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Design, Development and Testing of Circular Waveguide Taper for Millimeter Wave Transmission Line

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ABSTRACT

This paper presents design and development of a circular waveguide taper and its transmission measurement over D-band frequency range (110-170 GHz). It is designed for testing of oversized waveguide components over millimeter wave frequency bands. Linear waveguide taper was fabricated and measurements were carried out using a low power mm wave test facility. Simulation of taper is done using Finite Element method based code COMSOL Multiphysics v5.1.Simulation results are compared with experimental results and discussed in the paper.

Key words: Circular waveguide taper, low mode conversion loss, millimeter waves, COMSOL Multiphysics (RF Module)

1. INTRODUCTION

A tapered waveguide section is often needed in microwave systems for connecting two waveguides of different apertures. The requirement of a waveguide taper is to provide good match between input and output of taper with very low spurious mode conversion and loss. In the past few decades, significant work has been done on circular waveguide tapers.

H. G. Unger described that raised cosine profile taper have very low mode conversion or low spurious modes [1]. In next year, L. Solymer proved that by making the non-uniform waveguide more and more gradual (we can say linear shaped taper), the amplitude of all spurious modes tend to zero [2]. CCH Tang designed an optimum taper of minimum length with the assumption that the taper possess perfect symmetry and its axis is perfectly straight, only TE_{0n} modes will be excited in the tapered region [3]. One could design various non linear taper profiles like Parabolic, Exponential [4, 5], Raised Cosine [5] and linear taper. Flügel and Kühn considered modified Dolph-Chebychev tapers for the analysis and design of circular waveguide tapers [6]. Development of computer codes has improved speed of calculations and avoided complexity. In the meantime, Jeff M. Neilson [7] working on development of cascaded scattering matrix code for analysis of tapers with complicated electromagnetic equations. This code solves equations of coupling coefficients for tapers. W. G. Lawson at the University of Maryland developed a similar code which require less memory, had rapid convergence for the backward modes, and could rapidly find results for the forward modes [8]. Our analysis from various literatures shows that linear taper offers better transmission than any other shape for given dimensions.

Main issue with tapers is mode conversion loss. Spurious modes are generated due to continuous change in waveguide dimensions. Waveguide tapers are built in such a way that mode conversion loss is minimum. A waveguide taper transmit the entire power incident on it with very little reflection for any profile. However in most cases, the power at output is not same as incident mode rather mode conversion occurs to the spurious modes. These spurious modes are unwanted modes in the measurement method [9].

We are using a D-band source which has fundamental rectangular output. A fundamental rectangular to circular waveguide transition is available. Using this, we can’t measure attenuation of oversized waveguide components. Therefore, a linear circular waveguide taper is designed and developed to perform the measurement of oversized components transmission attenuation. Millimeter wave testing facility is also discussed and experimental results are compared with numerical results.

2. THEORETICAL APPROACH

The linear tapers were analyzed by Solymer [2].This approach suggests that if we gradually increase the radius of the taper than impedance mismatching problem can be avoided. On basis of this concept the normalized amplitude coupling coefficient C for linear taper at the output junction is given by [2],

$$C = 0.142\frac{d_2(d_2-d_1)}{\lambda L} \qquad (1)$$

Here, d_1 and d_2 are diameter of input and output section of taper respectively. L is length of taper and λ is wavelength corresponding to frequency. This taper is to be used for W-band (70-110 GHz) application as well so, length of taper is optimized at 90 GHz frequency. As per our requirement, Input and output diameters of taper are 2.64mm and 19mm respectively. Ideally, value of coupling coefficient should be zero but for this value taper length becomes infinite which is not possible to fabricate practically. In our case, we can tolerate maximum 1% power loss in spurious modes. Using above equation, length of taper is obtained as 132.72mm for given parameters.

3. NUMERICAL SIMULATION

For the simulation, RF Module of COMSOL Multiphysics v5.1 is used. Finite element discretization is used by COMSOL for solving the governing equations. Under the assumption that material response is linear with field strength, COMSOL formulates Maxwell's equations in the frequency domain given as [10],

$$\nabla\times\left(\mu_r^{-1}\nabla\times E\right)-\frac{\omega^2}{c_0^2}\left(\epsilon_r-\frac{j\sigma}{\omega\epsilon_0}\right)E=0 \qquad (2)$$

where μ_r is the permeability, ε_r the permittivity and the electric conductivity of the material; ε_0 is the permittivity of the vacuum, ω the wave angular frequency and E the electric field. Fields are computed in the dielectric and air medium inside waveguide and waveguide wall. For our application in waveguide taper, all the properties are assumed as isotropic and unchanged over working frequency range.

