

Design and Development of a D-Band Corrugated Horn Antenna for Millimeter-Wave Plasma Diagnostics

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Abstract—In fusion reaction, plasma parameters such as the density and temperature of electrons should be diagnosed continuously. There are various methods to diagnose plasma parameters. In these, reflectometry systems are widely used to measure the electron density and plasma physics study. In reflectometry systems, antenna plays an important role as a transmitter/receiver element. This paper presents the design of a D-band (110–170 GHz) corrugated horn antenna suitable for reflectometry system. The simulated results for antenna are compared with that of the measurements. Further, different structures are proposed to ease fabrication complexities and reduce cost.

1. INTRODUCTION

In the situation of energy scarcity, fusion plasma energy is one of the vital energy sources. To generate fusion power, highly dense plasma in the range of 10^{20} m^{-3} is required. Plasma density affects the behavior of fusion plasma. The number of free electrons per unit volume, also known as electron density, gives the degree of ionization of the plasma [1]. Hence, it should be monitored continuously. Reflectometry system is widely used to diagnose the plasma [2]. It works on the principle of Radio Detection and Ranging (RADAR).

Antenna plays a very important role in a reflectometry system. Generally, horn antennas are preferred to transmit/receive the electromagnetic waves in such systems. Sakaguchi et al. [3] have proposed horn antenna for an ECRH system, i.e., a system for a single frequency.

There are several horn antenna options [4] available for quasi-optical systems. These include the conventional conical and pyramidal horns [5, 6], Potter horn [7], corrugated horn [8], dielectric horn [9, 10], metamaterial horn [11, 12], etc. In some fusion devices, oversized waveguides are also utilized as antennas [13]. Among all, corrugated horn antenna satisfies all the requirements for a reflectometry system due to high quasi-optical coupling [14]. It offers high gain, low cross-polarization over a wide bandwidth and can produce a Gaussian-like radiation pattern [15, 16] with spatial resolution necessary for analyzing the density profile for the fusion plasma. However, at the millimeter-wave frequencies, the dimensions of the corrugations are in submillimeter range. Therefore, the fabrication of a horn is quite challenging. In recent years, many researchers have proposed a few solutions to mitigate this challenge [17–20].

In this paper, the design of a D-band (110–170 GHz) corrugated horn antenna suitable for fusion plasma diagnostics in a swept reflectometer system is discussed. The simulated and measured results of the antenna are compared and presented. The horn fabrication challenges are also discussed. To ease the fabrication complexities and to reduce the cost, different structures are proposed.

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2. REFLECTOMETRY SYSTEM FOR PLASMA DIAGNOSTICS

A basic block diagram of the reflectometry system used for the plasma diagnostics is shown in Fig. 1. It consists of a signal generator, multiplier, isolator, variable attenuator, 3-dB directional coupler, mixer, and transmitting/receiving horn antennas. In this setup, the signal generator (Keysight N5173B, 9 kHz to 20 GHz) is used as a microwave source to generate the power at different frequencies. The multiplier multiplies the input signal with the value of the multiplication factor (here, 12) and increases it to the higher frequencies (D-band). The isolator is used to prevent the damage of the source from the reflected power, and the variable attenuator is used to control the power level. The 3-dB directional coupler is used to divide the input power. Half of the power is applied to the transmitting horn antenna, and the other half is sent to the mixer as the reference power. The reflected power from the receiver is passed to the mixer for further process. Using quadrature mixer, the phase difference between the reflected and incident waves can be obtained. The same is analyzed by applying all the frequencies of the D-band. It is minimum when the correlation of the waves is maximum.

