Conceptual design of X band waveguide dual circular polarizer

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A new design of dual circular polarizer is presented in this paper. This innovative design converts radiofrequency (rf) energy from TE₁₀ mode in a rectangular waveguide to two polarized TE₁₁ modes in a circular waveguide. A reflection less than −20 db is achieved and breakdown field is less than 42 MV/m at input of 1 MW. Meanwhile, this polarizer has a megahertz bandwidth, and the thermal stability is also discussed. This device can be used for broadcasting and receiving the circular polarized signals.

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I. INTRODUCTION

X band microwave orthomode transducer (OMT) is widely used for different experiments such as cosmist microwave background polarization experiment [1]. The transducer with an antenna is used to separate orthogonally polarized microwave signals into different rectangular waveguides [2,3]. By investigating the amplitudes and phase of the received signals, one can learn the rf characteristics of the emitters. From the perspective of broadcasting rf wave, rf modes can be split into polarized modes in a circular waveguide [4–6]. It is convenient to use TE₁₀ mode of rectangular waveguide from a rf source. OMT transducers usually have four waveguides. On the top of this junction, there is a circular waveguide which outputs two circular polarized TE₁₁ modes [7,8]. Recent studies utilize insertion posts at the bottom of the circular waveguide to match the rf modes [9,10]. Those posts limit the maximum rf power due to magnetic field enhancement and the thermal instability [11]. We propose here a converter design which has no post at the bottom of the circular waveguide. Output signals on the circular waveguide are right hand circular polarized (RHCP). On the other hand, the power from the second rectangular waveguide is converted and output as left hand circular polarized (LHCP) on the circular waveguide. The whole polarizer, shown in Fig. 1 can be divided into three major compartments. The two converters (green) on both ends and they are identical. The center unit (yellow) is the multiple modes converter. On the very top section (red) is a corrector that adjusts the phase and amplitude of two circular polarized modes and it can be optional. This device will transfer rf power from port 1 to port 3 with good isolation to port 2

and minimal reflection to port 1. The mechanism of each section is explained in detail in the following sections.

II. ANALYTICAL DESIGN METHODOLOGY

This whole device has three physical ports. Two of them are rectangular ports that support one TE₁₀ mode and one circular port supports two TE₁₁ dipole modes. Rf power is converted among four modes. We used scattering matrix to represent the amplitude and phase changes of the voltage among different modes at different ports. In this study, a 4 by 4 scattering matrix is engineered for the rf mode conversion. The modes sequence in the matrix are TE₁₀ mode in port 1, TE₁₀ mode in port 2 and two TE₁₁ modes in port 3. To achieve the function as we described in the introduction, this scattering matrix is described as the following for the four modes:

$$S = \begin{bmatrix} S(1:1,1:1) & S(1:1,2:1) & S(1:1,3:1) & S(1:1,3:2) \\ S(2:1,1:1) & S(2:1,2:1) & S(2:1,3:1) & S(2:1,3:2) \\ S(3:1,1:1) & S(3:1,2:1) & S(3:1,3:1) & S(3:1,3:2) \\ S(3:2,1:1) & S(3:2,2:1) & S(3:2,3:1) & S(3:2,3:2) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \sqrt{2}/2 & -\sqrt{2}i/2 \\ 0 & 0 & -\sqrt{2}i/2 & -\sqrt{2}/2 \\ \sqrt{2}/2 & -\sqrt{2}i/2 & 0 & 0 \\ -\sqrt{2}i/2 & -\sqrt{2}/2 & 0 & 0 \end{bmatrix} \quad (1)$$

Where S:M:N means Nth mode on M port. This matrix is a symmetric and unitary matrix. The matrix in the later context will follow this scattering pattern.

