

WC-281 Circular Waveguide Terminator Essential in Microwave Plasma Interaction Experiments for SYMPLE

Jitendra Kumar^{1, *}, Raj Singh², and V. P. Anitha²

Abstract—This work presents the novel design and development of a WC-281 circular waveguide terminator or termination for microwave plasma interaction experiments. Final waveguide terminator is designed by using the quad wedge of FR4, cone of resistive material, i.e., Kanthal and Teflon discs. Kanthal is a composition of aluminium, chromium, and iron. Wedge shape geometry helps in gradually changing the impedance and thus decreasing the return loss, while resistive material Kanthal attenuates the field before reaching the receiving end. This makes it suitable for use as the finest microwave termination. The final model of terminator decreases the reflection coefficient (S_{11}) up to -40 dB while reduces the transmission coefficient (S_{21}) immensely up to -63 dB at 2.85 GHz.

1. INTRODUCTION

SYstem for **M**icrowave **P**lasma **E**xperiments (SYMPLE) is an experimental system to investigate the physics of linear and nonlinear interaction of high-power microwave (HPM) with plasma in Institute for Plasma Research (IPR), Gandhinagar, India [1]. The experimental system is conceived to investigate the physics of interaction of extremely intense electromagnetic waves ($\omega_p > \omega_{em}$). The supposed study has relevance in understanding laser-plasma interactions applicable in inertial fusion [2]. Impedance mismatches in a radio-frequency (RF) electrical transmission line cause power loss and reflected energy. In an RF transmission system, the reflection of power from the receiving end in a system decreases the efficiency of the system. Sometimes it may even cause damage to the generator attached at the sending end. Matched loads or terminations are designed to absorb incident energy without appreciable reflection. Matched termination is the most required part of the passive waveguide components like directional couplers and filters [3]. Coaxial terminations and waveguide terminations are collectively known as RF terminations or microwave terminations. They are used to absorb energy and prevent a signal from reflecting back from mismatch ports. The design and development of the matched terminations for a rectangular waveguide operation on fundamental mode are well established [4, 5]. However, circular waveguide terminations are not available conventionally, and some concepts related to circular waveguide termination are given in [6]. Hence, R&D efforts are required to have the termination with the circular waveguide.

Present work provides the design, development, and simulated results of termination along with a systematic approach based on a circular geometry. Microwave termination is generally used in networking equipment, optical transmission device, network analyzer, bit error ratio testing system (BERTS), fixed wireless access (FWA), and for measurement purposes in other applications like S -parameters of waveguides, directional couplers, and filters. Here, a matched terminator is designed for WC-281 circular waveguide. Terminations should have features like high performance, full assortment of impedance matching, low voltage standing wave ratio (VSWR), and usability over wide bandwidth.

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* Corresponding author: Jitendra Kumar (jitu.kumar87@gmail.com).

¹ Muwaves Components Research and Development Pvt. Ltd., India. ² Institute for Plasma Research, Gandhinagar, India.

2. MATCHING NETWORK

Electromagnetic energy is often passed through a waveguide to transfer the energy. A waveguide may be terminated in a resistive load that is matched to the wave impedance of the waveguide otherwise without proper impedance matching, and standing waves cause a large decrease in the efficiency of the waveguide [7]. The resistive load is most often called a dummy load because its only purpose is to absorb all the energy in a waveguide without causing standing waves. There is no place on a waveguide to connect a fixed termination resistor; therefore, several special arrangements are used to terminate waveguides [4, 5, 8–10]. One method is to fill the end of the waveguide with a graphite and sand mixture, as illustrated in Fig. 1(a). When the fields enter the mixture, they induce a current flow in the mixture which dissipates the energy as heat. Another method for terminating a waveguide is the use of a wedge of highly resistive material, as shown in of Fig. 1(b). The plane of the wedge is placed perpendicular to the magnetic lines of force. When the magnetic field lines cut through the wedge, current flows in the wedge and causes a power loss. As with the other methods, this loss is in the form of heat, since very little energy reaches the end of the waveguide, and reflections are minimum.

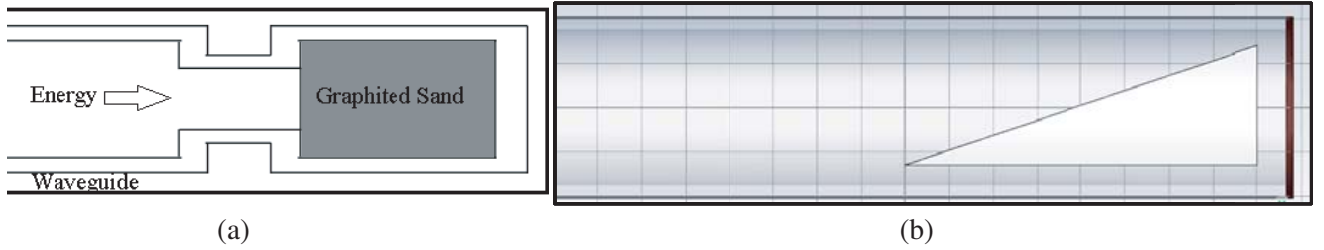


Figure 1. Matched Termination: (a) Graphited sand based, (b) wedge of highly resistive material based.

