

Oversized Circular Corrugated Waveguides Operated at 42 GHz for ECRH Application

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Abstract—The design, analysis, and manufacturing of an oversized circular metallic corrugated waveguide with rectangular and square grooves for transmitting power from gyrotron to tokamak or dummy load have been carried out. To carry high power at millimeter wave with lower transmission loss, a corrugated waveguide is preferred. A corrugated waveguide with HE₁₁ mode gives lower attenuation than a smooth circular waveguide with TE₁₁ mode. The theory behind the depth and width selection of corrugations required to carry the linearly polarized (HE₁₁) mode is explained in this paper. The proposed structures are designed and simulated in CST microwave studio software. Rectangular and square groove circular corrugated waveguides each having a length of 500 mm were fabricated and tested using ZVA50 vector network analyzer. Based on performance results, it is derived that the square groove corrugated waveguide gives lower insertion loss of 0.08 dB/meter than rectangular groove corrugated waveguide which gives insertion loss of 0.11 dB/meter.

1. INTRODUCTION

Aditya tokamak uses magnetic field to confine plasma which is heated up to very high temperature. For plasma heating, gyrotron is used as a high-power millimeter wave source. In India, a 42 ± 0.2 GHz, 200 kW gyrotron for plasma fusion application is developed [1]. It is desired to build up the transmission line system from gyrotron to tokamak or dummy load. The transmission line should be able to carry high power with minimum loss. The main component of this transmission line system is a waveguide. Traditional methods using rectangular and smooth wall circular waveguides are sufficient for transmitting high power up to microwave frequency. However, due to mode conversion and high attenuation, use of rectangular or circular waveguides with a smooth wall for transmission of high power at millimeter wave over a long distance is not feasible [2–5]. Insertion of corrugation in metallic waveguides makes the surface electric field component zero. It is indicated that there is no skin current flowing thus reducing the insertion loss. Another advantage of corrugation is in antenna design [6], in which insertion of corrugation on the surface of dielectric material acts as a leaky-wave antenna, and it enhances the gain and also offers merit like electronic beam steering.

Available gyrotron in [1] generates power in TE₀₃ mode which is in unpolarized mode with no energy content on the axis (it does not contain facility of internal mode conversion). For efficient heating of plasma only TE or TM modes cannot be used because it requires an axis symmetric linearly polarized mode having a Gaussian field characteristic. This type of characteristic exists in LP (linearly polarized) mode or HE (hybrid) mode. Linearly polarized mode is used in many applications such as design of antennas and polarizers [7]. HE mode is the fundamental or low loss propagating mode in a

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corrugated waveguide. It is used for carrying power over long distance transmission, antenna feeder in satellite communication, and in mode converters [4, 7].

It has been published in the literature that an oversized circular corrugated waveguide has low attenuation over a long distance because of the boundary condition of corrugation [7, 8]. In this case, HE_{11} mode in a corrugated waveguide is the best choice as it radiates a symmetric beam with lower side lobes level and better isolation from cross polarization component [9]. The performance of corrugated waveguide mainly depends on the depth and width of corrugation groove. Therefore, research work has been carried out to optimize loss in terms of corrugation groove shape. In this manuscript, we have proposed a method to analyze the performance in terms of the corrugation groove depth and width. For carrying 200 kW power at 42 GHz from gyrotron to tokamak or dummy load, it is required to design corrugated waveguide with specifications as mentioned in Table 1.

Table 1. Specifications of corrugated waveguide.

Parameter	Value
Frequency	42 GHz
Length up to	1 m
Bandwidth	400 MHz
Insertion Loss	better than 1 dB
Return Loss	better than 10 dB

In this paper, we propose two oversized circular corrugated waveguides: (i) rectangular grooves and (ii) square grooves, for carrying power at 42 ± 0.2 GHz. Both the proposed structures have been optimized in terms of corrugation groove depth and period to obtain better performance. The organization of the paper is as follows. Section 2 describes brief theory and design considerations of the corrugated waveguide. Section 3 covers simulation results of the proposed corrugated waveguides with different widths and depths of the corrugation groove. Finally, section 4 incorporates the concluding remark.

2. THEORY AND DESIGN

The purpose of the corrugated surface is to provide low loss propagation of HE_{11} mode within the waveguide. HE_{11} mode is basically a combination of TE and TM modes (ideal HE_{11} mode contains 85% TE_{11} mode and 15% TM_{11} mode) [4]. For this combination to propagate as a single entity, waveguide must have anisotropic surface-reactance properties (explained later in this section). Figure 1 shows the geometry of corrugated waveguide with direction of polarization of HE_{11} mode.