Note in this matrix, $S(1:1,1:1)$ and $S(1:1,2:1)$ are zero, which means the reflection and transmission are zero. In addition, $S(3:1,1:1)$ and $S(3:2,1:1)$ are $\frac{\sqrt{2}}{2}$ and $-\frac{\sqrt{2}i}{2}$. This suggests that when the rf power from port 1 is split equally into mode 1 and mode 2 in the third port, the two modes have 90 degree phase difference. This is a RHCP mode. On the other hand, rf power from port 2 is split equally into those two modes with 270 (or −90) degree delay. This is a

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FIG. 1. Mechanical configurations of this circular polarizer. A is the full assembly of the polarizer. B is the rf mode converter in the center (yellow). C is configuration of the rf mode converter on both ends (green). D is the adjuster which is added to correct the phase and amplitude (red).

LHCP mode. When the power is received on port 3 at 180 degree phase difference, the input rf power would be distributed equally on two rectangular ports. In any case, port 1 and Port 2 are isolated.

Matrix (1) is simplified because the length of the waveguide can cause phase delay while the amplitude does not change. The phase shift is related to the lengths of waveguides. Therefore we need to cascade this core

scattering matrix (1) with the phase shift $e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})}$ and we will use the same size rectangular waveguide on both ends. L_1 and L_2 are the lengths of rectangular and circular waveguides, while β_1 and β_2 are the propagation constants in each waveguide. Therefore, the general form of this 4 by 4 scattering matrix [i.e. matrix (2)] is shown as following.

$$S = \begin{bmatrix} 0 & 0 & \sqrt{2}/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & -\sqrt{2}i/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} \\ 0 & 0 & -\sqrt{2}i/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & -\sqrt{2}/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} \\ \sqrt{2}/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & -\sqrt{2}i/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & 0 & 0 \\ -\sqrt{2}i/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & -\sqrt{2}/2 \times e^{-j\omega(\frac{L_1}{\beta_1} + \frac{L_2}{\beta_2})} & 0 & 0 \end{bmatrix} \quad (2)$$

We designed different components to achieve the mode conversion. The final scattering matrix should match matrix 2.

III. ANALYTICAL DESIGN AND SCATTERING MATRIX

Now we need to design the converter to match matrix 2. As mentioned in Sec. I, this full polarizer assembly has three sections: two ends pieces, a center convertor and a corrector. Each component has different amount of ports and modes, which will be reflected in the individual scattering matrix. In this section, we set up the targeted scattering matrix of each component, and we use the numerical method to achieve these matrixes in the next section. The designing concepts on each component are explained one by one in this section.

A. Design of the center unit

The function of this center unit is to output the rf power to circular port in a form of two TE₁₁ modes. These two TE₁₁ modes on the circular waveguide port are orthogonal. Therefore, we can obtain them independently from two orthogonal modes on a rectangular waveguide. The electric field patterns of TE₁₁ modes from a circular waveguide are shown in Fig. 2.

Two lowest order modes in a rectangular waveguide are TE₁₀ and TE₂₀ modes. The electric field patterns (top view) of TE₁₀ and TE₂₀ in a rectangular waveguide are shown in Fig. 3.

Two modes in Fig. 3 are easily electrically coupled to different TE₁₁ mode presented in Fig. 2, respectively. Both coupling effects are independent, since the electric field of

FIG. 2. Electric field pattern on TE₁₁ modes in a circular waveguide with different polarizations. A: TE₁₁ mode in horizontal polarization; B: TE₁₁ mode in vertical polarization.

FIG. 3. Demonstration on vector electric field patterns of TE10 and TE20 in a rectangular waveguide. A: TE10 mode; B: TE20 mode. Electric fields are along the longitude direction. The black arrow is the electric field direction.

both mode-pairs are orthogonal at the center of a rectangular waveguide. Note, the reflection and transmission are not zero in this center unit between rectangular waveguides. We used the two end units to reflect the leakage power back to center unit, which is described in Sec. III B.