3. DESIGN AND ANALYSIS

Matched termination depends on the type of waveguide, frequency range, and also type of feed for TE or TM mode. This report deals mainly with TE mode. The matched termination works on the principle of attenuating the microwaves. The attenuation depends on whether absorbing material is placed parallel to the electric field lines in the case of loss on relative permittivity, or it is placed parallel to the magnetic field lines for the case of loss on the basis of relative permeability of the material.

WC-281 circular waveguide of aluminium is used for investigation. The inner diameter of WC-281 circular waveguide is 71.42 mm, and the length is multiple of guided wavelength (λ_g). The operating range of WC-281 is between 2.82 and 3.88 GHz. Here, the operating frequency is considered nearly 3 GHz for all calculations. The calculated cutoff frequency ($f_c = c/\lambda_c$) for TE₁₁ mode comes out to be 2.46 GHz, and the guided wavelength (λ_g) is 174.71 mm. To terminate the waves, different shapes of the wedge with a length nearly $3\lambda_g/4$ are used in the circular waveguide. Wedges are made up of FR-4 (epoxy resin) dielectric material having permittivity (ϵ_r) 4.3 with dissipation factor ($\tan \delta$) 0.025. A resistive cone is to be placed after the FR-4 wedge to minimize the energy (almost nil) at receiving port. The cone is made of Kanthal (a composition of aluminium, chromium, and iron) which is a resistive material. To further increase the absorption and refine the results, circular discs of Teflon of thickness 5 mm are placed before and after the resistive cone. The final specification of the proposed model of terminator for WC-281 circular waveguide is shown in Fig. 2. The long edges of the FR-4 wedge are blended so as to get fit inside the circular waveguide.

The development steps of the proposed termination assembly inside the circular waveguide are demonstrated in Fig. 3. Originally a slab is placed along the axis to terminate the wave as shown in Fig. 3(a). Then, by changing this slab to a wedge shape, significant termination of the wave is obtained as shown in Fig. 3(b). To further improve the return loss, a quad wedge is used as shown in Fig. 3(c). Subsequently, a resistive cone of Kanthal material is placed after the quad wedge to minimize the energy

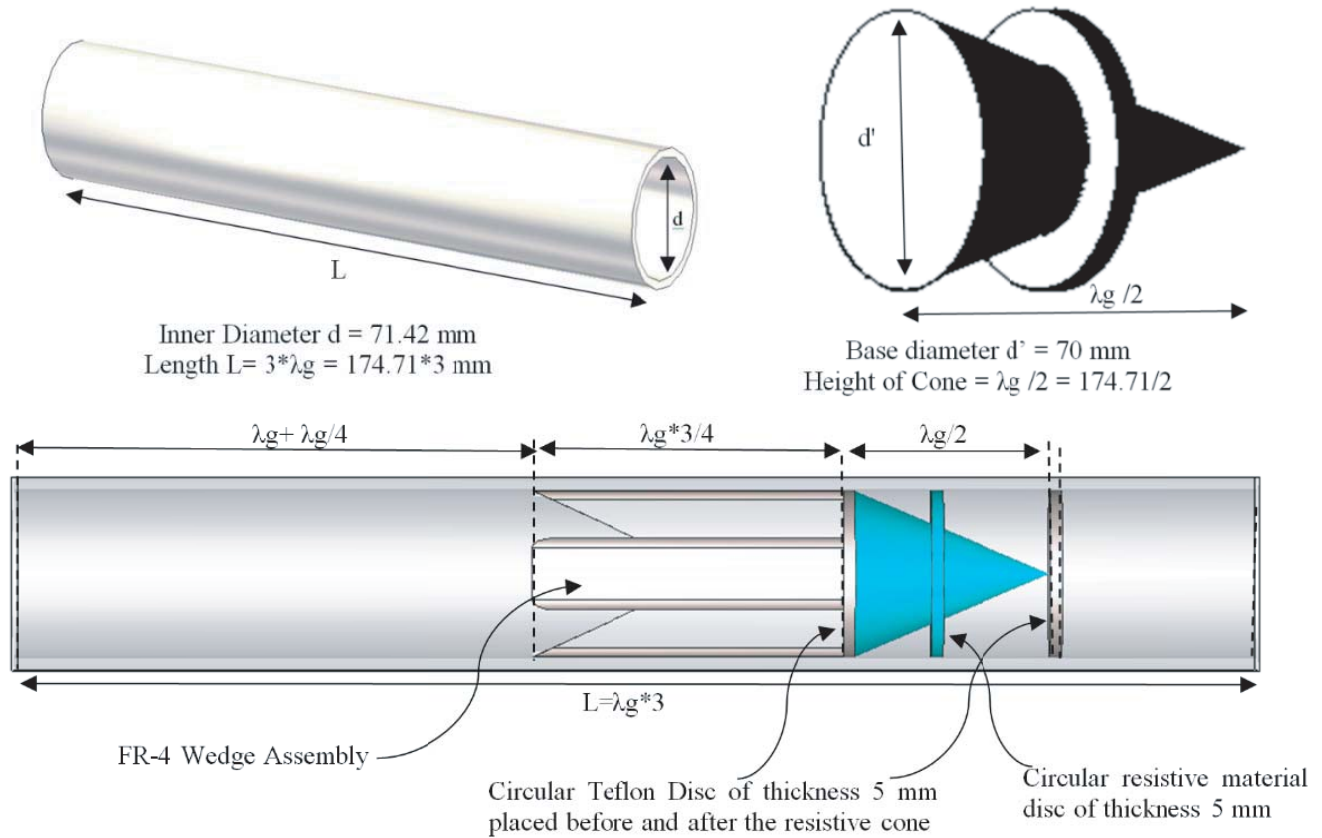


Figure 2. Specification of the proposed model of termination.