Now, the following equations show how the field pattern inside a corrugated waveguide is affected due to a corrugated wall. The dominant mode in oversized corrugated waveguide is HE_{11} which has the

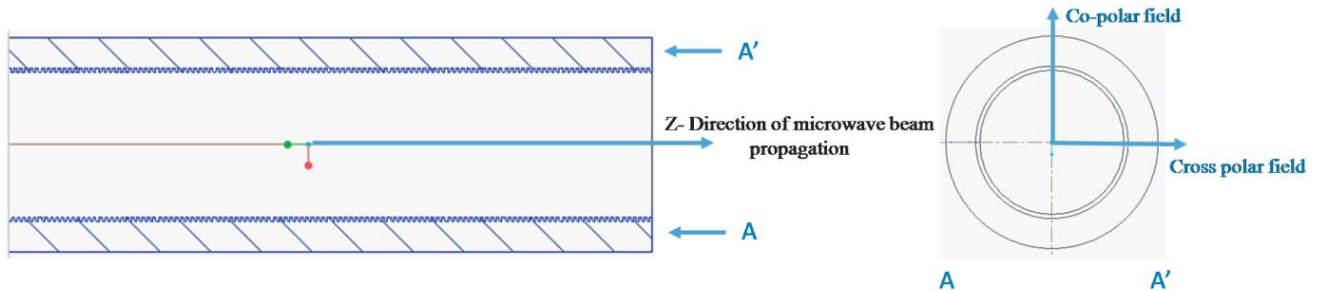


Figure 1. Radiation geometry used for corrugated waveguide.

following aperture electric fields [10],

$$E_x = E_{01} \cdot J_0 \left(\frac{\chi_{mn}}{R} \cdot r \right) - \frac{(Z - Y)}{k \cdot R} \cdot E_{02} \cdot J_2 \left(\frac{\chi_{mn}}{R} \cdot r \right) \cdot \cos(2 \cdot \phi) \quad (1)$$

$$E_y = \frac{(Z - Y)}{k \cdot R} \cdot E_{02} \cdot J_2 \left(\frac{\chi_{mn}}{R} \cdot r \right) \cdot \sin(2 \cdot \phi) \quad (2)$$

where $\chi_{mn} = 2.405$ (root of HE₁₁ mode in corrugated waveguide, m and n are the radial and azimuthal indexes of the mode); $J_0(k \cdot r)$, $J_2(k \cdot r)$ are Bessel's functions of the first kind; k is the free space wave number; E_{01} and E_{02} are the amplitude coefficients; R is the waveguide radius; Z and Y are the impedance and admittance at the boundary $r = R$ given by [10],

$$Z = -j \cdot \frac{E_\phi}{H_z \cdot \frac{1}{Z_0}} \quad (3)$$

$$Y = j \cdot \frac{H_\phi}{E_z \cdot \frac{1}{Z_0}} \quad (4)$$

where $Z_0 = 377 \Omega$ is free space impedance. From Equation (1) it can be said that if the difference between Z and Y becomes zero, the aperture field becomes independent of the angular variable ϕ , and E_y turns out to be zero which means that no cross polarized field exists. For making $Z - Y = 0$, either Z or Y should have finite equal values, or both should be zero. If Z and Y both are zero, then it is called balanced hybrid condition. To make $Z = 0$ [10], period of corrugation should be less than wavelength so that $E_\phi = 0$. Now consider equations below for $Y = 0$ [11]

$$Z_2 = \frac{1}{Y} = \frac{E_z}{H_\phi} \approx jZ Z_0 \quad (5)$$

where Z is the normalized reactance and approximated as [12]

$$Z = \frac{w_1}{p} \frac{\tan(k \cdot d)}{1 + \frac{\tan(k \cdot d)}{2ka}} \quad (6)$$

where d , w_1 , and p are depth, width, and period of corrugation, respectively. The ratio $\frac{w_1}{p}$ indicates that if the width of corrugation is small, it reduces reactance. Moreover, if the depth of corrugations is $\frac{\lambda}{4}$, the slots act as a short circuit transmission line because of $\tan(kd)$ term. As a result, axial current is zero, which is generated by H_ϕ . Furthermore, from this condition it can be said that cross-polarization only happens at a specific frequency since the condition $Y = 0$ is dependent on frequency [13]. Other parameters of corrugation should also be chosen properly. For instance, the period p is kept around 0.3λ to 0.4λ [14], and corrugation width is slightly less than the half of period [15]. According to [16], w_2 should be less than 0.2λ . To obtain low loss, width of groove (w_1) and spacing between corrugations (w_2) are optimized.