At high frequencies in GHz range, 3D geometry modeling of taper in COMSOL needs to solve large number of degree of freedom which requires high computation power so, instead of simulating 3D geometry, we simulated it using 2D axial symmetry as taper is symmetrical in term of geometry. This approach reduces number of D.O.F and also time required for simulation. 2D axial symmetry is used as waveguide taper has circular symmetry around r=0 axis. It is shown in figure 1.

Port boundaries are used to excite TE_{11} at input of waveguide. At output side, TE_{11} mode was set to check power in the same mode. The waveguide boundary is made of Aluminum of conductivity 5×10^6 S/m. Aluminum is applied at wall using Impedance boundary condition. Mesh element length are maintained by λ/ 10 at 170 GHz.

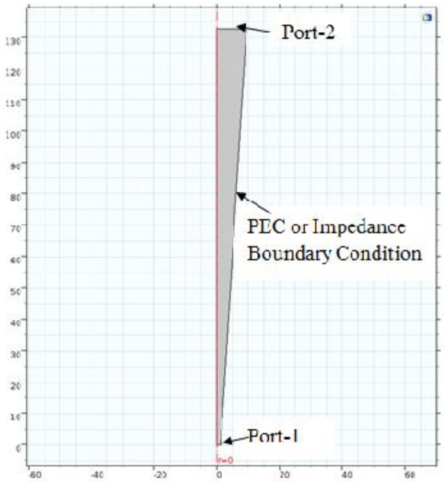

Figure 1: 2D axial symmetrical modeling of Circular waveguide taper

Figure 2 shows result for single taper in which almost 99% power is coupled to TE_{11} mode. It shows agreement with analytical calculations. Practically it is not possible to measure the loss of a single taper. So, we have measured loss for back to back tapers. To validate experimental results, we have also simulated back to back tapers. Its transmission is given in figure 3.

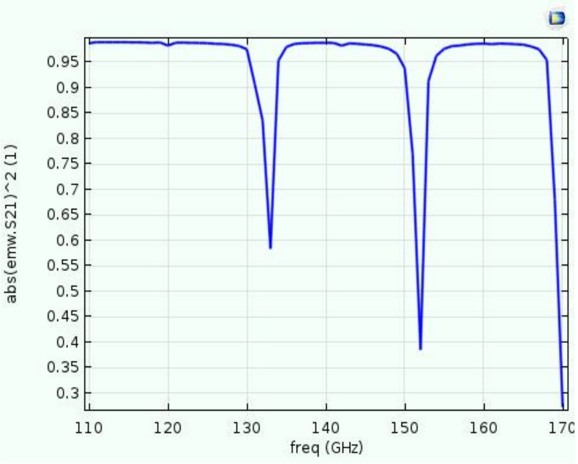

Figure 2: Transmission of Single taper

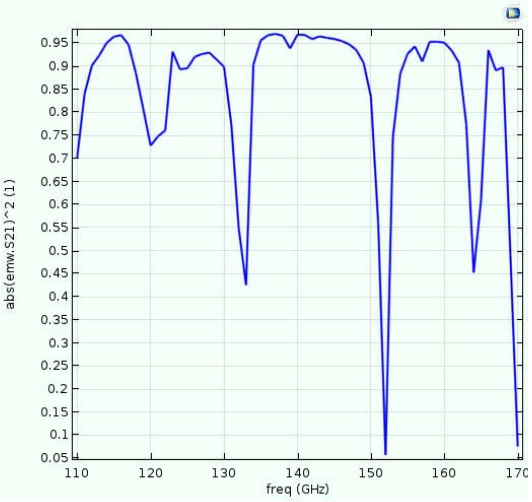

Figure 3: Transmission of back to back tapers

4. FABRICATION AND EXPERIMENTAL MEASUREMENT

Waveguide taper shown in figure.3 is fabricated using wire cut EDM technology. Wire EDM Machining (or Spark EDM) is an electro thermal production process in which a thin single-strand metal wire (usually brass) in conjunction with de-ionized water (used to conduct electricity) allows the wire to cut through metal by the use of heat from electrical sparks. Due to the inherent properties of the process, wire EDM can easily machine complex parts and precision components out of hard conductive materials [12].

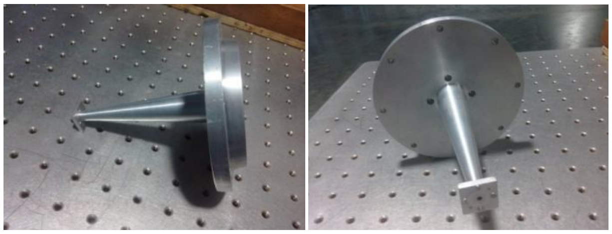

Figure 4: Fabricated component

Transmission was measured using S-Parameter analysis. It is a well-established technique for measuring the transmission and reflection of the passive microwave components. S-Parameter analysis considers effect of the entire system under test in measuring the transmission loss of a particular device under test. It involves three steps:

1. Perform measurements without including device under test (DUT)
2. Perform measurements including device under test
3. Compare both results by taking ratio to compute S-metrics of DUTs.