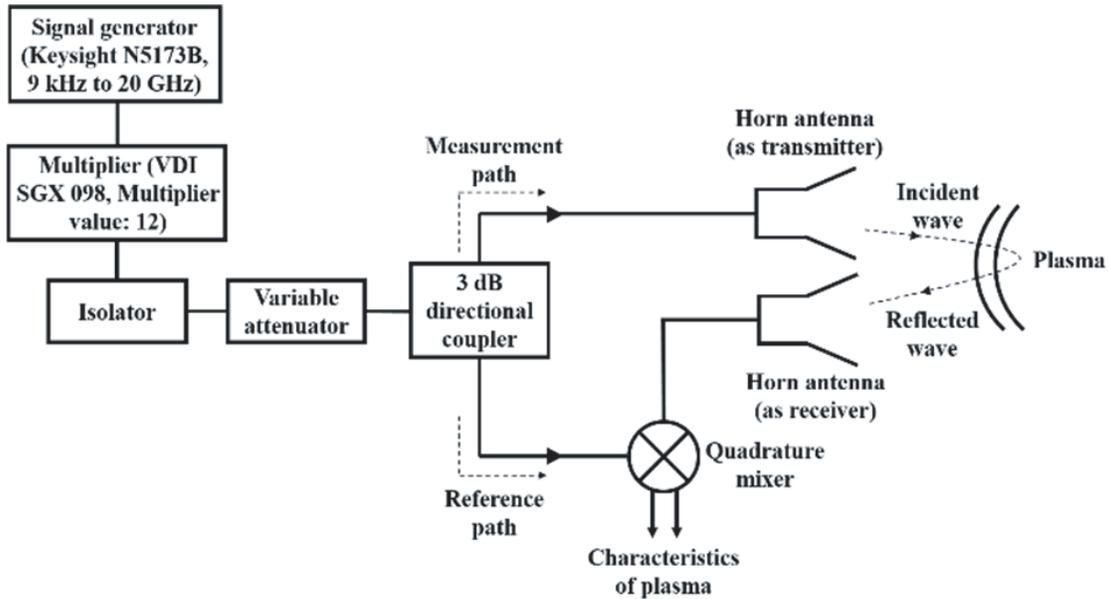


Figure 1. Basic block diagram of the reflectometry system for plasma diagnostics [20].

Plasma contains different layers with different density values as per the slab model [21]. In a reflectometry system, to obtain the density value at different layers of the plasma, the electromagnetic waves with different frequencies are incident to the plasma under test. Out of all incident frequencies, when a particular frequency becomes equal to the plasma frequency, maximum waves will be reflected back. Using this frequency, the density (n_e) of the layer can be obtained using the procedure described in the subsequent paragraphs.

Propagation of the electromagnetic waves within the plasma can be of two types: ordinary ($\vec{E} \parallel \vec{B}$) and extraordinary ($\vec{E} \perp \vec{B}$) waves, where \vec{E} is the electric field vector of the antenna, and \vec{B} is the applied magnetic field to the plasma. For ordinary waves, the dispersion relation for the frequency of the incident wave (ω) can be given as Eq. (1).

$$\omega^2 = \omega_p^2 + c^2 k^2 \quad (1)$$

where c is the speed of light, k the wave number, and ω_p the plasma frequency [22] which can be expressed as Eq. (2)

$$\omega_p = \sqrt{\frac{n_e \cdot e^2}{\epsilon_0 \cdot m_e}} \quad (2)$$

where n_e is the density of electrons, ϵ_0 the free space permittivity, e the electric charge of the electron (in esu), and m_e the effective mass of the electron (in grams).

Similarly, for extraordinary waves, the dispersion relation between the incident and plasma frequencies can be given as Eq. (3).

$$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2} \cdot \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2} \tag{3}$$

where $\omega_h^2 = \omega_p^2 + \omega_c^2$ in which ω_h is the upper hybrid frequency, and ω_c is the electron cyclotron frequency. By putting $k = 0$ for cutoff condition, Eq. (3) can be summarized as Eq. (4).

$$\omega_{R/L} = \frac{1}{2} \left[\pm \omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2} \right] \tag{4}$$

where ω_R and ω_L are the right and left cutoff frequencies. For extra ordinary waves, the waves cannot propagate and reflect back for plasma frequency between 0 to ω_L and ω_h to ω_R . The density profile of the plasma can be obtained by applying the frequencies of D-band that can be summarized as Eq. (5).

$$n_e = \frac{\epsilon_0 \cdot m_e [\omega^2 \mp \omega \cdot \omega_c]}{e^2} \tag{5}$$

Similarly, by analyzing different layers of the plasma, the total density profile can be obtained.