Two conditions are required to get a RHCP mode: (i) The output TE11 modes have the same amplitude; (ii) TE11 modes have 90 degree phase difference. At the entrance of the center unit, TE10 and TE20 modes need to have equal power and certain phase delay in the rectangular waveguide. Two coupling coefficients are introduced for TE10/TE11 vertical and TE10/TE11 horizontal, respectively. Since the couplings are independent, we can adjust separately two coupling coefficients to an equal number, then the two TE11 modes in the circular waveguide will have the same power. On the other hand, the phase delay of these two TE11 polarizations are determined by the initial

phase difference of the two modes in rectangular waveguide. Due to the different propagation constants and the guided wavelengths, these two modes will generate a phase delay within a given period of rectangular waveguide. In a rectangular waveguide, the guided wavelengths of TE modes are only related to the width of the waveguide [12]. It is also necessary to avoid higher order mode propagation in this waveguide. With such considerations, the width and length of rectangular waveguide require optimization to adjust the correct phase.

Now we need to obtain the scattering matrix of this center unit. In Fig. 1(b), the center unit has three ports and each port supports two modes. Therefore, the scattering matrix is a 6-by-6 matrix in this center unit. This matrix is also symmetric and unitary. To ensure the matrix unitary with minimal number of variables, we introduced a scattering matrix $S1$ which comprises 2 variables θ and ϕ in Eq. (3).

$$\begin{aligned}
 S1 &= \begin{bmatrix} S(1:1,1:1) & S(1:1,1:2) & S(1:1,2:1) & S(1:1,2:2) & S(1:1,3:1) & S(1:1,3:2) \\ S(1:2,1:1) & S(1:2,1:2) & S(1:2,2:1) & S(1:2,2:2) & S(1:2,3:1) & S(1:2,3:2) \\ S(2:1,1:1) & S(2:1,1:2) & S(2:1,2:1) & S(2:1,2:2) & S(2:1,3:1) & S(2:1,3:2) \\ S(2:2,1:1) & S(2:2,1:2) & S(2:2,2:1) & S(2:2,2:2) & S(2:2,3:1) & S(2:2,3:2) \\ S(3:1,1:1) & S(3:1,1:2) & S(3:1,2:1) & S(3:1,2:2) & S(3:1,3:1) & S(3:1,3:2) \\ S(3:2,1:1) & S(3:2,1:2) & S(3:2,2:1) & S(3:2,2:2) & S(3:2,3:1) & S(3:2,3:2) \end{bmatrix} \\
 &= \begin{bmatrix} \frac{-\cos[\theta]-e^{i\phi}}{2} & 0 & \frac{-\cos[\theta]+e^{i\phi}}{2} & 0 & \frac{\sin[\theta]}{\sqrt{2}} & 0 \\ 0 & \frac{-\cos[\theta]-e^{i\phi}}{2} & 0 & \frac{-\cos[\theta]+e^{i\phi}}{2} & 0 & \frac{i\sin[\theta]}{\sqrt{2}} \\ \frac{-\cos[\theta]+e^{i\phi}}{2} & 0 & \frac{-\cos[\theta]-e^{i\phi}}{2} & 0 & \frac{\sin[\theta]}{\sqrt{2}} & 0 \\ 0 & \frac{-\cos[\theta]+e^{i\phi}}{2} & 0 & \frac{-\cos[\theta]-e^{i\phi}}{2} & 0 & \frac{i\sin[\theta]}{\sqrt{2}} \\ \frac{\sin[\theta]}{\sqrt{2}} & 0 & \frac{\sin[\theta]}{\sqrt{2}} & 0 & \cos[\theta] & 0 \\ 0 & \frac{i\sin[\theta]}{\sqrt{2}} & 0 & \frac{i\sin[\theta]}{\sqrt{2}} & 0 & -\cos[\theta] \end{bmatrix} \quad (3)
 \end{aligned}$$

FIG. 4. The schematic matrix cascading at a steady state of the whole transducer system. The input and output of the center unit and end unit are 6-elements vectors and 3-elements vectors, respectively.

Where S:M:N means Nth mode on M port. The first four modes are TE₁₀ and TE₂₀ modes in rectangular waveguides, while the last two modes are the two polarizations of TE₁₁ in the circular waveguide.