Table 2. Design parameters of corrugated waveguide.

Parameters	Value (Square)	Value (Rectangular)
Frequency	42 GHz	42 GHz
Diameter (a)	63.5 mm	63.5 mm
depth (d)	0.25λ	0.25λ
period (p)	0.3λ	0.3λ
w_1	0.17λ	0.24λ
w_2	0.17λ	0.10λ

By considering all of the above mentioned conditions, corrugated waveguides are designed with parameters stated in Table 2. Geometric structures of the proposed square grooves and rectangular grooves oversized corrugated waveguides are shown in Figure 2 and Figure 3, respectively. Here, w_1 is the width of the corrugation, w_2 the spacing between corrugations, p the groove period, d the depth of the groove, and a the diameter of the waveguide without corrugation.

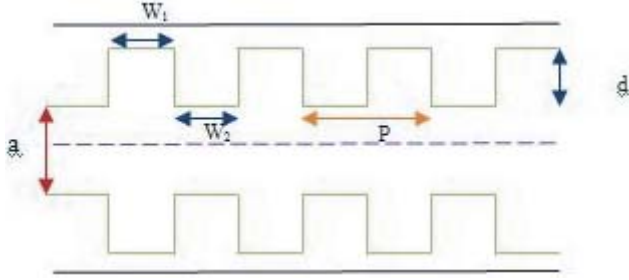


Figure 2. Oversized circular corrugated waveguide with square grooves.

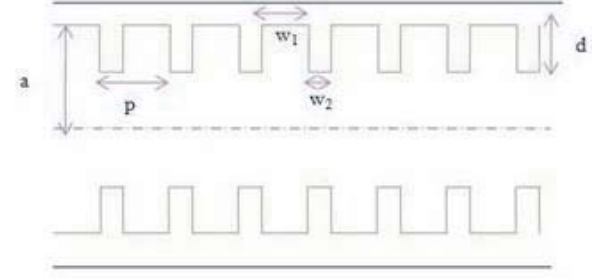


Figure 3. Oversized circular corrugated waveguide with rectangular grooves.

3. SIMULATION RESULTS

The proposed structures of corrugated waveguides are designed and simulated in computer simulation technology (CST) microwave studio software. According to the specifications mentioned in Table 1, we have to design corrugated waveguides having length up to 1 meter. However, it would have taken more than 10 days to simulate the corrugated waveguide with available facility. Therefore, in order to limit the simulation time, small part (500 mm) of both the corrugated waveguides are simulated. It is not possible to directly excite HE_{11} mode in CST software (either TE_{11} mode or TM_{11} mode can excite directly). Moreover, HE_{11} mode contains mixture of TE_{11} and TM_{11} modes of 85% and 15% (ideal combination) respectively which is not possible to adjust when being excited. Therefore, it is required to design a HE_{11} mode exciter. There are two possible ways to generate HE_{11} mode: (i) TE_{11} to HE_{11} mode converter [17] and (ii) TM_{11} to HE_{11} mode converter [18]. As an integral part of this transmission line system, the TM_{11} to HE_{11} mode converter is already designed using a circular corrugated waveguide [18]. In TM_{11} to HE_{11} , the mode converter has varying corrugation wall profile. Its corrugation depth is varied from 0 to $\frac{\lambda}{4}$ with corrugation profile given by:

$$d(z) = \left(\frac{\lambda}{4}\right) \left(\frac{z}{L}\right)^N \quad (7)$$

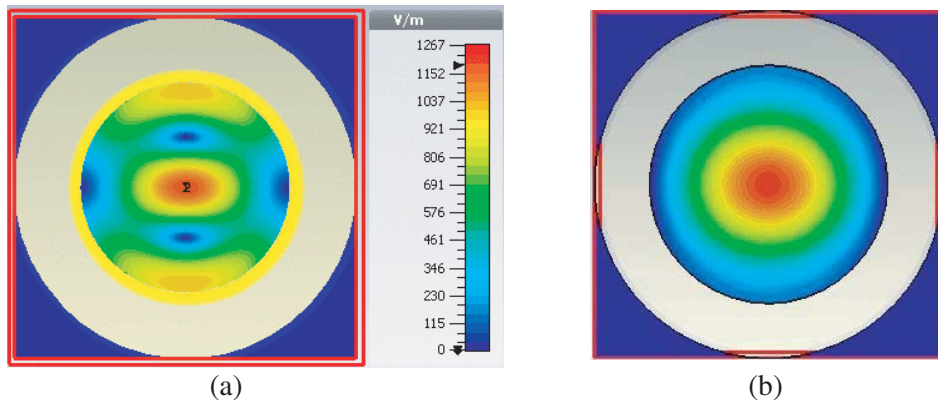


Figure 4. (a) Input TM_{11} mode, (b) output HE_{11} mode pattern.

