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High Power Over-Mode 90° Bent Waveguides for Circular TM_{01} and Coaxial TEM Mode Transmission

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Abstract—Three bent waveguides are proposed and investigated, two for circular waveguide TM_{01} mode and one for coaxial TEM mode. For high power-handling capacity, all of them are over-mode waveguides. In the bend, circular or coaxial waveguides transmitting only sector waveguide TE_{11} modes are split into several same sector waveguides by metal plates and metal rod. These sector waveguides are grouped by their lengths. Length differences of sector waveguides lead to phase differences of the sector waveguide TE_{11} modes after bending. Due to requirements of mode conversion, the phase difference regulated by radii of circular waveguide and metal rod must be $2n\pi$, $n = 0, 1, 2, \ldots$. Since the phase difference is independent of bend radius, the radius could be as small as possible. One of the prototypes is experimentally verified, and the test results of the VSWR show that simulation has good match to experiment. Insertion loss is 0.2 dB at 8.4 GHz, which proves the feasibility of the prototype.

1. INTRODUCTION

Many high-power microwave (HPM) sources produce microwaves which have axial symmetry, and circular waveguide (CWG) TM_{01} mode and coaxial transverse electromagnetic (TEM) mode are common ones [1–3]. In order to reasonably arrange the overall system, the bent waveguides transmitting CWG TM_{01} mode and coaxial TEM mode are often used to connected HPM source and subordinate system, such as array antenna [4–7]. Therefore, performance of waveguide bends is very important. Meanwhile, the developing trend of HPM System claims for a more compact structure of the bent waveguides. It means that CWG TM_{01} mode and coaxial TEM mode should be transmitted in waveguide bends with a small bend radius.

There have been some works on the transmission of CWG TM_{01} mode and coaxial TEM mode in bent waveguides [8–10]. The authors propose a design of bent CWG based on mode coupling theory, which can achieve CWG TM_{01} mode bent transmission with a high efficiency of 99.7% at 10 GHz. However, its bend radius is more than 500 mm, and transmittable high-order mode is only CWG TM_{01} mode which means that its power-handling capacity is low [8]. In [9], using metal plates a structure with a bend angle of 45° is designed and tested for CWG TM_{01} mode bent transmission at 2.856 GHz, and the bend radius is 123.7 mm. This one also has a low power-handling capacity at high frequency band because there are just two CWG modes, named TE_{11} and TM_{01}, which could propagate in the CWG. As for coaxial TEM mode, the authors give a bent waveguide filled by dielectric materials which decrease the power-handling capacity and increase losses [10]. In this paper, for high transmission efficiency, high power-handling capacity and small bend radius, three high over-mode bent waveguides used for CWG TM_{01} mode and TEM mode transmission are designed at 8.4 GHz. In addition, CWG TM_{01} mode and coaxial TEM mode can be mutually transformed easily [11].

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2. DESIGN CONCEPT AND BASIC STRUCTURE

In this section, three bent waveguides are designed. Two of them transmitting CWG TM_{01} mode include a metal rod and four metal plates and bend respectively with different angles. The third containing six metal plates is used to transmit coaxial TEM mode.

2.1. Four Metal Plates Bending 90° for CWG TM_{01} Mode Transmission

Figure 1 shows the bend of over-mode CWG [12]. A metal rod marked with t is inserted into CWG and changes the CWG to coaxial waveguide. Four metal plates, marked with 1, 2, 3 and 4, are inserted into the coaxial waveguide, and accordingly the coaxial waveguide is separated into four sector waveguides (SWGs). The starting position and ending position of four metal plates are same. The bend angle is θ.

