated axial ratios of the polarizer are shown in Fig. 6. When b increases, the polarizer tends to work at higher frequency. A similar tendency can be found for a. The 3-dB axial ratio bandwidth is much wider when $a = 40$ mm and $b = 20$ mm. The width of the elliptical slot is swept and shown to have little influence on the performance of the polarizer. Taking the processing error into account, the width of the slot is set to 13.5 mm. The total length of the polarizer is 91 mm. The simulated results are shown in Fig. 9. The return losses of

two orthogonal components are better than -16.7 dB, and transmit losses are less than 0.29 dB. With input power of 0.5 W, the simulated maximum E-field intensity of polarizer is 1425 V/m at the central frequency of 10.4 GHz as shown in Fig. 7. The calculated power handling capacity of the polarizer is
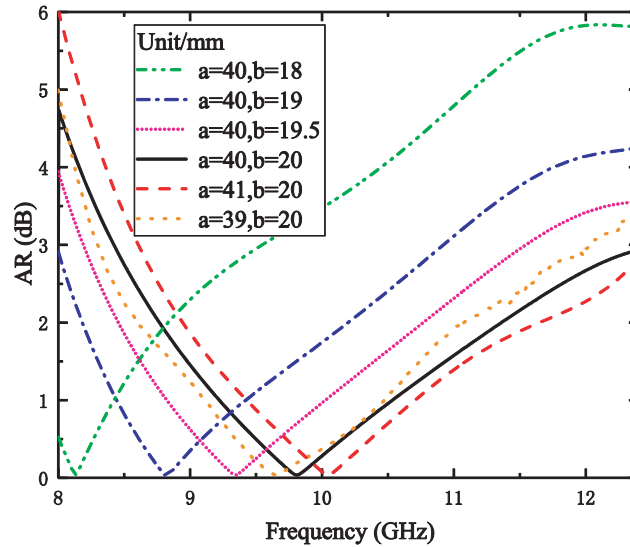

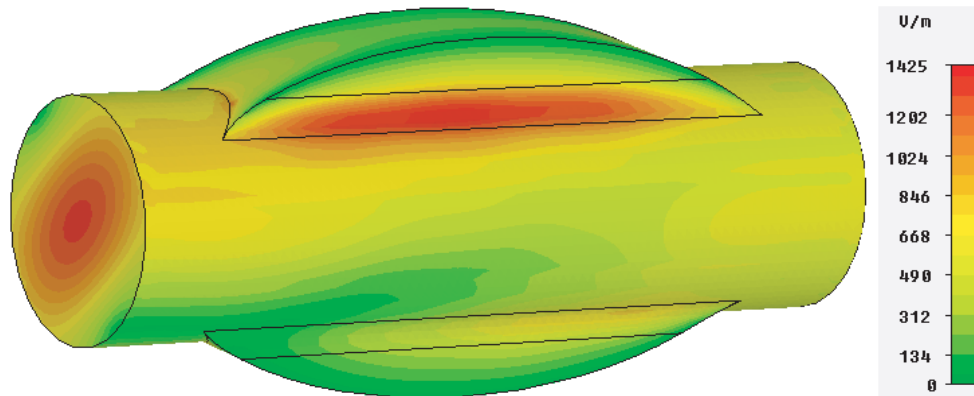**Figure 6.** Influence of a and b on axial ratios of polarizer.