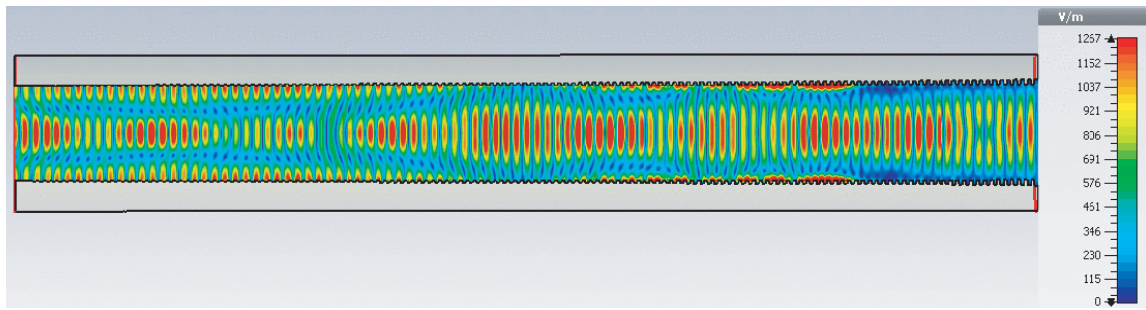


Figure 5. The field conversion inside the TM_{11} to HE_{11} mode converter.

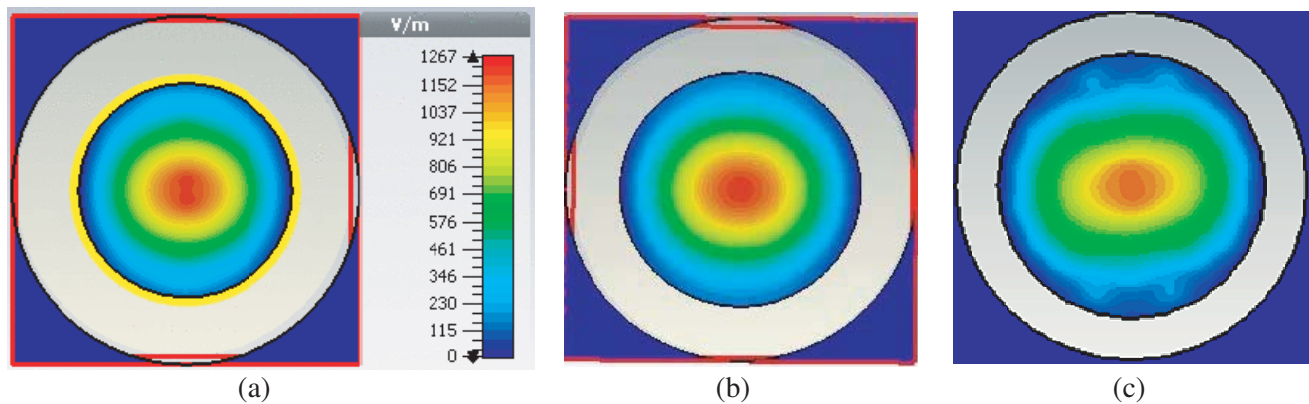


Figure 6. (a) Input HE_{11} mode, (b) output HE_{11} mode at square grooves. (c) Output HE_{11} mode at rectangular grooves.

where N is 1 for linear and greater than 1 for nonlinear; z is the wave propagating direction; and $d(z)$ is the depth profile of corrugation. Initially, the depth of profile is varied slowly as it controls the generation of higher order modes (HE_{21} and HE_{12}) [12], and then it increases nonlinearly. The total length of this mode converter is approximately 238 mm, and diameter is 31.75 mm. It is excited by TM_{11} mode as shown in Figure 4(a), and it generates the output mode pattern of HE_{11} as shown in Figure 4(b). The electric field conversion inside the TM_{11} to HE_{11} mode converter is shown in Figure 5. It can give conversion efficiency more than 95%. Remaining power is transferred to other spurious modes. The conversion efficiency of mode converter can be increased up to 99% by increasing the high order nonlinear depth profile. However, the fabrication of corrugation depth for such a mode converter is toilsome which requires fabrication accuracy of less than 1 micron. It is difficult to achieve this precision with the available computer numerical controlled (CNC) machine facility.