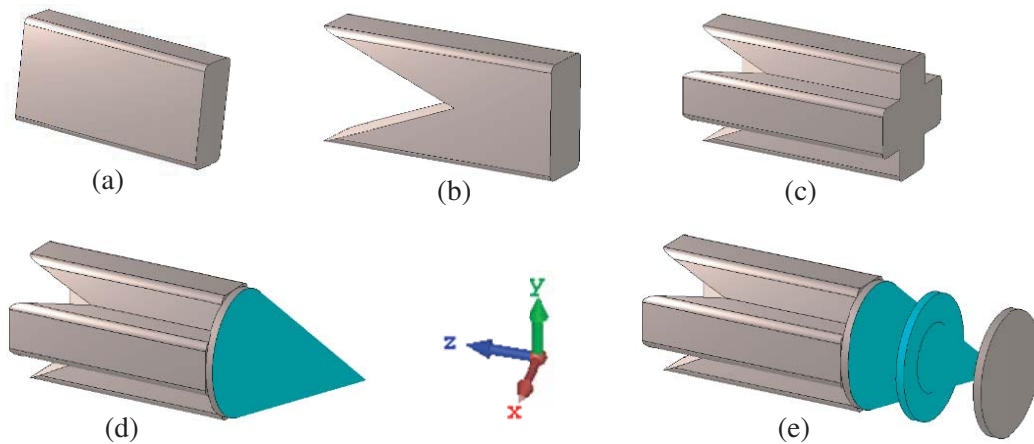


Figure 3. Development steps of the termination assembly inside the circular waveguide: (a) Slab, (b) wedge, (c) quad wedge, (d) quad wedge with cone, (e) quad wedge with cone & discs.

(almost nil) at receiving port as shown in Fig. 3(d). Finally, 2 discs of Teflon and a resistive disc are placed to increase the absorption and refine the results as shown in Fig. 3(e).

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The results for a standard WC-281 circular waveguide are discussed first. The analysis is done based on two steps (1) Minimizing reflection and (2) Increasing absorption. The design and optimization

of terminator are carried out using the CST Microwave Studio [11], full-wave electromagnetic (EM) simulation software.

Figure 4 shows the variation of S -parameter versus frequency for WC-281 circular waveguide. It is observed that the simulated cutoff frequency is nearly 2.5 GHz, and after the cutoff, there is very good transmission without any reflection. To analyse the propagation of Electric field (E-field), a field-monitoring tool is used. The E-field propagation of EM wave in the circular waveguide at 3 GHz is shown in Fig. 5. It is clearly perceived that wave is completely propagated from the first end to the last end of the waveguide without any disturbance.

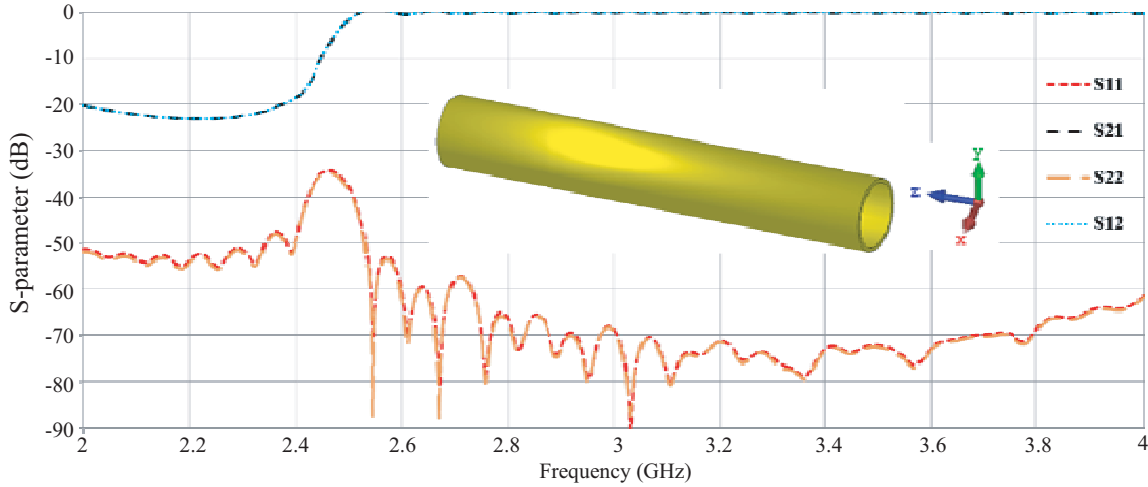


Figure 4. S -parameters versus frequency for WC-281 circular waveguide.