Figure 7. Field distribution of polarizer with input power of 0.5 W.
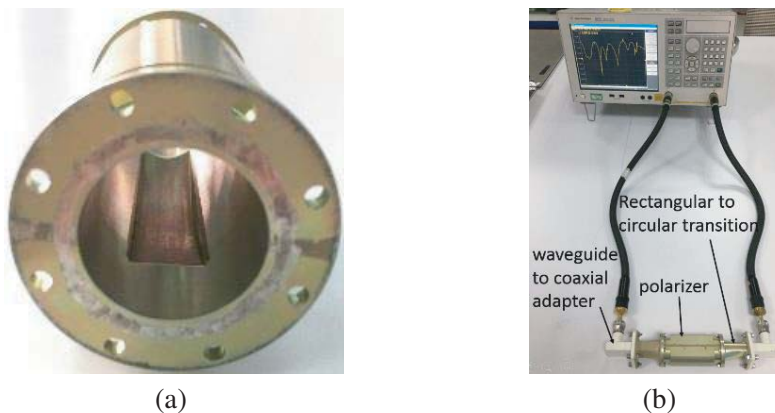

(a)   (b)

Figure 8. Photograph of polarizer and the device under measurement.

1.53 GW with the E-field breakdown threshold of 80 MV/m under vacuum condition.

The prototype of the fabricated polarizer and the device under measurement are shown in Fig. 8. Rectangular to circular waveguide transitions are designed to connect the polarizer and waveguide to coaxial adapters. The experiments were done with an E5071C network analyzer. The scatter parameters of E_x and E_y components were measured separately. As shown in Fig. 9, the measured transmit losses are less than 0.3 dB, and return losses are better than -12.7 dB, which are a little worse than simulation. The difference is mainly attributed to the manufacture errors, and the VSWR of the waveguide to coaxial adapter also deteriorates the losses. The measured axial ratio is less than 3 dB in the range of 8.6–12.2 GHz and consistent well with simulations.
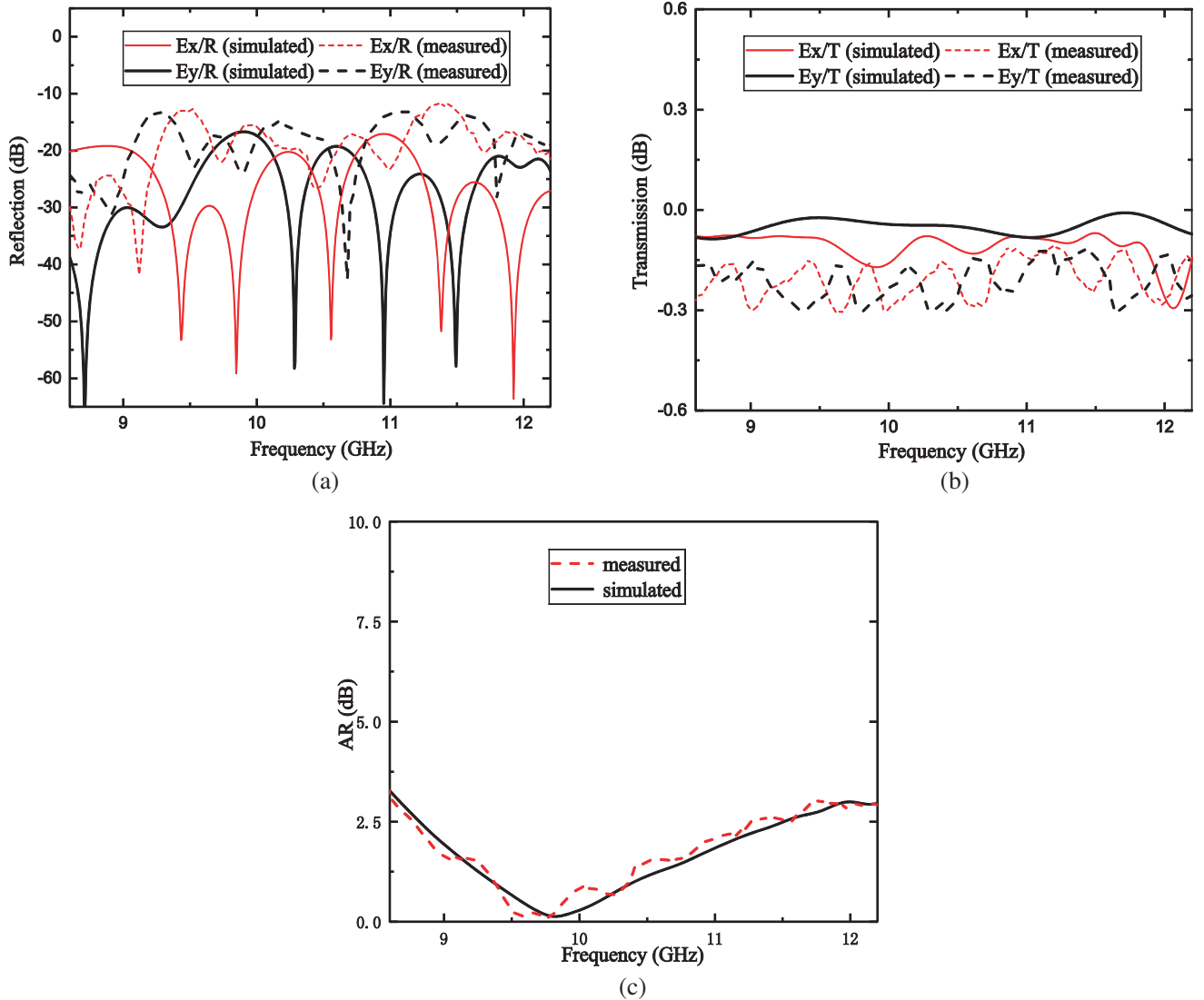