The output of TM_{11} to HE_{11} mode converter is used to excite HE_{11} mode in oversized circular rectangular grooves and square grooves corrugated waveguides shown in Figure 6(a). The output mode patterns of both the corrugated waveguides are shown in Figures 6(b) and 6(c). The proposed design of an oversized circular corrugated waveguide with square groove and the electric field inside corrugated waveguide is shown in Figure 7. Here, the diameter of corrugated waveguide is 63.5 mm, and the designed TM_{11} to HE_{11} mode converter diameter is 31.75 mm, so we have connected up taper between them. Figure 7 shows the electric field flow from TM_{11} to HE_{11} mode converter, up taper and square groove corrugated waveguide. Similarly, the electric field flow inside the rectangular waveguide is also shown in Figure 8. The insertion losses of both the proposed designs are shown in Figure 9.

Figure 9 shows the insertion losses of square and rectangular groove circular corrugated waveguides along with TM_{11} to HE_{11} mode converter and up-taper. The insertion losses for square and rectangular groove circular corrugated waveguides are 0.78 dB and 0.8 dB, respectively. However, the individual insertion loss generated by both the corrugated waveguides is very low compared to combined loss

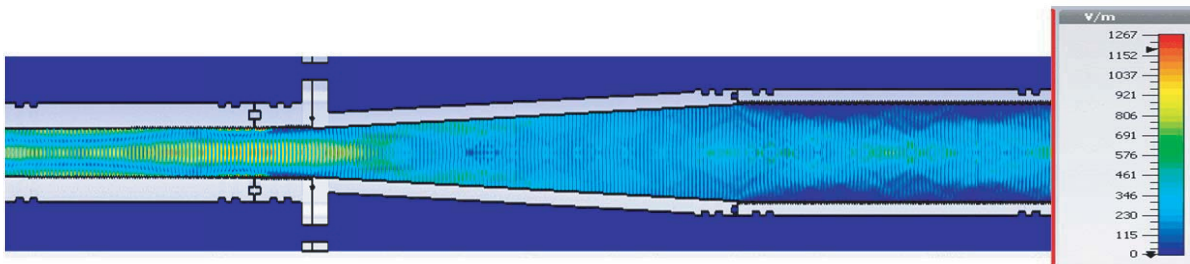


Figure 7. The electric field flow inside circular corrugated waveguide with square groove.

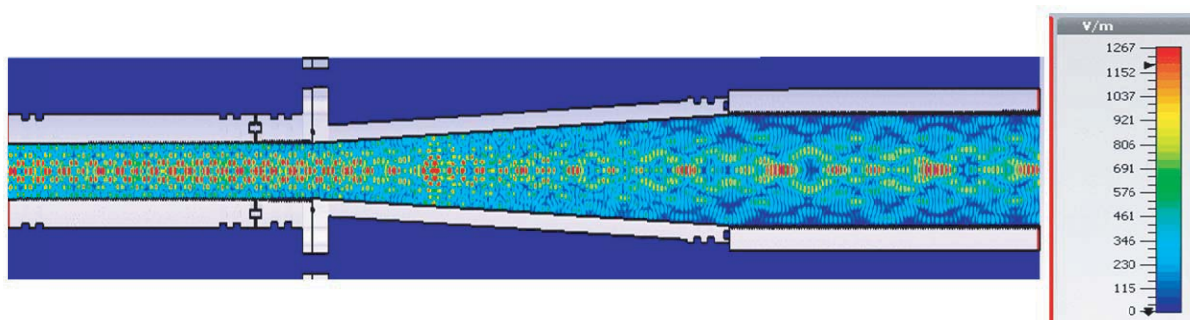


Figure 8. The electric field flow inside rectangular corrugated waveguide with rectangular groove.