Generally, for fusion reaction, the plasma has a very high density in the range of 10^{20} m^{-3} . Hence, to diagnose the plasma in this range millimeter-wave reflectometry setup in the D-band, i.e., 110–170 GHz, is required.

3. MILLIMETER-WAVE CORRUGATED HORN ANTENNA

To diagnose the plasma using a reflectometry system, the transmitting/receiving horn antenna should have a Gaussian-like radiation pattern [15, 16]. The Gaussian beam has its energy concentrated at the center and gradually reduces towards the boundaries. Generally, a hybrid mode horn is used to obtain a Gaussian-like radiation pattern. It has high coupling to the fundamental free space Gaussian mode (TEM₀₀) [14]. The hybrid mode (HE₁₁) is the combination of two modes (85% of TE₁₁ and 15% of TM₁₁). It produces linear electric field lines at the aperture of the horn antenna which forms a symmetric beam pattern [4]. Due to symmetricity of the fields in E and H planes, the cross-polarization is also relatively low. Different techniques, such as step change, slope/profiling, pins/posts, and corrugations, can be used to generate the hybrid modes. Among these, corrugated mode converters [23, 24] are widely used. They give a nearly ideal field pattern at the aperture.

Various performance parameters of the corrugated horn antenna are controlled by different design regions as shown in Fig. 2. It shows the inner structure of the conical radially corrugated horn geometry.

The step-by-step design procedure for the corrugated horn antenna is described by Granet and James [24]. In fact, it starts with a list of desired specifications. Different geometrical parameters like input radius, length of the horn, pitch, width, depth of the corrugations, aperture radius, etc. are decided after a series of iterations to achieve required performance of the antenna.

In the present case, the antenna specifications were decided for the reflectometry system as given in Table 1.

Table 1. Specifications of D-band corrugated horn antenna.

<i>Specifications</i>	<i>Desired values</i>
Frequency range	D-band (110–170 GHz)
S_{11} (dB)	≤ -10 dB
Gain (dB)	≥ 22 dB
Radiation pattern	Gaussian

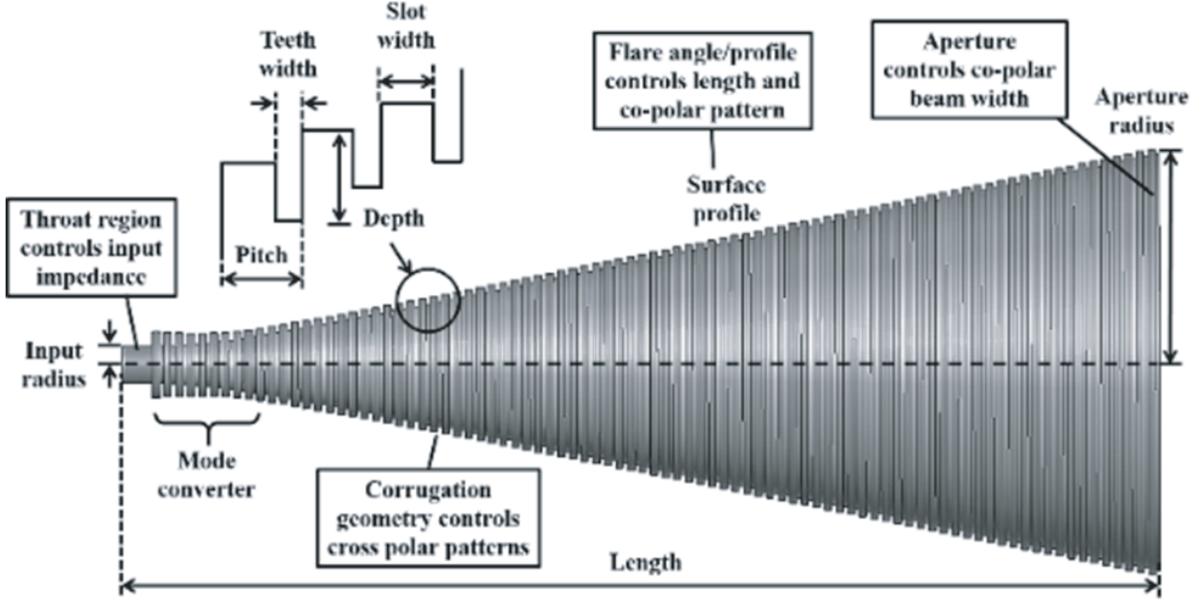


Figure 2. Various design regions of the corrugated horn antenna.