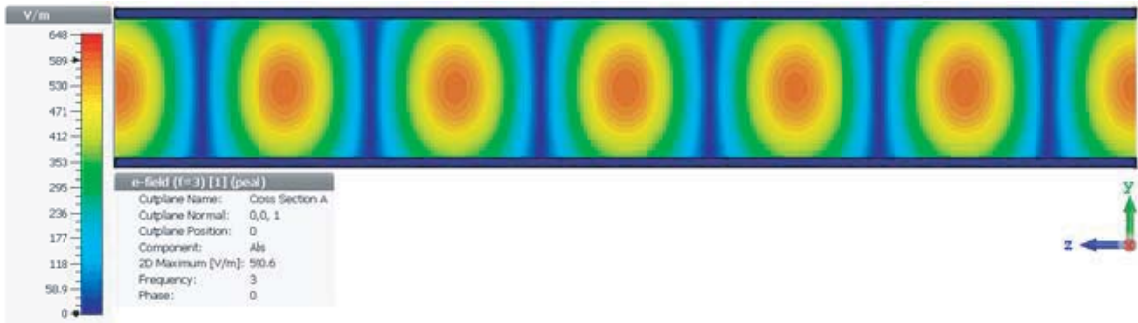


Figure 5. Propagation of EM wave in the circular waveguide at 3 GHz.

Then, a slab of FR-4 dielectric (epoxy resin) is placed along the axis to terminate the waves as well as prevent the reflection. It is easily depicted from S -parameters plot that this slab reduces the reflection coefficient (S_{11}) to about -9 dB only and absorption (S_{21}) to about -64 dB before the receiving port at frequency 2.95 GHz as shown in Fig. 6. It means that nearly 10% power is reflected back at the input end of the terminator. Fig. 7 shows the E-field propagation of EM wave in the circular waveguide for slab assembly of terminator at 2.95 GHz which also verifies the less termination at slab structure.

Further, to improve the return loss, a wedge structure by changing the slab shape of terminator is used. These structures help in reducing the reflection as shown in Fig. 8. It is observed that wedge structure reduces the reflection to about -22 dB at frequency 3 GHz with maintaining good absorption ($S_{21} = -64$ dB) before the receiving port. Hence, the reflection level is improved with respect to the last design. The E-field propagation of EM wave in the circular waveguide for wedge structure of terminator at 3 GHz is shown in Fig. 9 which also verifies the less termination of EM wave at wedge structure.

Next, a quad wedge of terminator is used to make symmetry with reference to z -plane (face) of the

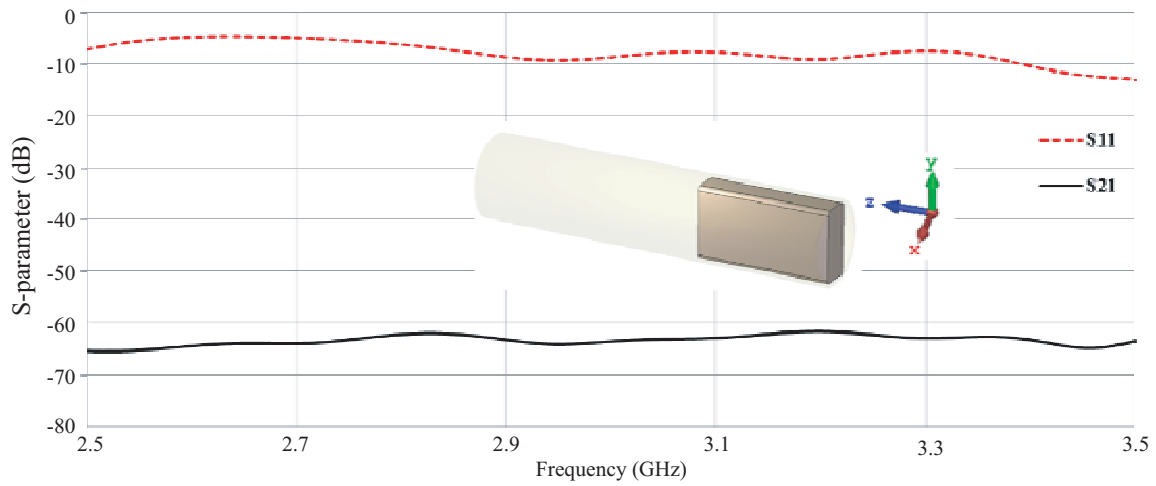


Figure 6. S -parameters versus frequency for slab assembly of terminator.

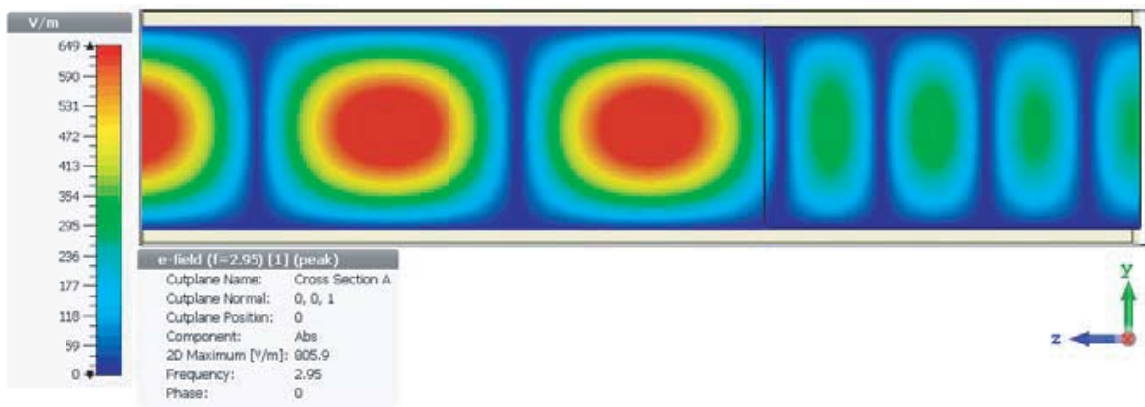


Figure 7. Propagation of EM wave in the circular waveguide for slab assembly of terminator at 2.95 GHz.