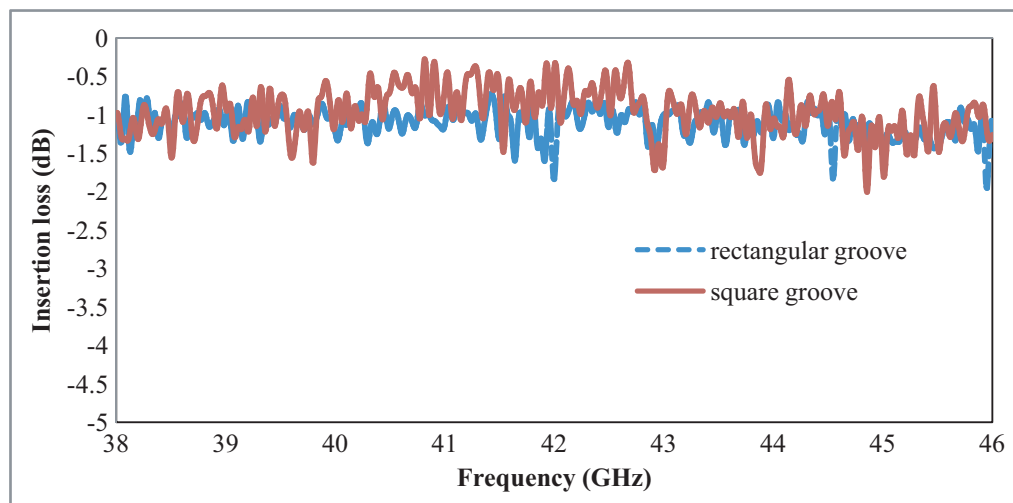


Figure 9. Insertion loss of corrugated waveguide with rectangular and square groove.

generated by up-taper and TM_{11} to HE_{11} mode converter (up-taper and mode converter loss is approximately 0.7 dB). Based on the simulation results, it is comprehensible that the square grooves corrugated waveguide gives lower insertion loss than rectangular grooves corrugated waveguide.

The radiation patterns of circular corrugated waveguides with rectangular and square grooves are shown in Figure 10 and Figure 11, respectively. Figure 10 indicates that square grooves corrugated waveguide gives an ideal radiation pattern like Gaussian beam, and it gives 28.5 dB isolation from cross polar component. The comparisons of the proposed corrugated waveguides are mentioned in Table 3.

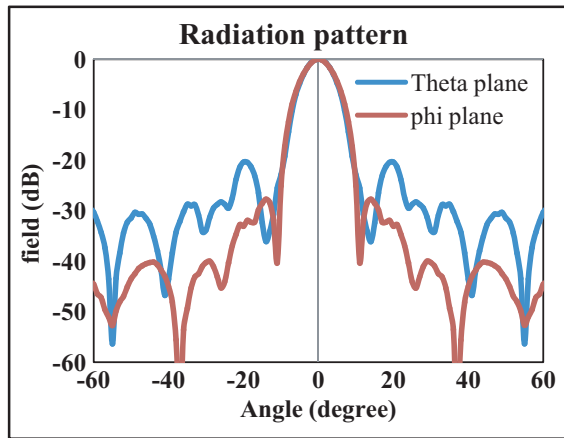


Figure 10. Radiation pattern of circular corrugated waveguide with rectangular grooves.

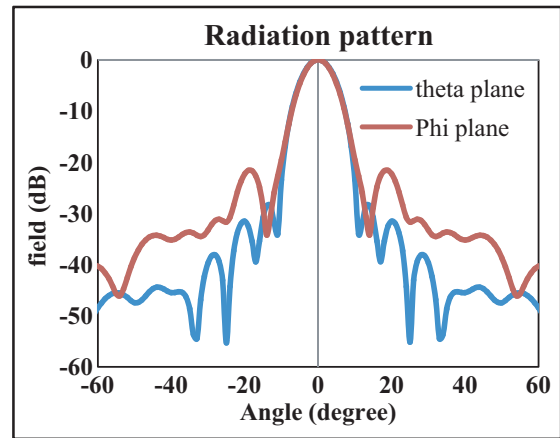


Figure 11. Radiation pattern of circular corrugated waveguide with square grooves.

Table 3. Comparisons of circular corrugated waveguide with square and rectangular grooves.

Parameter	Square groove circular corrugated waveguide		Recatngular groove circular corrugated waveguide	
	Theo. value	Opti. value	Theo. value	Opti.value
Corrugation width (mm)	1.19	1.19	0.70	0.48
Corrugation depth (mm)	1.79	1.785	1.79	1.785
Insertion loss (dB)	0.20	0.08	0.25	0.12
Cross polar isolation (dB)	22	28.5	15	20
Side lobe level (dB)	20	21.6	28	27.7

4. FABRICATION AND TESTING OF THE CORRUGATED WAVEGUIDE

One of the most important segments in fabrication is precise manufacturing of the corrugations in the waveguide. A small variation on fabrication may create a huge impact on the performance. To examine its effect, sensitivity analysis has been carried out to predict the fabrication tolerance for TE₀₃ to TE₀₂ mode converter [19]. It gives fabrication tolerance up to ±100 μm at 42 GHz operating frequency. In