We used the same size rectangular waveguides on both ends of this transducer. Therefore the reflections in the circular waveguide are the same. In addition, the elements in upper left 4 by 4 matrix represents the reflection and transmission among the modes between the rectangular waveguides. It is worth noticing that the power leakage from rectangular waveguides is not zero. These portions of power should be reflected back to the center unit and eventually output to the circular waveguide. Therefore, we need to add two end units where power is fully reflected. Based on this consideration, we have to determine the values of parameters θ and ϕ with the end unit matrix in the next section.

B. Design of the end units

Two end units have two major functions: 1. Convert TE₁₀ mode from a klystron to required input for the center

unit. The required input condition is a combined mode of TE₁₀ and TE₂₀ with the same amplitude at the entrance of center unit. 2. Reflect the leaked power from center unit back to itself. The power transmission out to the rf source side is negligible.

Based on these requirements, this end unit has two physical ports: one port connects the single mode TE₁₀ from the rf power source; the other port connects the center unit and supports both TE₁₀ and TE₂₀ modes. The scattering matrix is a 3 by 3 unitary matrix. In the matrix, the first mode is TE₁₀ mode in a rectangular waveguide from the rf source side and the rest two modes are TE₁₀ and TE₂₀ in the rectangular waveguide from the center unit side. Similarly, to ensure the matrix unitary with minimal number of unknown variables, we can introduce another two unknown variables θ_1 and ϕ_1 in the matrix. Matrix S2 should have a general form in Eq. (4). To minimize the reflection to the rf source, $S(1:1,1:1)$ in S2 should be 0. Therefore the value of θ_1 and ϕ_1 are determined.

$$S2 = \begin{bmatrix} S(1:1,1:1) & S(1:1,2:1) & S(1:1,2:2) \\ S(2:1,1:1) & S(2:1,2:1) & S(2:1,2:2) \\ S(2:2,1:1) & S(2:2,2:1) & S(2:2,2:2) \end{bmatrix} = \begin{bmatrix} \frac{\cos[\theta_1]}{2} & \frac{\sin[\theta_1]}{\sqrt{2}} & -\frac{\sin[\theta_1]}{\sqrt{2}} \\ \frac{\sin[\theta_1]}{\sqrt{2}} & \frac{-\cos[\theta_1] - e^{i\phi_1}}{2} & \frac{-\cos[\theta_1] + e^{i\phi_1}}{2} \\ -\frac{\sin[\theta_1]}{\sqrt{2}} & \frac{-\cos[\theta_1] + e^{i\phi_1}}{2} & \frac{-\cos[\theta_1] - e^{i\phi_1}}{2} \end{bmatrix} \xrightarrow[\phi_1 = 0^\circ]{\theta_1 = 90^\circ} \begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2} \end{bmatrix} \quad (4)$$

The four elements in the right lower corner (2 by 2) have the same magnitude. This matrix has several useful properties, which can be expressed by:

TABLE I. The scattering matrix of device in Fig. 5.

S1	S:1:1	S:1:2	S:2:1	S:2:2	S:3:1	S:3:2
S:1:1	0.3357, 104.1°	0.0007, 149.3°	0.6633, -78.3°	0.0002, 147.2°	0.6687, 175.2°	0.0006, 11.3°
S:1:2	0.0007, 149.2°	0.4316, -131.1°	0.0003, -26.7°	0.5973, -21.6°	0.0003, 61.9°	0.6759, -108.1°
S:2:1	0.6633, -78.3°	0.0003, -26.3°	0.3378, 104.5°	0.0008, -36.4°	0.6677, 175.2°	0.0006, -163.1°
S:2:2	0.0002, 148.5°	0.5973, 21.6°	0.0008, -36.4°	0.4317, -131.1°	0.0002, -85.3°	0.6759, -108.2°
S:3:1	0.6687, 175.8°	0.0003, 61.5°	0.6677, 175.2°	0.0002, -84.4°	0.3269, -110.5°	9.9917e - 5, -63.4°
S:3:2	0.0006, 11.4°	0.6759, -108.2°	0.0006, -163.1°	0.6759, -108.1°	0.0001, -61.9°	0.2937, -15.3°

