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CASCADING OF TWO RECTANGULAR WAVEGUIDES BY USING HFSS, CASCADE AND MATLAB SOFTWARE

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ABSTRACT- This project studies the analysis of cascading of two rectangular waveguide of different cross-Section It also shows how to combine all the scattering matrices of a microwave circuit to obtain its overall scattering parameters of the circuit .Simulation of cascading of two rectangular waveguide with different dimensions by using HFSS and computer program in MATLAB is developed to calculate the S parameter of cascaded two rectangular waveguide. Finally above these two results are compared with the results obtained from the CASCADE. CASCADE is a highly efficient and accurate tool for designing 2-port waveguide components, RF windows, and waveguide systems. The program is very user-friendly and executes very rapidly on standard personal computers.

Keywords- Junction Discontinuities, Scattering Matrix, Reflection coefficient, Transmission Coefficient.

1. INTRODUCTION

A closed waveguide is an electromagnetic waveguide that is tubular, usually with a circular or rectangular cross section, has electrically conducting walls that may be hollow or filled with a dielectric material, can support a large number of discrete propagating modes, though only a few may be practical in which each discrete mode defines the propagation constant for that mode, in which the field at any point is describable in terms of the supported modes In this there is no radiation field, and discontinuities and bends cause mode conversion but not radiation.

The dimensions of a hollow metallic waveguide determine which wavelengths it can support, and in which modes. Typically the waveguide is operated so that only a single mode is present. The lowest order mode possible is generally selected. Frequencies below the guide's cutoff frequency will not propagate. It is possible to operate waveguides at higher order modes, or with multiple modes present, but this is usually impractical. Waveguides are almost exclusively made of metal and mostly rigid structures.

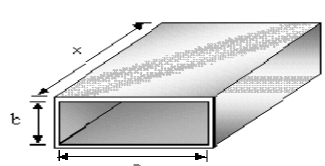


Figure 1. Geometry of a Waveguide

2. WAVEGUIDE IN PRACTICE AND MODAL EXPANSION IN WAVEGUIDES

In practice, waveguides act as the equivalent of cables for super high frequency (SHF) systems. For such applications, it is desired to operate waveguides with only one mode propagating through the waveguide. With rectangular waveguides, it is possible to design the waveguide such that the frequency band over which only one mode propagates is as high as 2:1 (i.e. the ratio of the upper band edge to lower band edge is two). The relationship between the longest wavelengths that will propagate through a rectangular waveguide is a simple one. Given that W is the greater of its two dimensions, and lambda is the wavelength, then lambda = 2W. Because rectangular waveguide have a much larger bandwidth over which only a single mode can propagate, standards exist for rectangular waveguides, but not for circular waveguides. In general (but not always), standard waveguides are designed such that one band starts where another band ends, with another band that overlaps the two bands the lower edge of the band is approximately 30% higher than the waveguide's cutoff frequency the upper edge of the band is approximately 5% lower than the cutoff frequency of the next higher order mode the waveguide height is half the waveguide width.

3. WAVEGUIDE DISCONTINUITES

The abrupt changes in a waveguide will give rise to a discontinuity that will create standing waves. The basic concept of the mode matching algorithm will lead to an accurate method for analyzing the propagation characteristics of wave guide discontinuities. Discontinuities in dielectric waveguides play an important role in designing components in millimeter, sub millimeter and optical circuitry. Quit often in these applications an open waveguide with one particular cross-section must be joined to a waveguide of another cross-section. The open waveguides to be connected differ sometimes not only in size but also in their cross-sectional form. Usually these waveguide connectors are required to launch as much as possible of the power that is incident in one waveguide into the other waveguide.

In such waveguide transitions power may be lost to reflection and radiation. The transition should be designed to keep radiation reflection loss at a minimum. Transitions between different dielectric waveguides in form of gradual waveguide tapers are particularly well suited for open waveguides because of their microscopic dimensions. An

H-plane discontinuity presents an incident electric field parallel to the unchanged transverse direction. It is found that abrupt changes in a waveguide will give rise to a discontinuity that will create standing waves.

Typical step discontinuities are shown in figure below

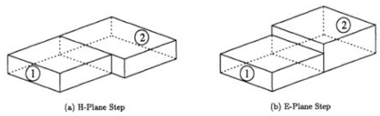


Figure 2. Typical step discontinuities

4. SCATTERING MATRIX OF THE PLANER DISCONTINUITIES

A planar junction, including higher order mode interactions, may be completely represented by an N-port device. Many N-port devices may be connected together, and the scattering characteristics of the overall devices are deduced using fundamental microwave network theory. The cascading method allows the analysis of more complicated devices, by first computing the scattering matrix of the planer discontinuities, computing S-matrix for section of uniform waveguide and cascading the S-matrices.