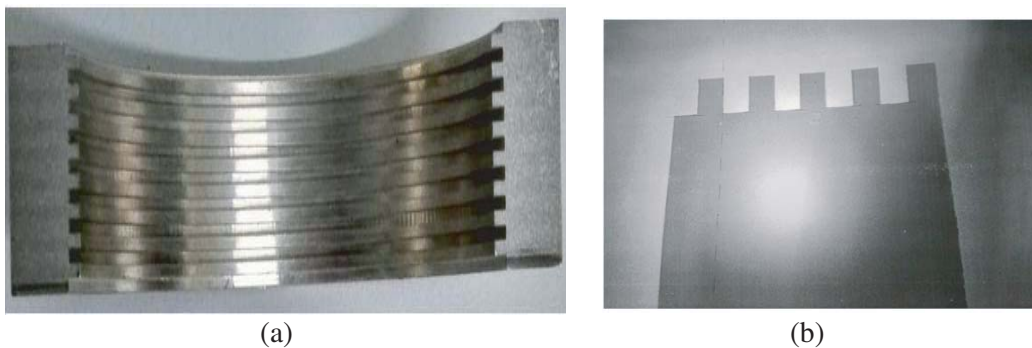


Figure 12. (a) Cross section view. (b) Profile projected image of an oversized circular square groove corrugated waveguide.

order to achieve this, a small piece has been manufactured first, and the corrugation width, depth, and thickness are measured with 20 times zoom image on profile projections as shown in Figure 12(a) and Figure 12(b). The cross-section of the manufactured part of the corrugated waveguide is shown in Figure 12(a). After the measurement of the dimensions, the final manufacturing process commences. In general, as the length of the waveguide increases, the internal vibration of the tool used for fabrication also increases. The vibrations in the tool and boring bar create chattering on the corrugations which in-turn degrades the overall performance of the manufactured unit. In the final process, keeping in mind the manufacturing technology as the primary stage, the small circular waveguide pieces are fabricated to maintain the corrugation dimensions. In order to achieve the lossless waveguide, these pieces are brazed together.

Here, we have manufactured both the square and rectangular grooved corrugated waveguides with length of 500 mm. The test setup for them is shown in Figure 13. We have used ZVA50 vector network

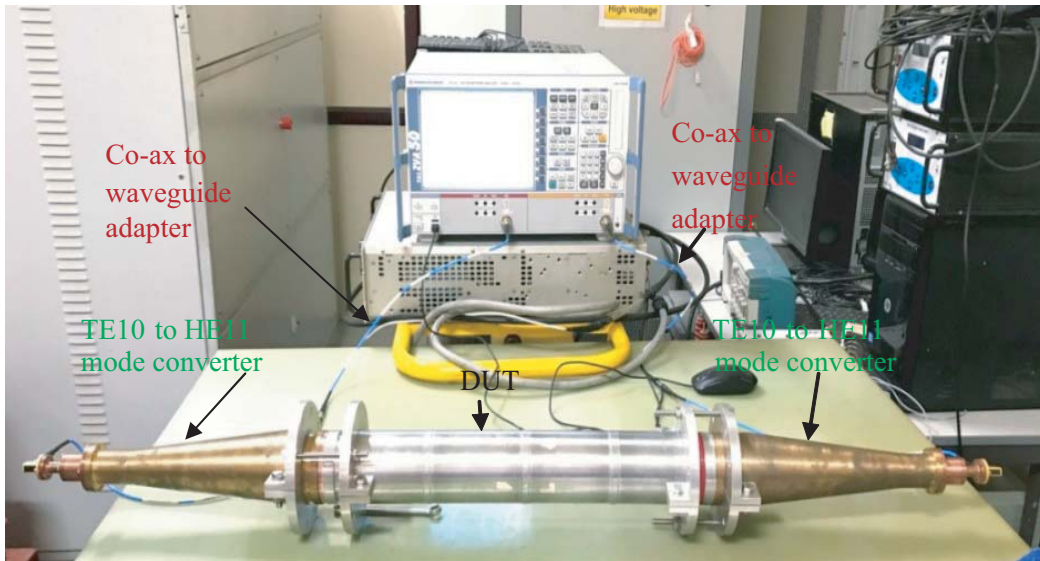


Figure 13. Test setup for corrugated waveguide.