FIG. 5. A snapshot of E field patterns on the mode converter. Port 1 and port 2 are T overmoded rectangular waveguides, and port3 is the circular waveguide. A. The input power on port1 is 1 W in TE₁₀ modes. B. the input power on port1 is 1 W in TE₂₀ modes.

$$\begin{pmatrix} 0 \\ \frac{a}{\sqrt{2}} \\ -\frac{a}{\sqrt{2}} \end{pmatrix} = S2 \begin{pmatrix} a \\ 0 \\ 0 \end{pmatrix}; \quad \begin{pmatrix} 0 \\ -c \\ c \end{pmatrix} = S2 \begin{pmatrix} 0 \\ c \\ -c \end{pmatrix}; \quad (5)$$

Variables a and c can be any complex number. The first equation above expresses that the power from rf source will be split in half with 180 degree phase delay. The second equation above suggests that input power from the center unit will be reflected back with negligible transmission.

Once Eq. (5) is fulfilled, the two major functions of the end units are achieved as stated above.

C. Assembly of the whole transducer

Now we cascade S1 of center unit and S2 of end units and determine the unknown variables for the full assembly. Cascade mechanism is illustrated in Fig. 4 and the diagram complies with the Fig. 1 assembly. We relabeled the port numbers here for clarification. rf source power from port 1 converts into TE10 and TE20 modes on port 4 at the entrance of the center unit (black) in Fig. 4. These two modes are transferred to port 3 with transmission to port 5 and reflection to port 4. The end units (red) take the transmission and the reflection and fully return them to the center unit. At a steady state, the input and output vectors of each unit are given in Fig. 4. The characteristics of end unit that have been described in Eq. (5) are used here.

The net power flow on port 5 should be zero. At a steady state, the scattering matrix S1 for the center unit has to fulfill the condition presented in Eq. (6).

$$\begin{pmatrix} b \\ -b \\ -c \\ c \\ d \\ id \end{pmatrix} = S1 \begin{pmatrix} a \\ -a \\ c \\ -c \\ 0 \\ 0 \end{pmatrix} \quad (6)$$

In this equation, the left and right vectors are input and output of the center unit. Unknown complex variables

a, b, c, and d represent the power amplitudes and phases of each mode on different ports. The first four modes are TE10 and TE20 on both rectangular waveguides and the last two modes in the vectors are TE11 modes in the circular port. Input from port 1 has 180° degree phase difference due to the end units' design. We labeled input power with unknown variable a. We expect that the reflection and transmission on port 4 and 5 of the center unit have the same amplitude and 180° degree difference. We labeled transmission and reflection with unknown variables b and c. In the end, the outputs on port 3 should have the same amplitude and 90° degree phase difference. We labeled the outputs on port 3 with variable d.

The conditions in Eq. (6) should be satisfied for all unknown complex numbers. The values of parameters θ and ϕ are determined. The solution of center unit matrix is simplified in the following matrix:

$$S1 = \begin{bmatrix} -\frac{1}{3} & 0 & \frac{2}{3} & 0 & \frac{2}{3} & 0 \\ 0 & -\frac{1}{3} & 0 & \frac{2}{3} & 0 & \frac{2i}{3} \\ \frac{2}{3} & 0 & -\frac{1}{3} & 0 & \frac{2}{3} & 0 \\ 0 & \frac{2}{3} & 0 & -\frac{1}{3} & 0 & \frac{2i}{3} \\ \frac{2}{3} & 0 & \frac{2}{3} & 0 & -\frac{1}{3} & 0 \\ 0 & \frac{2i}{3} & 0 & \frac{2i}{3} & 0 & \frac{1}{3} \end{bmatrix} \quad (7)$$

The first four modes are TE10 and TE20 modes in rectangular waveguide port 1 and port 2. The rest two modes are TE11 two polarizations in the circular waveguide port3.

FIG. 6. TE10 to TE10/TE20 converter and a snapshot of electric field pattern on the surface. The input power on port 1 is 1 W in TE10 modes. Port 2 is TE10 and TE20 overmoded rectangular waveguide.

TABLE II. The scattering matrix of device in Fig. 6.