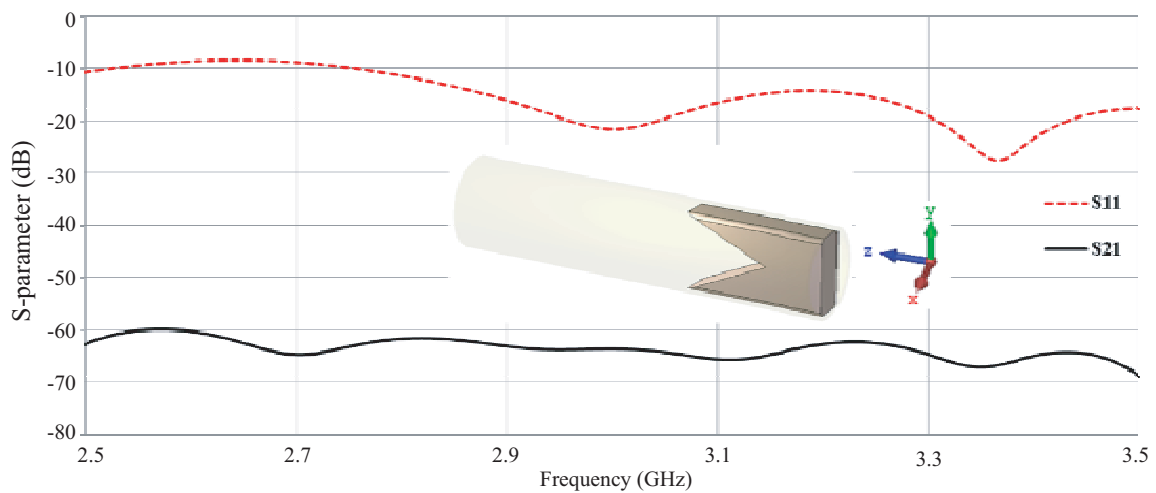


Figure 8. S -parameters versus frequency for wedge structure of terminator.

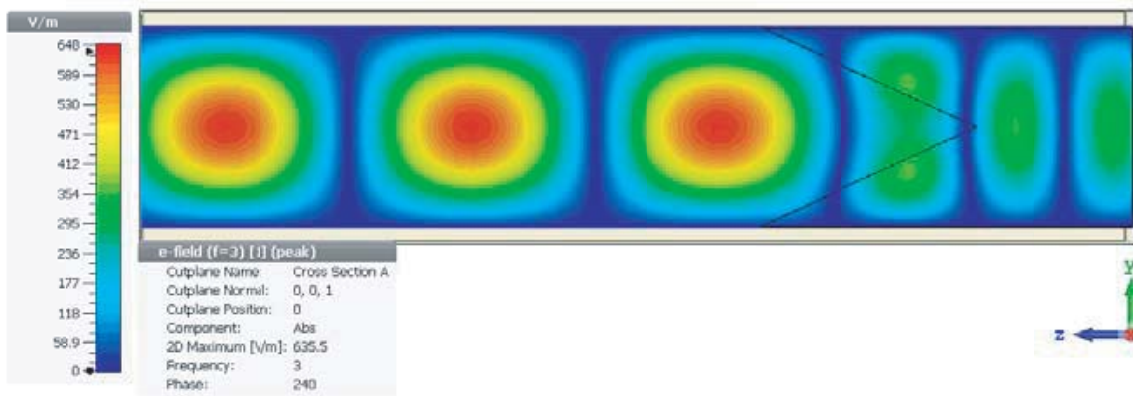


Figure 9. Propagation of EM wave in the circular waveguide for wedge structure of terminator at 3 GHz.

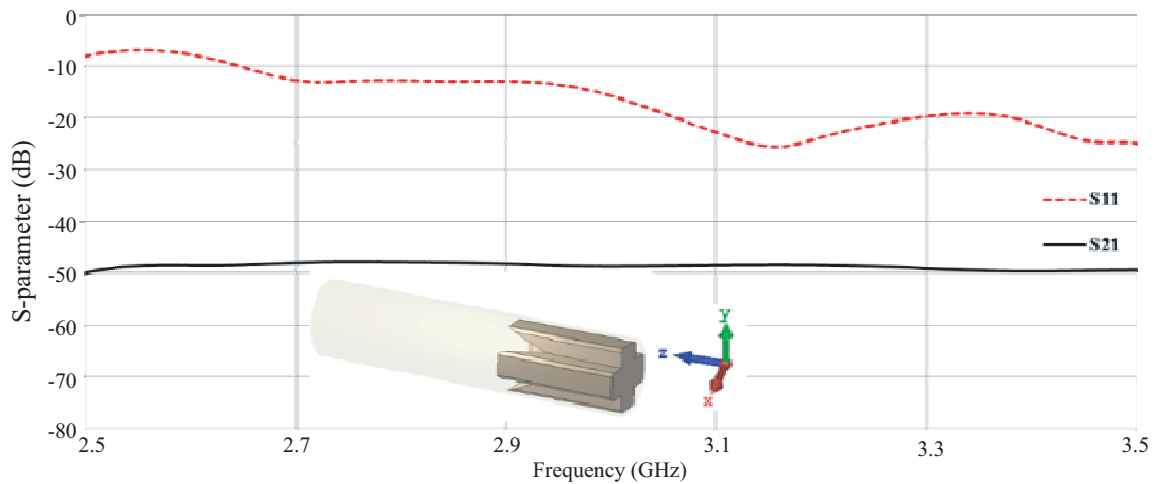


Figure 10. S-parameters versus frequency for quad wedge of terminator.