The schematic diagram of the test is shown in figure.4. D-Band frequency source is used for the measurements. At, output side D-band detector is used to detect power level.

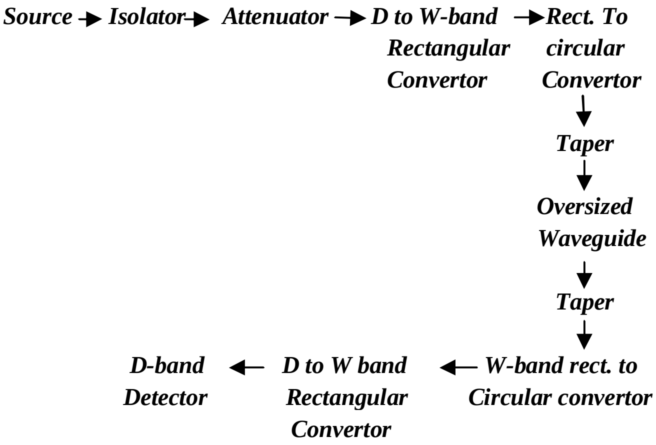

Figure 5: The schematic diagram of experiment set up for taper measurement

We cannot measure loss of single taper directly because at output side, detector input has fundamental dimension of D-band. Figure.5 shows experimental set up with back to back arrangement of taper.

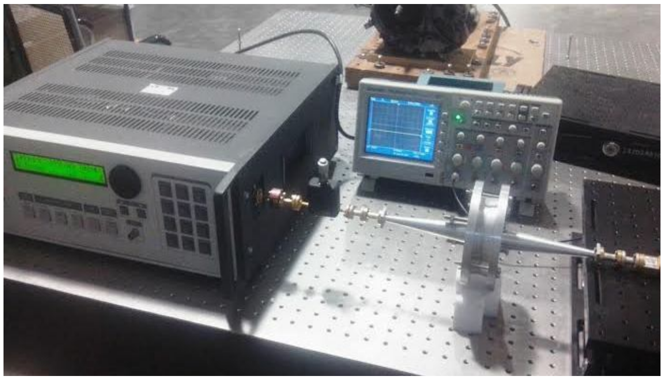

Figure 6: Low power mm wave test facility for Back-to-Back taper measurement

Plot in figure 7 gives comparison of experimental results and Simulation results. A small decrease in the transmission coefficient and shifting of a narrow deep at 149 GHz might be due to the inner surface quality of the taper. The plot shows that narrow deeps are generated at certain frequencies. This indicates occurrence of resonance. At resonant frequencies, propagating modes are trapped inside tapered region. Large amount of power is converted from desired mode to spurious mode [2].

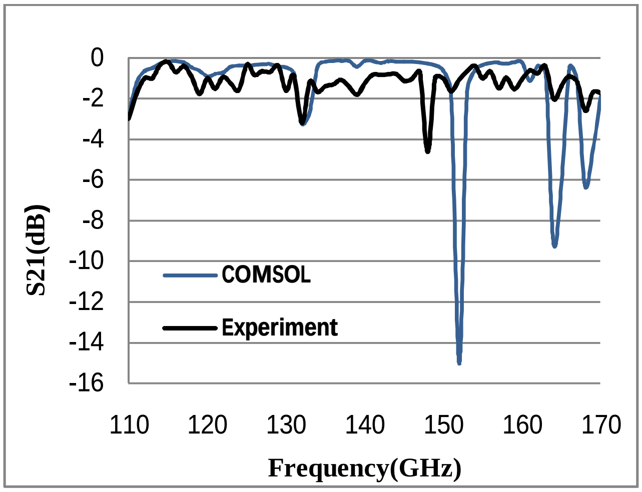

Figure 7: Comparison of simulation and experimental results

5. CONCLUSION

This paper presents analytical design, simulation and measurements of the Linear Circular waveguide taper for millimeter wave transmission line. Linear waveguide taper with input radius 1.32mm, output radius 9.5mm and length 132.71mm was designed and mm wave transmission was measured. Narrow deeps generated in transmission plot indicate that modes are trapped inside geometry. So, large amount of power is converted into the spurious modes at resonance frequencies. Numerical results were compared with experimental results. Both results match reasonably.

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