S2	S:1:1	S:2:1	S:2:2
S:1:1	0.0538, 128.2°	0.7284, -111.1°	0.6830, 17.6°
S:2:1	0.7284, -111.1°	0.4873, -138.1°	0.4842, 80.8°
S:2:2	0.6830, 17.6°	0.4842, -80.8°	0.5469, 33.9°

Now we have the targeted matrix for the center unit and end units in matrixes (4) and (7). In the next step, we will implement numerical simulation to achieve these scattering matrixes S1 and S2.

IV. NUMERICAL DESIGN IMPLEMENTATION

A. Design of the center unit

To achieve the goals represented in S1 and S2 matrixes, we employed HFSS simulation to obtain the numerical solution [13]. Our working frequency is 11.424 GHz. As stated above, higher order modes should be avoided in the rectangular and circular waveguide at this frequency. The requirement provides a range of the radius of the circular waveguide and the width of rectangular waveguides. Within the range, the width and depth of the rectangular waveguide and radius of the circular waveguide are optimized. The numerical scattering matrix is obtained in Table I. This matrix agrees with the phase and amplitude of S1 in matrix (7).

Where S:M:N means Nth mode on M port. In this matrix, S parameters have two values. The first number is amplitude and the second number is phase delay from input port. The phase delay unit is degree. A fixed precision is shown with accuracy of 4 and 3 decimal digits.

The modes sequence matches with matrix 7. Figure 5 shows the snap shot of E field patterns when 1W TE10 and 1W TE20 modes power inputs from port 1, respectively. It is shown that TE10 and TE20 are independently coupled to TE11 vertical and horizontal polarization, respectively. With an input of a combination of TE10 and TE20 mode with the same amplitude and correct phase at port 1, the output on port 3 would be two polarized TE11 modes in the circular waveguide with ± 90 degree phase delays. The polarized TE11 modes are either RHCP (90°) or LHCP (-90°) rotations and the rotation direction is depended on the initial phases of TE10 and TE20 modes in the rectangular waveguide. From Figure 5, the max electromagnetic field occurs at the bottom of the circular waveguide where we blend 2 mm radius to minimize the H field enhancement.

B. Design of the end units

We also used HFSS to design the end units. This device is illustrated in Fig. 6. Port 1 is chosen to be a standard rectangular waveguide WR 90 [13]. Port 2 has the same dimension as the center unit. Several tapers are used to

FIG. 7. A snap shot of electric field on assembly of OMT dual polarizing circular converter. The input power on port 1 is 1 W in form of TE10 modes. Port 1 and port 2 are standard WR90 rectangular waveguide while port 3 is the circular waveguide.

TABLE III. The scattering matrix of device in Fig. 7.

S	S:1:1	S:2:1	S:3:1	S:3:2
S:1:1	-20.5, 120.1°	-23.4, 105.1°	-3.19, -18.3°	-3.03, 68.4°
S:2:1	-23.4, 105.5°	-17.2, 119.1°	-3.19, -92.6°	-3.03, -70.7°
S:3:1	-3.19, -18.3°	-3.19, -92.6°	-13.9, -120.2°	-51.3, -79.9°
S:3:2	-3.03, 68.4°	-3.04, -70.6°	-51.3, 79.8°	-23.1, -94°

minimize the reflection, and to tune the amplitude and phase of output TE10 and TE20 modes. Double arc structures are utilized to smooth field transition [14]. Arc lengths and angles are optimized in simulation. We obtained the scattering matrix of these two ports system in Table II. This matrix has a good agreement with S2 in Eq. (4). Therefore, this converter can split TE10 from RF source to TE10/TE20 with equal power and 180 degree phase difference at port 2.

Where S:M:N means Nth mode on M port. A fixed precision is shown with accuracy of 4 and 3 decimal digits.

The modes sequence is the same as matrix 7. A snap shot of E field pattern is shown in Fig. 6 with 1 W input power from port 1. The input port 1 supports TE10 mode from rf source, and output in port 2 is the combination of TE10 and

TE20. We can adjust their phase difference by adding a period of rectangular waveguide.