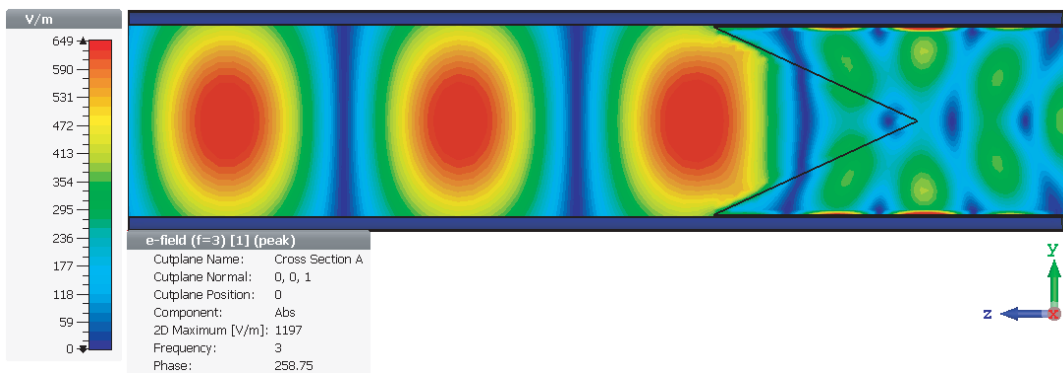


Figure 11. Propagation of EM wave in the circular waveguide for quad wedge of terminator at 3 GHz.

circular waveguide. The comparable results are achieved at 3 GHz with less termination of the wave at wedge as shown in Figs. 10 and 11.

To reach minimum energy (almost nil) at receiving port and reduce the reflection, a cone of Kanthal material is to be placed after the FR-4 wedge which also helps in increasing the range of operating

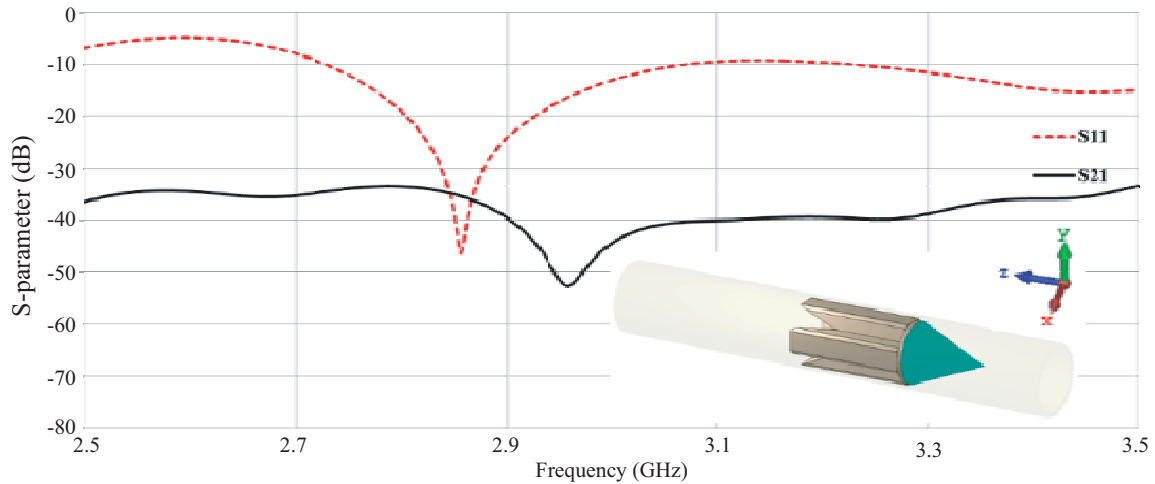


Figure 12. S -parameters versus frequency for quad wedge with cone of terminator.

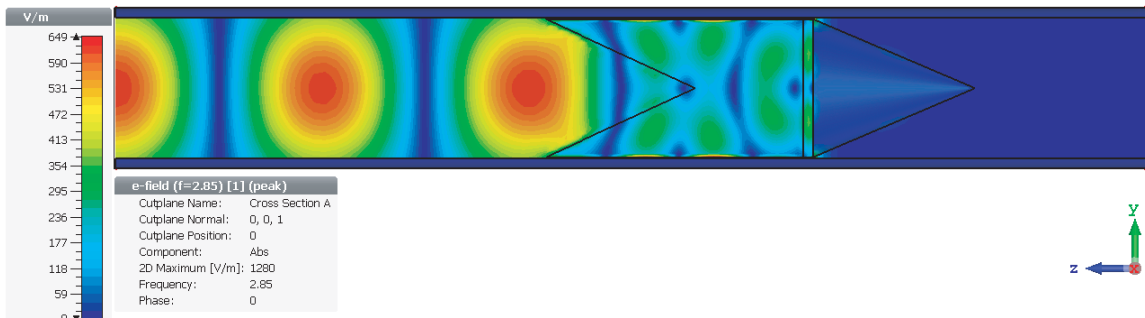


Figure 13. E-field propagation in circular waveguide for terminator with quad wedged and cone at 2.85 GHz.