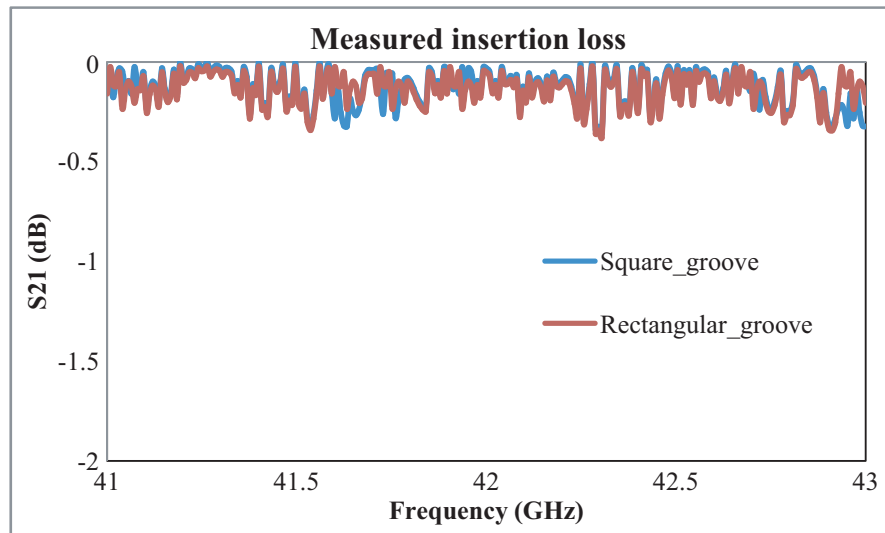


Figure 14. Measured insertion loss of oversized circular corrugated waveguides.

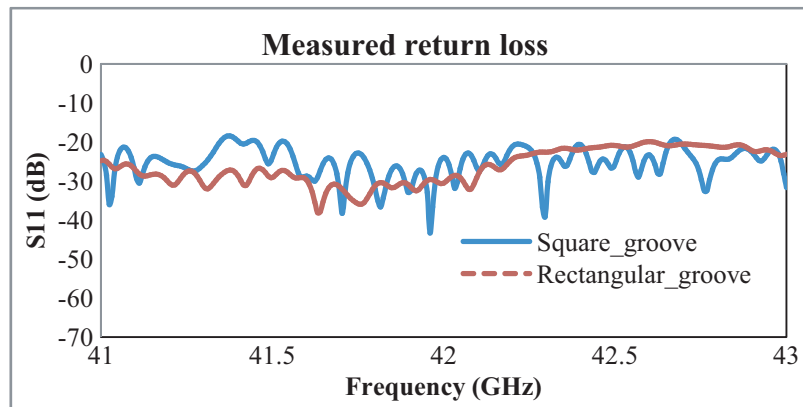


Figure 15. Measured return loss of oversized circular corrugated waveguides.

analyzer (VNA) for extracting the scattering parameters of the oversized circular corrugated waveguide. As shown in Figure 13, VNA is connected with a small male aperture (SMA) connector to the rectangular waveguide adaptor. Then this adaptor is connected with TE_{10} mode to HE_{11} mode exciter which is imported from Gycom Russia. It gives mode purity of more than 98%. The scattering parameters (insertion loss and return loss) for square groove and rectangular groove are shown in Figure 14 and Figure 15. In Figure 14, the presence of high frequency oscillations is due to the TE_{10} to HE_{11} mode exciter which is not 100% pure, or it contains the presence of higher order modes and longer propagation in corrugated waveguide (500 mm). Mode filter is not used which will remove the higher order modes as well as improve insertion loss. Based on the measured results, it is concluded that the loss generated by the square groove corrugated waveguide (average insertion loss in gyrotron bandwidth 0.08 dB) is less than the rectangular groove corrugated waveguide (average insertion loss in gyrotron bandwidth 0.08 dB).

5. CONCLUSION

We have designed and manufactured oversized circular corrugated waveguides at 42 GHz with two different geometries: rectangular grooves and square grooves. In CST, HE_{11} is not directly possible to be excited, so we have designed TM_{11} mode into HE_{11} mode converter with 95% mode conversion efficiency and excited both proposed structures. Based on the simulation results, it is observed that square groove corrugated waveguide provides lower insertion loss than the rectangular grooves. Moreover, square grooves are more preferred than rectangular grooves due to mechanical feasibility. However, the microwave performance of rectangular grooves is more sensitive with respect to the corrugation width. In both the cases, they give more than 8 GHz operating bandwidth centered at 42 GHz frequency.

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