C. Assembly of dual circular polarizer

With the designs of both center and end units, a full geometry of the polarizer is shown in Fig. 7. This full assembly has three ports and the length is less than 15 cm. The scattering matrix is demonstrated in Table III. In this matrix, the first two modes are TE10 on port 1 and port 2. The last two modes are TE11 on the circular waveguide. The reflection on port 1 and port 2 is less than -20 db and -17 db, respectively. The transmission is less than -23 db between them. Meanwhile, the input power is split in half to TE11 mode in the circular waveguide and their phase

FIG. 8. Ellipse converter and E field pattern on the surface. The power from input port is 1 W for each polarization, and two polarizations are 90 degree apart. Peak E field is smaller than the peak E field in the OMT in Fig. 7.

TABLE IV. The scattering matrix of device in Fig. 8.

Frequency: 11.424 GHz	S:1:1	S:1:2	S:2:1	S:2:2
S:1:1	-35.1, -148.1°	-41.9, 47.3°	-0.0016, -29.7°	-59.7, -25.6°
S:1:2	-41.9, 47.3°	-26.6, -129.2°	-58.3, 27.5°	-0.0098, -58.8°
S:2:1	-0.00163, -29.7°	-56.6, 27.5°	-35.1, -54.3°	-41.9, 104.1°
S:2:2	-62.1, -25.6°	-0.00983, -58.8°	-41.9, 104.1°	-26.6, -168.1°

difference is around 90 degree. This matrix is in accordance with the scattering matrix from Eq. (2).

Where S:M:N means Nth mode on M port. Units are decibel (dB) and degree. A fixed precision is shown with accuracy of 3 and 3 decimal digits.

The modes sequence is the same as in matrix 2. Therefore the device can convert TE₁₀ mode from a rf source to a RHCP mode in circular waveguide.

V. DISCUSSIONS

A. Phase and amplitude adjust and control

If there is an ellipticity error of amplitude or phase on circular waveguide fabrication, an ellipse corrector can be added on top of the circular waveguide. Its function is to

add a small difference to counterbalance the output amplitude and phase error. By doing that way, the output TE₁₁ polarization modes would have exactly the same amplitude and ± 90 degree phase delay.

Ellipse waveguides have two different radiuses on each polarization axis and have two different propagation constants for each polarization. [15] Two polarized TE₁₁ modes can generate different phase delays which are related to the choice of two radiuses. For this reason, the two polarizations would generate an additional phase difference to counterbalance the phase error between two polarized modes from the center unit. In order to connect an ellipse waveguide to circular waveguide in the center unit, a transition is required. This transition taper would have different reflection coefficients for each polarization.

FIG. 9. Final assembly of ellipse corrector and OMT converter. Port 1 and 2 are standard WR 90 rectangular waveguides and port 3 is the circular waveguide which supports two TE₁₁ polarizations. The input power on port 1 is 1 W.

TABLE V. The scattering matrix of the final polarizer with ellipse corrector.

S	S:1:1	S:2:1	S:3:1	S:3:2
S:1:1	-21.6, 176°	-22.6, -94°	-3.01, -34.9°	-3.12, 51.1°
S:2:1	-22.6, -94°	-21.2, -161°	-3.1, 145°	-3.04, 51.4°
S:3:1	-3.01, -34.9°	-3.1, 145°	-20, -30.5°	-35.9, -106°
S:3:2	-3.12, 51.1°	-3.04, 51.4°	-35.9, 106°	-18.2, 58.2°

Therefore output amplitudes of each mode are changed. The changes of reflection coefficients are related to the length of the taper. The additional reflection difference can countervail the amplitude error between two polarized modes from the center unit. A long taper is preferred to achieve smooth match, while short taper would generate an unpredictable reflection and higher order modes [14]. We choose two exact same tapers to attach to both ends of the ellipse waveguide. Three parameters should be optimized to adjust the amplitude and phase discrepancy. They are the lengths of transition tapers and two radiuses of the ellipse waveguides. In this study, a design of ellipse converter is illustrated in Fig. 8. This device has two physical ports, and each port supports two TE11 polarization modes.