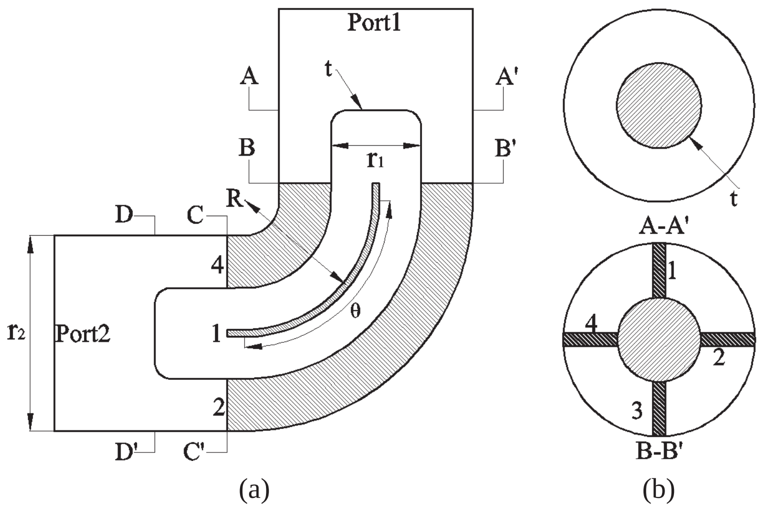


Figure 1. Bend of the CWG with a bend angle of 90°. (a) Sectional view, (b) two sections of the structure marked in (a).

The process of mode conversion and corresponding E-field patterns in different regions are shown in Figure 2. A CWG TM_{01} mode is injected from port 1. In region AA'-BB', the microwave propagates into coaxial waveguide and is transformed to coaxial TEM mode. At cross section BB', the coaxial TEM mode is converted to four 90°-SWG TE_{11} modes where phases of the SWG TE_{11} mode are same. In region BB'-CC', four 90°-SWGs bend with an angle of θ, 90°. To avoid energy coupling to high-order mode, propagating mode should be only SWG TE_{11} mode in the bend of SWGs. At the end of metal plates, to combine and excite coaxial TEM mode the phase difference of SWG TE_{11} modes must be $2n\pi$, $n = 0, 1, 2, \ldots$. It means that L_1 and L_2 should satisfy the following equation

$$\beta(L_1 - L_2) = 2n\pi \tag{1}$$

where β is the propagation constant of SWG TE_{11} mode. L_1 is the length of two bent SWGs located on the outside of the bend while L_2 is that of the inner one shown in Figure 3. L_1 and L_2 can be estimate with the following equations

$$L_1 = 2\pi\left[R + \left(\frac{r_1 + r_2}{2}\right) \cdot \frac{\sqrt{2}}{2}\right] \cdot \theta/360 \tag{2}$$

$$L_2 = 2\pi\left[R - \left(\frac{r_1 + r_2}{2}\right) \cdot \frac{\sqrt{2}}{2}\right] \cdot \theta/360 \tag{3}$$

r_1 and r_2 are radii of metal rod and the CWG shown in Figure 1. β is determined by r_1 and r_2. In region CC'-DD', four 90°-SWG TE_{11} modes convert to coaxial TEM mode. Finally, at the end of the metal rod, the TEM mode is converted to CWG TM_{01} mode output from port 2.