frequency for the same waveguide terminator. Fig. 12 shows the variation of reflection (S_{11}) and transmission (S_{21}) versus frequency. The resonance for S_{11} is obtained at 2.85 GHz with a bandwidth of ~ 130 MHz for $S_{11} < -20$ dB ranging from 2.80 to 2.93 GHz with satisfactory absorption. This can also be verified from Fig. 13 which shows the E-field propagation of EM wave in the circular waveguide for quad wedged with a cone. There is almost perfect absorption at terminator assembly, i.e., quad wedge with cone.

To further refine the results, circular discs of FR4 and Teflon with thickness of 5 mm are placed before and after the resistive cone. Teflon discs decrease the reflection coefficient (S_{11}) to about -42 dB, and the transmission coefficient (S_{21}) parameter is also immensely reduced nearly below -62 dB at 2.85 GHz as clearly shown in Fig. 14. The final model of terminator also achieves the bandwidth of ~ 130 MHz for $S_{11} < -20$ dB ranging from 2.80 GHz to 2.93 GHz. The proposed model of terminator decreases the reflection coefficient (S_{11}) up to -40 dB while reduces the transmission coefficient (S_{21}) immensely up to -63 dB at 2.85 GHz. The S -parameter for the geometry indicates that purpose for absorption of energy such that it must not reach at receiving port is met. It also satisfies the reflection level. It is perceived from S_{21} parameter that energy is absorbed in the cone itself.

The E-field propagation of EM wave in the circular waveguide for quad wedge with cone and discs of terminator at 2.85 GHz is shown in Fig. 15. It is observed that the field is appreciably terminated, i.e., perfect absorption of the wave before reaching the receiving port. If there are electric or magnetic losses inside of the calculation domain, the sum of the electric and magnetic power dissipated inside these materials will be recorded by the field monitoring tool. It can also be visualized how the power is lost in the wedge structure by analysing power loss density. The power loss density imposes at the

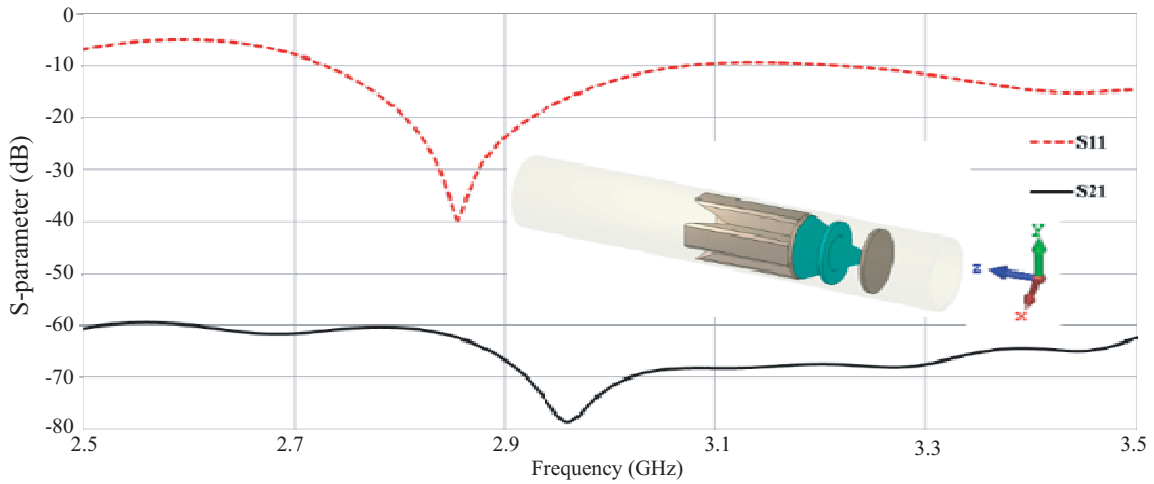


Figure 14. S-parameters versus frequency for quad wedge with cone and discs of terminator.

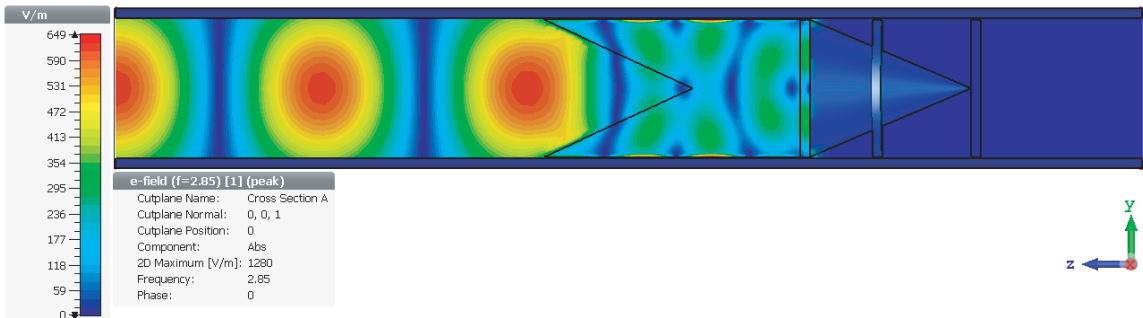


Figure 15. E-field propagation in circular waveguide for terminator with quad wedged, cone and Teflon discs.