The theoretical calculation was done to determine geometrical parameters of the horn antenna to meet the specifications. The simulation was performed using the commercially available software (Ansys HFSSv16). Once the design parameters are calculated, a parametric study was carried out using the software simulator to obtain the best performance, and optimized design parameters are listed in Table 2.

Table 2. Optimized design parameters of D-band corrugated horn antenna.

<i>Design parameters</i>	<i>Optimized values</i>
Input radius (a_i)	$0.611 \cdot \lambda_c$
Length of a horn (L)	$34.336 \cdot \lambda_c$
Slot width of the corrugation (w)	$0.243 \cdot \lambda_c$
Pitch of the corrugation (p)	$0.383 \cdot \lambda_c$
Depth of the corrugation (d)	$\lambda_c/2$ to $\lambda_c/4$
Aperture radius (a_o)	$6.944 \cdot \lambda_c$

In order to study the dimensional tolerances, the sensitivity analysis was carried out by varying all the design parameters equally by $\pm\lambda_c/200$, $\pm\lambda_c/150$ and $\pm\lambda_c/100$ microns (where λ_c is the wavelength at the center frequency of 140 GHz). From this analysis, it was found that the antenna performance was acceptable for dimensional variations below $\pm\lambda_c/200$ microns. Detailed discussion on the sensitivity analysis, corresponding results, and the conclusions of the study can be found in [25].

After getting the desired simulated performance, it was decided to fabricate the prototype antenna. Initially, there was a plan to fabricate the entire horn in a single piece, i.e., as one fabricated unit. However, due to submillimeter dimensions of the corrugations of the horn antenna at millimeter-wave frequencies, the first fabrication attempt was not successful. In fact, the cutting tool of the Computer Numerical Control (CNC) turning machine could not perform the operation due to a very small throat section of the horn antenna. Also, the vibration of a cutting tool due to the large horn length resulted in poor dimensional accuracy.

Subsequently, it was decided to fabricate the horn in multiple parts. The horn was then fabricated in two axially split (symmetric) parts, and each part was individually fabricated using the mechanical

turning process. These parts were then joined with each other. Photographs of the fabricated antenna (iteration 1) are shown in Fig. 3. Due to the axially split antenna structure, the performance of the horn was not satisfactory because of the misalignment of a large number of corrugations (total 87 corrugations). Based on this experience, it was decided to split the horn such that the majority of the corrugations remain unsplit. Accordingly, in the subsequent fabrication attempt, the major part of the horn with a broader diameter was fabricated in a single piece. Only the compact throat section (up to sixteenth corrugation) was axially split and fabricated in two pieces. Photographs of the fabricated horn antenna with rectangular to circular transition is shown in Fig. 4.

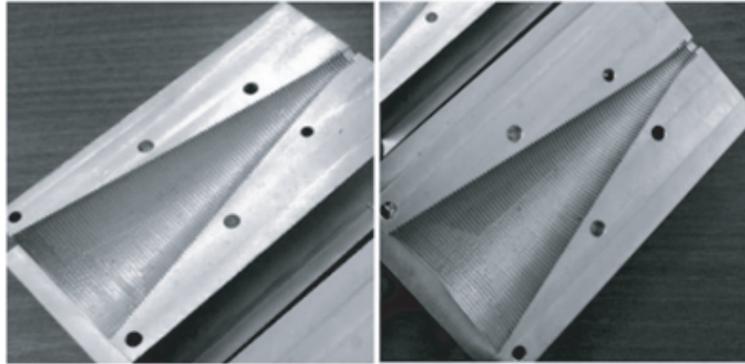


Figure 3. Axially splitted D-band corrugated horn antenna (Iteration 1).



Figure 4. Photographs of the fabricated D-band corrugated horn antenna with transition (Iteration 2).