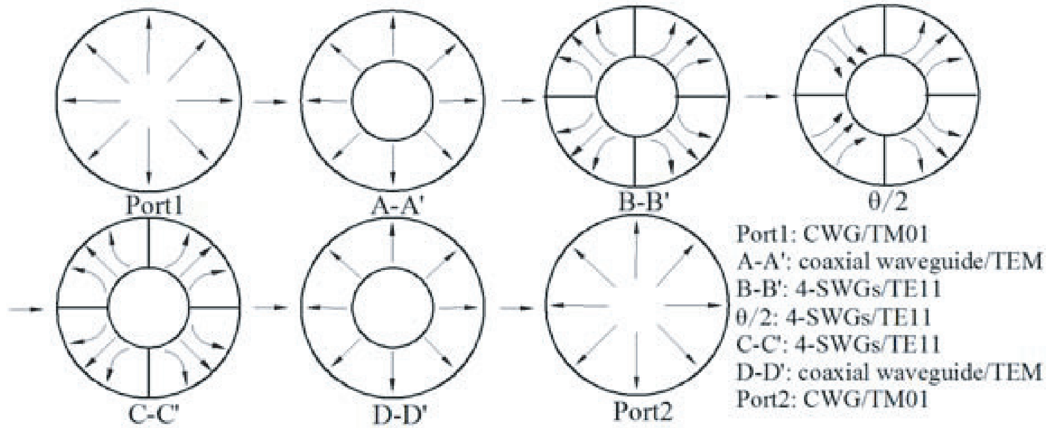


Figure 2. The process of mode conversion and corresponding electric field patterns in various regions.

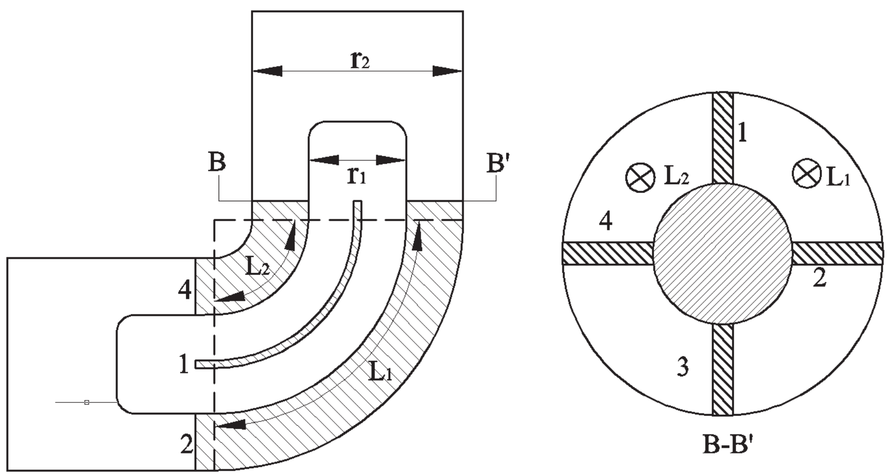


Figure 3. Annotation of several main parameters.

At the start and end of metal plates, new coaxial microwave modes whose angular-direction periods of E-field are 4 or multiple of 4, like coaxial TE_{41}, TE_{81} mode, etc., will be excited [13, 14]. Therefore, the CWG TE_{41} mode must be cut off. From Eqs. (2), (3) and (4), since the difference between L_1 and L_2 is irrelevant to bend radius of R, the value of R can be as small as possible.

2.2. Four Metal Plates Bending 80° for CWG TM_{01} Mode Transmission

It can also be seen from Equations (1), (2) and (3) that when r_1 and r_2 are changed, the bend angle θ can be selected to meet requirements of mode conversion at cross section CC'. Therefore, θ can be changed within a certain range.

Figure 4 shows a prototype whose bend angle θ is 80°. To fulfil requirement of single-mode transmission in SWGs, thickness of metal plates can also be regulated within a small range. The process of microwave propagation is identical to the previous one whose θ is 90°.

2.3. Six Metal Plates Bending 90° for Coaxial TEM Mode Transmission

Six metal plates are inserted into coaxial waveguide, and angles between metal plates are all 60°. When coaxial TEM mode propagates in waveguide, it is converted to six 60°-SWG TE_{11} modes by the metal plates. In the bend, single-mode SWGs only transmit SWG TE_{11} modes without energy coupling with

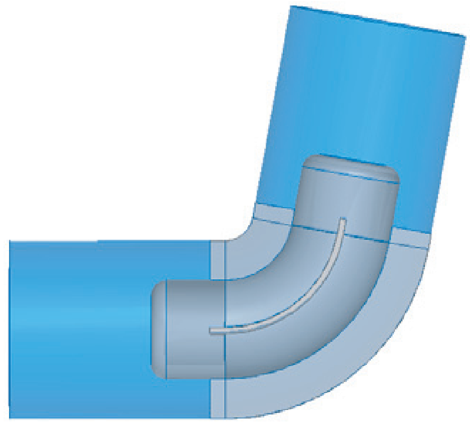


Figure 4. Prototype of bent CWG, $\theta = 80°$.

other modes. After bent transmission, six 60°-SWG TE_{11} modes combine and excite coaxial TEM mode, where six metal plates are removed.