There are two modes on each port, therefore a 4 by 4 matrix is needed to investigate the modes conversion in a scattering matrix. The scattering matrix is summarized in Table IV. In this matrix, the first two modes are TE11 modes on input port from center unit and the last two are TE11 modes on the other port. This corrector does not change the rotation direction. From this matrix, both modes are adjusted with a small amplitude and phase adjustments.

Where S:M:N means Nth mode on M port. Units are decibel (dB) and degree. A fixed precision is shown with accuracy of 3 and 3 decimal digits.

Combining this ellipse converter with the OMT in Fig. 9, the full assembly convertor can tune two TE11 dipole polarizations with correct amplitude and phase to form a RHCP mode. The integrated scattering matrix is shown in Table V and this matrix matches the design goal in matrix 2.

Where S:M:N means Nth mode on M port. Units are decibel (dB) and degree. A fixed precision is shown with accuracy of 3 and 3 decimal digits.

The electric field is normalized when the input power is 1 W from port 1. When the power input from one WR 90 rectangular waveguide is 1 W, the max E field on the surface is around 6 KV/m. If the input power is 50 MW, the max E field on the surface is 42 MV/m. This value is less than the breakdown E field (200 MV/m) for X band application [16].

B. Frequency response

This design of OMT convertor is operated at 11.424 GHz. It would be ideal to have a broad frequency bandwidth. The scattering matrix elements and the phase difference of two TE11 modes are obtained as a function of

frequency. The results are plotted in Fig. 10. The left vertical axis is the scattering amplitude and the right vertical axis is the phase delay angle of two TE11 polarizations in circular waveguide.

In this figure, more than 50 MHz bandwidth, the return and transmission loss are less than -30 db. On the other hand, within the range of 25 MHz bandwidth, the phase difference between two TE11 modes is less than 1 degree in this design. Therefore, the circular polarized mode bandwidth is limited by the minimum bandwidth of the phase and amplitude. The working bandwidth of this design is around 25 MHz. This bandwidth is large enough for our OMT applications. The bandwidth could be further optimized in future studies.

C. Thermal concern

This converter is designed to convert multi-megawatts rf power from an X band klystron to RHCP or LHCP modes in the circular waveguide. Due to the manufactory concerns, the converter will be machined from a single copper block. The rf dynamic loss on the surface can be nontrivial and should be estimated.

The schematic of rf dynamic loss density map is illustrated in Fig. 11 when the input power is 1W from port 1. This rf surface loss is estimated in HFSS physics package [13]. In this simulation, we presume the surface conductivity to be 5.8×10^7 siemens/m at room

FIG. 10. Frequency spectrum of the scattering parameter and phase difference of the dual polarizers. S parameters are plotted in color code. The S(1:1,1:1), S(2:1,1:1), S(3:1,1:1) and S(3:2,1:1) are labeled in red, dark blue, brown and magenta respectively. The light blue curve shows the phase difference between two polarizations in circular waveguide.

FIG. 11. Schematic of surface rf loss density distribution for the dual polarizer at a steady state.

temperature. In this figure, the main rf power loss concentrates at the bottom of the circular waveguide where the magnetic field is enhanced. To minimize the magnetic field, blending chamfers are used to reduce the local H fields.

The integration loss over all surface is 0.0117 W when the input power is 1 W. The total loss is around 1% input rf power in a continuous wave operation mode. Hence, this device generates around 100 W rf surface loss when it delivers 1 MW pulsed rf power at 100 Hz repetition rate with pulse length 100 μ s. Active chilling water pipes would have enough capability to cool the exterior of whole system to room temperature [17].

VI. CONCLUSION

We present a design for X band dual circular polarization transducers. The design used all simple geometry and it will be easy to manufacture. This design has a 25 megahertz operation bandwidth and a good thermal stability. This polarizer can be utilized for several applications, including broadcasting and receiving circular polarized signals, high power rf loads and rf power compressors.

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