The rectangular to circular transition was fabricated using the Wire Electrical Discharge Machining (EDM) technique. The split throat section has two symmetrical parts. Both the parts were fabricated using Sink EDM technique. In this, the electrode made by turning operation is used for the electrical discharge process. The material of electrode should have high melting point as well as high wear resistance. Tungsten copper material was used for this. The second part of the horn having larger diameter was fabricated using the conventional and CNC turning operations. The accuracy of the dimensions was ensured by using the vision measurement system. By using the measuring probe and high definition camera, it was assured that the fabricated horn was under acceptable tolerance limit.

The measurement of all parameters of the fabricated horn antenna was carried out at the Institute for Plasma Research (IPR), Bhat, Gandhinagar. Three important parameters, i.e., S_{11} (Return-loss), gain, and the radiation characteristics of the horn, were measured. The measured performance in terms of S_{11} (dB) is compared with the simulated results in Fig. 5. For the fabricated horn in iteration 2, S_{11} (dB) is better than -10 dB for the entire D-band.

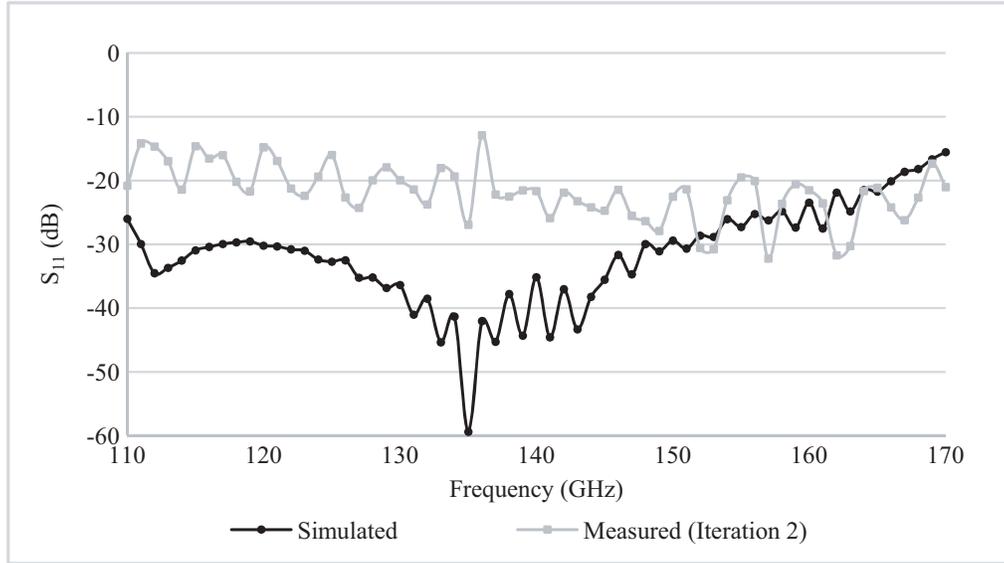


Figure 5. Measured and simulated S_{11} (dB).

The gain measurement of the fabricated horn antenna was also carried out. The measured results are compared with that of the simulated ones and shown in Fig. 6. It can be seen that the fabricated horn antenna gives better than 25.5 dB of gain for the entire D-band frequencies.

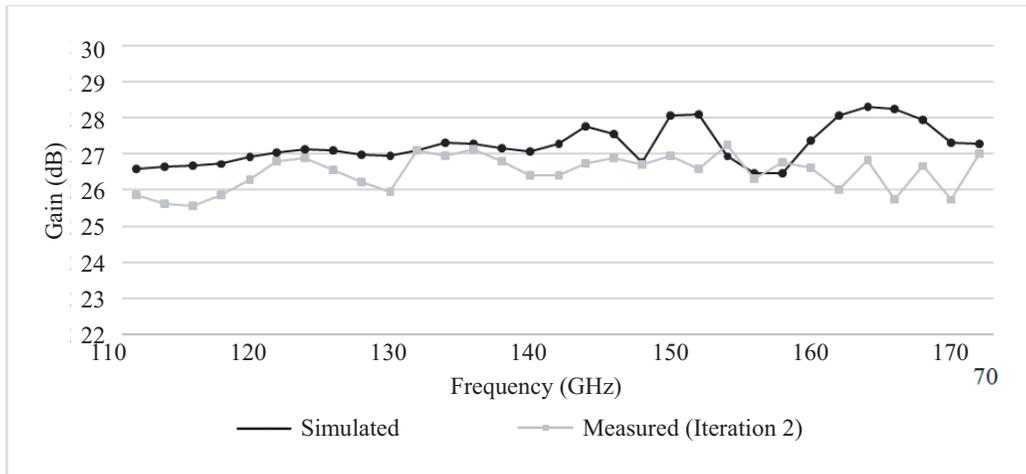


Figure 6. Measured and simulated gain (dB).