Those metal plates can be divided into 3 groups shown in Figure 5. Due to condition of mode conversion, phase difference between different groups must be $2n\pi$. Propagation constants of six SWGs are all the same, so the phase difference only depends on length difference of bent SWGs which can be seen from equation

$$d_3 - d_2 = d_2 - d_1 = 2\pi \cdot \left(\frac{r_1 + r_2}{2}\right) \cdot \frac{\sqrt{3}}{2} \cdot \theta/360 \tag{4}$$

d_1, d_2, d_3 are lengths of SWGs marked with 1, 2, 3 shown in Figure 5. As can be seen, phase difference can be regulated by r_1 and r_2 when θ is given. Since the angular-direction distribution of metal plates is even and the period is six, high-order modes will be excited at the interface of SWGs and coaxial waveguide. The angular periods of electric field of high-order modes must be multiple of 6, like coaxial TE_{61}, TE_{81}, $TE_{12,1}$ modes, etc. For high transmission efficiency, coaxial TE_{61} mode must be cut off.

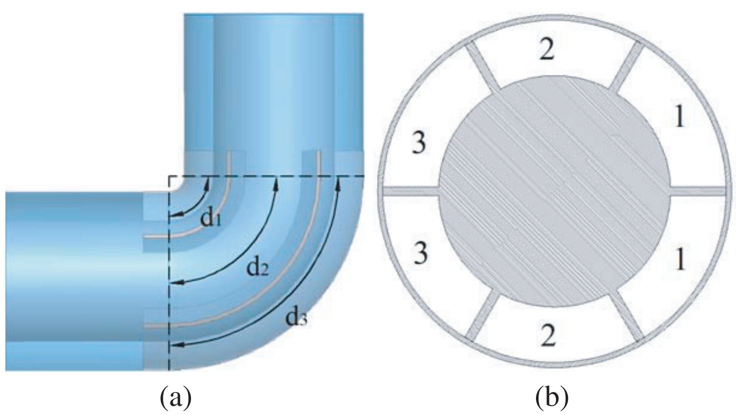


Figure 5. (a) Prototype of bent coaxial waveguide, $\theta = 90°$. (b) Three groups of SWGs.

In general, the inner and outer radii of the coaxial waveguide should meet three requirements, the single-mode transmission in SWGs, cutoff of coaxial TE_{61} mode, and phase difference of $2n\pi$ between SWG TE_{11} modes. Obviously, this waveguide has higher power-handling capacity.

Four metal plates can also be used to achieve bent transmission of coaxial TME mode, and the structure is just as the one shown in Figure 1 when Port 1 and Port 2 are respectively located at cross section AA' and DD'. However, compared with six metal plates, its power-handling capacity is lower.

As for 8 metal plates, 8-SWGs are grouped into four groups. However, length differences of neighboring SWGs are different, and $d_4 - d_3 = d_2 - d_1 \neq d_3 - d_2$ means that phase differences cannot be $2n\pi$ simultaneously.

3. SIMULATION AND EXPERIMENT

3.1. Simulation

The three models are designed at 8.4 GHz, and all of the parameters are optimized by means of finite integral method (FIM). Thickness of metal plates is 2 mm. If the thickness is less than 2 mm, the metal plates might be deformed in the bend. And when the thickness is too thick, *e*-field will be concentrated on the SWGs which reduces power-handling capacity, and besides, it will shorten the bandwidth.