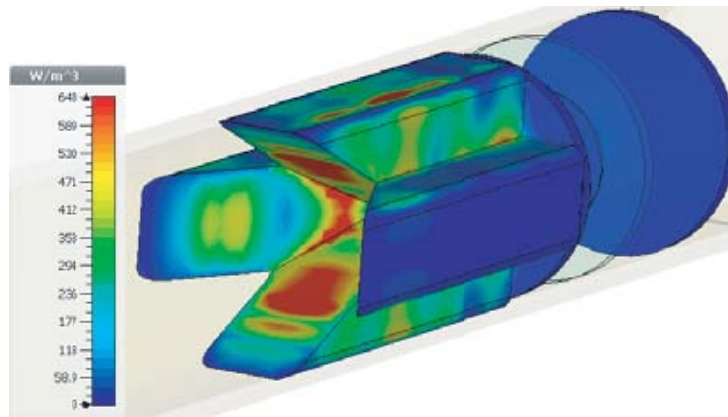


Figure 16. Power loss density in circular waveguide for terminator with quad wedged, cone and Teflon discs.

frequency of 2.85 GHz, and result is shown in Fig. 16. The power loss density value is expressed in units of watts per cubic meter (W/m^3). Table 1 compares the achieved outcome for step-by-step improvement of the proposed termination.

To validate the results, fabrication and measurement have been done. The reflection coefficient of the proposed terminator is measured using R&S®FSH8 Handheld Network Analyzer and is shown

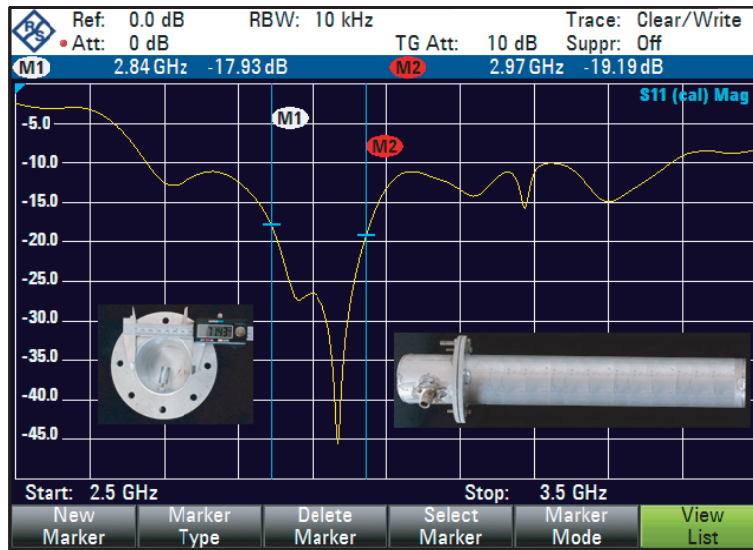


Figure 17. Measured reflection coefficient for proposed terminator.

Table 1. Comparison of the proposed structures.

Shape	f_r (GHz)	BW (MHz)	S_{11} (dB)	S_{21} (dB)	P (%)
Slab	2.95	0	-9.2	-64.1	12
Wedge	3	~ 80	-21.6	-63.6	0.7
Quad-wedge	3	0	-16.3	-48.7	2.3
Quad-wedge with cone	2.85	~ 130	-38.4	-34.9	0
Quad-wedge with cone & discs	2.85	~ 130	-37.6	-61.5	0

f_r — Resonant frequency, BW — Bandwidth for $S_{11} < -20$ dB, P — Reflected Power

in Fig. 17. The fabricated model of circular waveguide terminator and the used connector is shown in inset view. Commercially available N-type connector with a special structure of inner pin is used for the measurement of S -parameter (S_{11}). Due to unavailability of Kanthal material, an equivalent resistive material is used. The measured result achieves the bandwidth of ~ 120 MHz for $S_{11} < -20$ dB ranging from ~ 2.85 GHz to ~ 2.97 GHz. Table 2 compares the simulated and experimental results which are in decent agreement. However, the minor differences in simulated and measured results are mainly due to the fabrication inconsistencies and imperfections while drilling and welding. Thus, the proposed terminator can also be a suitable candidate for such an application where high performance and low VSWR are required.

Table 2. Comparison between simulated and measured results.

Parameters	f_r (GHz)	BW (MHz)	S_{11} (dB)	BW Range
Simulated	2.85	~ 130	-38	2.80–2.93
Measured	2.93	~ 120	-44	2.85–2.97

BW — Bandwidth for $S_{11} < -20$ dB

5. CONCLUSION

The waveguide termination based on resistive material for a WC-281 circular waveguide is successfully analysed, and results are discussed. The wedge shape geometry helps in gradually changing the impedance and thus decreasing the reflection S_{11} . To terminate the propagation, a resistive material Kanthal modeled in a conical shape is placed facing its tip to the receiving end and attenuates the field before reaching the receiving end. This makes the terminator suitable for practical use. The position and geometry of the structure being used to decide the parameters for return loss and attenuation. Through the existing literature, it is claimed that such a geometry has not been explored so far for a circular waveguide termination. Further work for enhancing the bandwidth is in process.

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