The S-matrix, S_u for a length L of uniform waveguide is

$$\mathbf{S}_u = \begin{bmatrix} \mathbf{0} & \mathbf{diag}\left\{e^{-jk^i_{zn}l}\right\} \\ \mathbf{diag}\left\{e^{-jk^i_{zn}l}\right\} & \mathbf{0} \end{bmatrix}$$

Where, diag $\left\{e^{-jk^i_{zn}l}\right\}$ is a square $(n \times n)$ diagonal matrix and k^i_{zn} is the propagation constant of n_{th} mode in the waveguide in region i and 0 is the $(n \times n)$ matrix of zeros.

5. SYMMETRICAL RECTANGULAR-TO-RECTANGULAR WAVEGUIDE STEP

A symmetrical rectangular-to-rectangular waveguide step discontinuity is formed, when two rectangular waveguides with different cross-sections are joined as show in figure 3. The discontinuity formed is said to be symmetric because both waveguides are cantered at the origin (at x = 0 and y = 0).

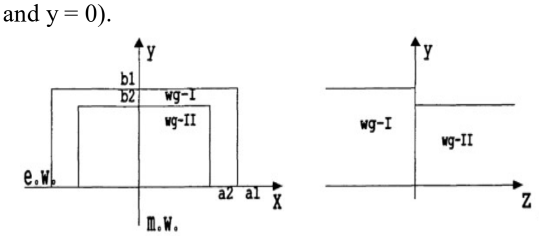
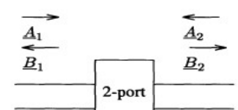


Figure 3. Two wave guides are in symmetrical positioned about the origin

A magnetic wall can be placed when it is known that the magnetic field lines are perpendicular to the magnetic wall surface and, therefore, only the transverse electrical field lines are present there. Similarly, an electric wall can be placed when it is known that the electric field Lines are perpendicular to the electric wall surface and, therefore, only the magnetic field lines are present there. By using these two symmetric planes, only one quarter of the discontinuity is considered during the analysis and the first quadrant, x > 0 and y > 0, will be considered in this the total electric and magnetic fields inside each waveguide section can be expressed by the superposition of the TE (or H) and TM (or E) wave component S.

6. TWO PORT NETWORK PARAMETER

A general two-port network is shown in figure 4. The ports are connected to transmission line and the wave amplitudes at either port may be considered to be a superposition of incident and reflected wave amplitudes. Since at microwave frequencies it is not possible to measure current and voltage directly, so to represent a two-port in terms of the power reflected and transmitted is necessary. It is possible to completely describe the behavior of a junction with four coefficients. These coefficients are collected into a matrix known as scattering matrix S.



A general 2-port junction, with incident and reflected wave amplitudes shown.

Figure 4. A general 2 port junction

6.1. Scattering Matrix representation off junctions

Let A_i is the complex amplitude of the incident wave at the i_{th} port and B_i be the complex amplitude of the reflected wave at the i_{th} port. The scattering matrix coefficients are ratio of the complex wave amplitudes.

$$S_{11} = \left.\frac{B_1}{A_1}\right|_{A_2=0} \qquad S_{12} = \left.\frac{B_1}{A_2}\right|_{A_1=0}$$

$$S_{21} = \left.\frac{B_2}{A_1}\right|_{A_2=0} \qquad S_{22} = \left.\frac{B_2}{A_2}\right|_{A_1=0}$$

$$S_{ij} = \left.\frac{B_i}{A_j}\right|_{A_{n\neq j}=0}$$

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}}_{\mathbf{S}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

The coefficients S_{ij} are in general complex, and range in magnitude from 0 to1. Each may be interpreted as the ratio of the reflected wave at port I to incident wave at port j in the absence of any other incident waves.

6.2. The cascading by Scattering Matrices

The two linear system, which shall be cascaded, are given by

$$\begin{pmatrix} A^- \\ B^+ \end{pmatrix} = \begin{pmatrix} S^a_{11} & S^a_{12} \\ S^a_{21} & S^a_{22} \end{pmatrix} \begin{pmatrix} A^+ \\ B^- \end{pmatrix} \text{ and } \begin{pmatrix} B^- \\ C^+ \end{pmatrix} = \begin{pmatrix} S^b_{11} & S^b_{12} \\ S^b_{21} & S^b_{22} \end{pmatrix} \begin{pmatrix} B^+ \\ C^- \end{pmatrix},$$

Or equivalently

$$\begin{cases} \boldsymbol{A}^- = \mathrm{S}^{\mathrm{a}}_{11}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{a}}_{12}\boldsymbol{B}^-, \\ \boldsymbol{B}^+ = \mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{a}}_{22}\boldsymbol{B}^-. \end{cases} \qquad \begin{cases} \boldsymbol{B}^- = \mathrm{S}^{\mathrm{b}}_{11}\boldsymbol{B}^+ + \mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-, \\ \boldsymbol{C}^+ = \mathrm{S}^{\mathrm{b}}_{21}\boldsymbol{B}^+ + \mathrm{S}^{\mathrm{b}}_{22}\boldsymbol{C}^-. \end{cases}$$