Figure 6 shows simulation results of bent CWG for TM_{01} mode transmission with $\theta = 90°$, $r_1 = 28$ mm, $r_2 = 13$ mm and $R = 38$ mm. The reflection of CWG TM_{01} mode decreases to less than -45 dB and at center frequency. There are three output modes, CWG TM_{01}, TE_{11} and TM_{11} mode. The TM_{01} mode is the desired mode, and its conversion is more than -0.1 dB in the range of 8.25 to 8.55 GHz. And the conversion is more than -0.01 dB at center frequency when conversions of CWG TE_{11} and TM_{11} mode are less than -35 dB. Though the CWG TE_{41} mode is cut off, its simulated result is also given in Figure 6. Reflection and conversion of other modes are very small which can be ignored.

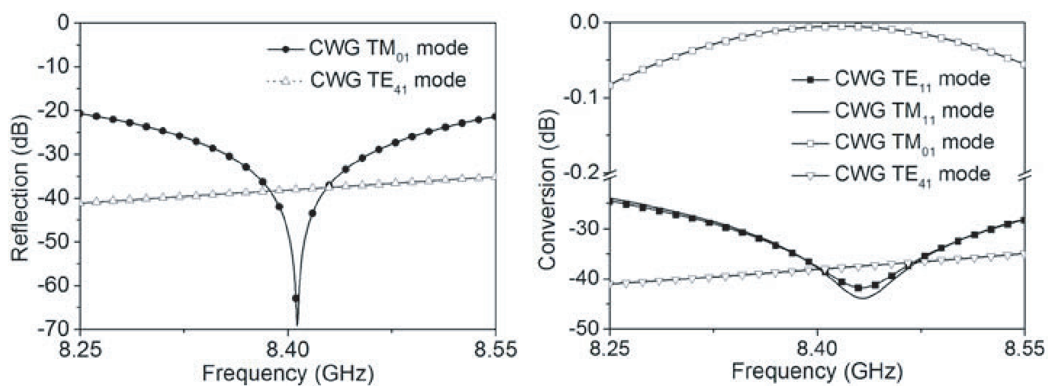


Figure 6. Reflection and conversion of 90° bent CWG transmitting CWG TM_{01} mode.

Figure 7 indicates simulation results of another structure for CWG TM_{01} mode transmission with $\theta = 80°$, $r_1 = 29$ mm, $r_2 = 16.1$ mm and $R = 38$ mm. Thicknesses of metal plates are all 2 mm. Results shown in Figure 7 and Figure 6 are similar.

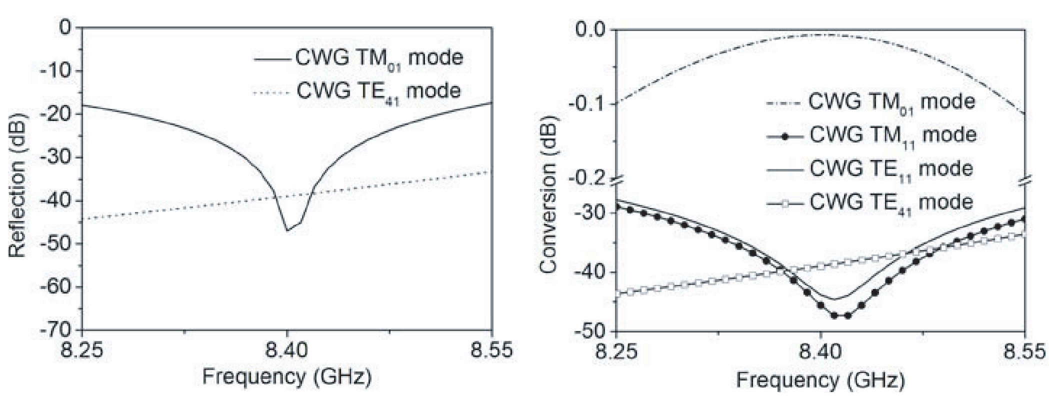


Figure 7. Reflection and conversion of 80° bent CWG transmitting CWG TM_{01} mode.