Figure 9. Simulated and measured results. (a) Reflection, and (b) transmission dependence on frequency for two orthogonal components, (c) axial ratio versus frequency.

6. PERFORMANCE COMPARISON

The performance comparison between the proposed polarizer and the representative all-metal polarizer designs is given in Table 1. The metal screws polarizer [3] and rectangular-grooved polarizer [10] have an approximate length with the proposed polarizer. But the bandwidth of the metal screws polarizer is

Table 1. Comparison of several representative polarizers.

Ref.	[3]	[6]	[8]	[10]	This work
Frequency (GHz)	8.3	5.8	94	21	10.4
Length	3.32λ	2.46λ	14.7λ	3.85λ	3.16λ
AR-Bandwidth	2.5 dB–7%	1.5 dB–16%	1.25 dB–21%	3.4 dB–19%	2 dB–21.1%
P-capacity	–	53.8 MW	142.5 MW	–	1.5 GW

much narrower than that of the proposed polarizer, which is attributed to the polarizers only operating in the waveguide where the dominant mode is accessible. The metal stepped septum polarizer [6] has the shortest length among the five polarizers, but the power capacity of the metal stepped septum polarizer is lower than that of the truncated waveguide polarizer [8] and the proposed polarizer for the application of tiny-size abrupt structure. The length of the proposed polarizer is more than 11λ shorter than that of the truncated waveguide polarizer [8]. The main reason of the miniature length is that the grooved structure can provide a bigger wavenumber difference than the truncated structure. From the above comparisons, the proposed polarizer demonstrates the best performance of high power capacity, wideband, and miniature simultaneously.

7. CONCLUSION

A novel high-power wideband elliptical-grooved over-mode circular waveguide polarizer has been proposed and investigated. Owing to the application of over-mode circular waveguide, the power capacity and bandwidth of the polarizer can be improved. Using a symmetrical gradient elliptical groove, the high order modes can be suppressed, and the big wavenumber difference of the two orthogonal components can be realized. An X-band polarizer prototype is designed with a central frequency of 10.4 GHz. Its performances have been simulated and measured. The 3-dB axial ratio bandwidth of the polarizer is over 34.6%, and the power-handling capacity is more than 1.5 GW. The experimental results in good agreement with simulations prove the design concept and verify the feasibility of the polarizer. By comparison, the polarizer has high power capacity, and it has wide band and compact size.

ACKNOWLEDGMENT

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