As mentioned previously, for the application of the horn antenna for plasma diagnostics, it should have Gaussian-like radiation characteristics at the aperture. Hence, after measurement of S_{11} and gain, the radiation characteristic of the horn was measured. Fig. 7(a) shows the graph of measured received power in the propagation direction ($z = 5.4$ cm) at 140 GHz for the horn antenna under consideration. In order to verify it, the theoretical 2-dimensional Gaussian function given in [26] was plotted as shown in Fig. 7(b). On comparison of the graphs shown in Figs. 7(a) and 7(b), it can be concluded that the measured results are in good agreement with the theoretical 2-D Gaussian function. The fabricated horn antenna has a Gaussian pattern with the side-lobes of -17 dB as it is less than 2% of the peak amplitude as shown in Fig. 7(a). The performance of the horn antenna under consideration satisfies the requirements of the plasma diagnostics having Gaussian shaped beam and high gain suitable for quasi-optical coupling as described in [1, 3, 14].

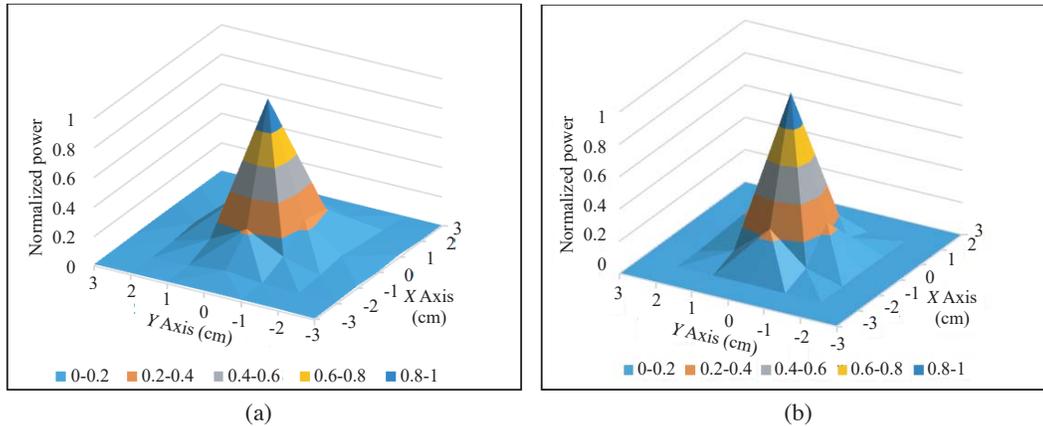


Figure 7. Normalized power for Gaussian pattern validation, (a) measured, (b) theoretical 2D Gaussian function.

4. CONCLUSIONS

In this paper, a D-band corrugated horn antenna useful for the fusion plasma diagnostics system is explained with the measured and simulated results. The fabrication issues of a corrugated horn antenna operating at millimeter-wave frequencies are discussed. The fabrication of the corrugated horn in a single piece affects the accuracy of the inner grooves and in turn degrades the horn performance. In fact, the narrow throat section and the small corrugations in the mode converter region impose serious fabrication challenges. The problem can be resolved by splitting the structure into multiple parts. However, utmost care must be taken in fabrication while splitting and assembling the horn. The axial splitting of the entire horn creates a mismatch in all the corrugations and leads to performance degradation.

The proposed horn design with multiple split structure satisfies all the requirements of a reflectometry system for the plasma diagnostics system. It gives S_{11} better than -10 dB and gain better than 25.5 dB for the entire D-band frequencies with less than -17 dB of side lobe level.

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