Figure 8 gives results of bent coaxial waveguide for coaxial TEM mode transmission when $\theta = 90°$, $r_1 = 38.5\,\text{mm}$, $r_2 = 26\,\text{mm}$ and $R = 45\,\text{mm}$. The reflection of coaxial TEM mode is decreased to less than $-50\,\text{dB}$ at 8.4 GHz. Conversions of coaxial TE_{11} and TE_{51} mode are all less than $-35\,\text{dB}$ when conversion of coaxial TEM mode is more than $-0.005\,\text{dB}$ at center frequency. In the range of 8.25 to 8.55 GHz, conversion of TEM mode is more than $-0.15\,\text{dB}$. Results of coaxial TE_{61} mode, which is cut off, are also shown in Figure 8. Other modes are ignored because their reflections and conversions are negligible.

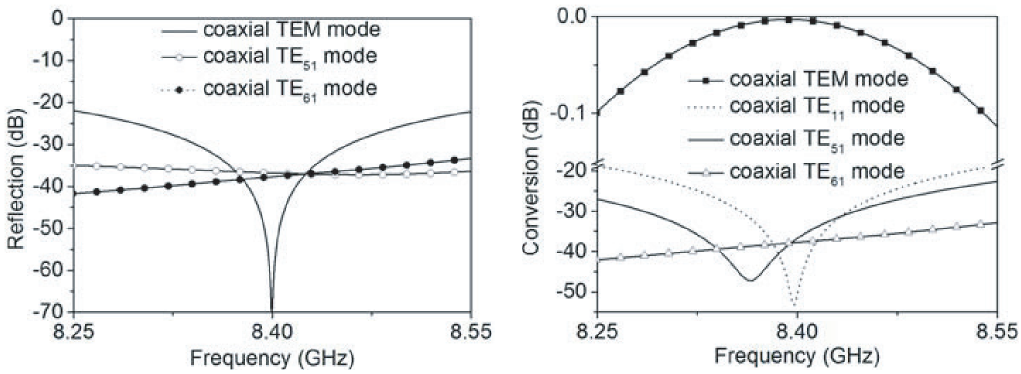
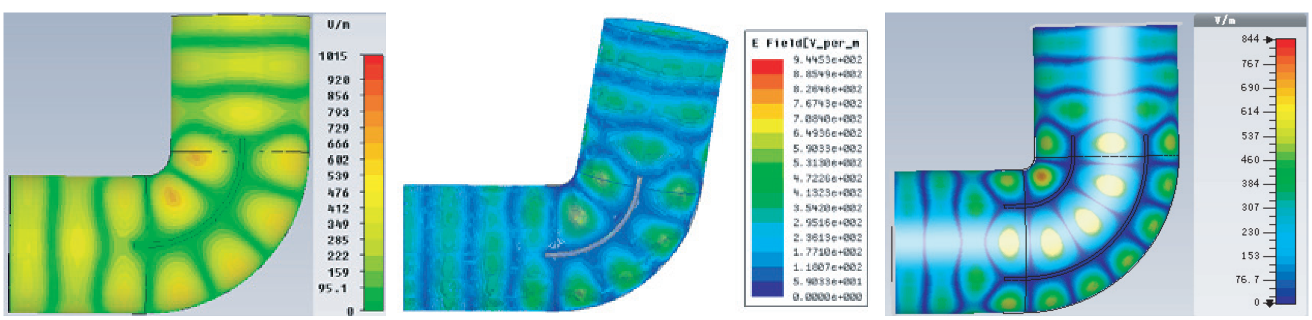


Figure 8. Reflection and conversion of 90° bent coaxial waveguide transmitting coaxial TEM mode.

Power-handling capacity can be estimated by equation of

$$P = \left(\frac{E_{\max}}{E}\right)^2 \cdot P_{in} \tag{5}$$

where P is the power-handling capacity, P_{in} the input power, E the maximum E-field when input power is P_{in}, and $E_{\max}$ the E-field breakdown threshold which can be calculated by Kilpatrick Guideline [15]. Figure 9 shows intensity distribution of E-field and the maximum E-field values of the three structures when input power P_{in} is 0.5 W. Choosing the electric field breakdown threshold $E_{\max}$ to be 75.6 MV/m in vacuum according to Kilpatrick Guideline, power-handling capacities of the three bent waveguides are 2.8 GW, 3.2 GW and 4 GW, respectively.



(a) (b) (c)

Figure 9. Intensity distribution of electric field. (a) Bent CWG with $\theta = 90°$, (b) bent CWG with $\theta = 80°$, (c) bent coaxial waveguide with $\theta = 90°$.

3.2. Experiment

The 90° bent CWG for TM_{01} mode transmission is manufactured and experimented. The experiment is done with an E5071C network analyzer. Two same impedance and mode converters are designed to connect the bent CWG and standard type N connector. The impedance and mode converters

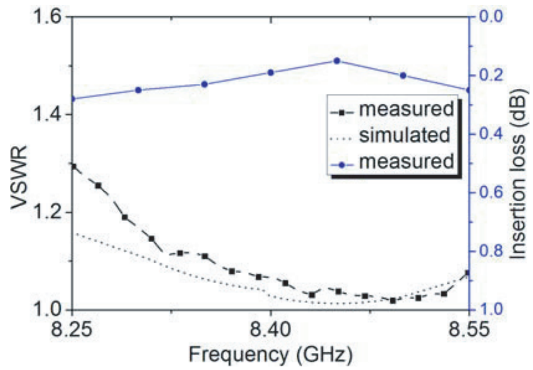
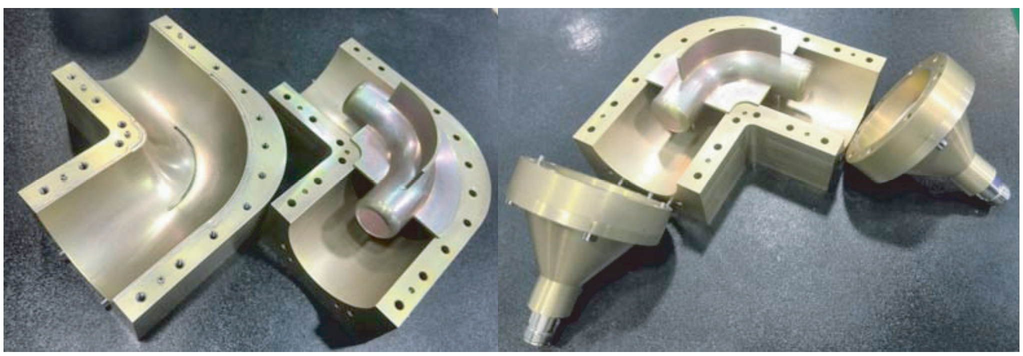


Figure 10. Experimental results of the VSWR and insertion loss.



(a) (b)

Figure 11. Photograph of (a) bent CWG and (b) cascade of bent CWG and two impedance and mode converters.

are designed and simulated with good performance. In order to calibrate, they are also docked for simulation and measurement. Therefore, the final accuracy of the measurement will be satisfactory. Figure 10 shows measured and simulated results. Simulation of the VSWR has good match with the measurement, which indirectly verifies the correctness of simulated results. The VSWR is below 1.3 in the range of 8.25 to 8.55 GHz and less than 1.07 at center frequency. The insertion loss is 0.2 dB at 8.4 GHz, from which losses of two same impedance and mode converters are subtracted. Figure 11 shows photographs of the bent CWG waveguide and two impedance and mode converters.

4. CONCLUSION

This paper presents three bent over-mode waveguides, two for CWG TM_{01} mode transmission and one for coaxial TEM mode transmission. The simulation demonstrates that all three have virtues of high transmission efficiency, high power-handling capacity and small bend radius. The 90° bent CWG is experimented, and measured results coincide approximately with simulated one, which proves the feasibility of the bent waveguides.

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