The lower-left expression is inserted in the upper-right expression, and the upper-right expression is inserted in the lower-left. This gives

$$\begin{cases} \boldsymbol{B}^- = \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22}\boldsymbol{B}^- + \mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-, \\ \boldsymbol{B}^+ = \mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11}\boldsymbol{B}^+ + \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-, \end{cases}$$
$$\begin{cases} (I - \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22})\boldsymbol{B}^- = \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-, \\ (I - \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11})\boldsymbol{B}^+ = \mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-. \end{cases}$$

After solving this gives

$$\boldsymbol{A}^- = (\mathrm{S}^{\mathrm{a}}_{11} + \mathrm{S}^{\mathrm{a}}_{12}(I - \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22})^{-1}\mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{21})\boldsymbol{A}^+ + \mathrm{S}^{\mathrm{a}}_{12}(I - \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22})^{-1}\mathrm{S}^{\mathrm{b}}_{12}\boldsymbol{C}^-,$$
$$\boldsymbol{C}^+ = \mathrm{S}^{\mathrm{b}}_{21}(I - \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11})^{-1}\mathrm{S}^{\mathrm{a}}_{21}\boldsymbol{A}^+ + (\mathrm{S}^{\mathrm{b}}_{22} + \mathrm{S}^{\mathrm{b}}_{21}(I - \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11})^{-1}\mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{12})\boldsymbol{C}^-.$$

The linear system can now be written with a scattering matrix as

$$\begin{pmatrix} \boldsymbol{A}^- \\ \boldsymbol{C}^+ \end{pmatrix} = \begin{pmatrix} \mathrm{S}^{\mathrm{c}}_{11} & \mathrm{S}^{\mathrm{c}}_{12} \\ \mathrm{S}^{\mathrm{c}}_{21} & \mathrm{S}^{\mathrm{c}}_{22} \end{pmatrix} \begin{pmatrix} \boldsymbol{A}^+ \\ \boldsymbol{C}^- \end{pmatrix},$$

Where, the elements of the scattering matrix are

$$\begin{aligned} \mathrm{S}^{\mathrm{c}}_{11} &= \mathrm{S}^{\mathrm{a}}_{11} + \mathrm{S}^{\mathrm{a}}_{12}(I - \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22})^{-1}\mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{21}, \\ \mathrm{S}^{\mathrm{c}}_{12} &= \mathrm{S}^{\mathrm{a}}_{12}(I - \mathrm{S}^{\mathrm{b}}_{11}\mathrm{S}^{\mathrm{a}}_{22})^{-1}\mathrm{S}^{\mathrm{b}}_{12}, \\ \mathrm{S}^{\mathrm{c}}_{21} &= \mathrm{S}^{\mathrm{b}}_{21}(I - \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11})^{-1}\mathrm{S}^{\mathrm{a}}_{21}, \\ \mathrm{S}^{\mathrm{c}}_{22} &= \mathrm{S}^{\mathrm{b}}_{22} + \mathrm{S}^{\mathrm{b}}_{21}(I - \mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{11})^{-1}\mathrm{S}^{\mathrm{a}}_{22}\mathrm{S}^{\mathrm{b}}_{12}. \end{aligned}$$

7. CASCADE– AN ADVANCED COMPUTATIONAL TOOL FOR WAVEGUIDE COMPONENTS AND WINDOW DESIGN

CASCADE is an advanced design program for 2-port waveguide components, RF windows, and waveguide systems. It provides rapid and user-friendly analysis of waveguide components such as filters, nonlinear tapers, mode converters, microwave cavities, and RF windows. It calculates scattering parameters (transmission/reflection coefficients) for general waveguide structures composed of cylindrical, rectangular, or coaxial waveguides. Transitions between waveguide types are also allowed. The program includes dielectric properties of ceramic and finite conductivity of metal surfaces. A built-in optimizer dramatically reduces design time, and the program can import scattering matrices from other program, such as HFSS or measured data, for total system scattering matrix analysis.

CASCADE is a highly efficient and accurate tool for designing individual components or large systems consisting of a series of components. The program is very user-friendly and executes very rapidly on standard personal computers. Because of its rapid execution, it becomes possible to implement automated optimization routines that can iterate geometrical parameters to achieve performance goals specified by the user. Thus, the computer can design the component or system with little interaction by the user, once the optimization process is initiated. This results in a dramatic reduction in engineering time with achievement of performance goals not practical with manual execution. The statistical tolerance feature in CASCADE allows the engineer to determine the impact of dimensional tolerances on device performance.

CASCADE is designed to model 2-port devices consisting of combinations of rectangular, cylindrical, or coaxial structures. The program can model dielectric materials and include the effects of finite conductivity. It can include the impact of 3D structures by importing calculated or measured scattering parameters. This allows performance optimization of complex waveguide systems.

8. PROGRAM OPERATION

CASCADE includes a user-friendly, intuitive interface for geometrical input and specification of execution parameters. Each geometrical section is described by completing a GUI screen determined by the type of section. Figure 5 shows the input screen for a rectangular waveguide section. The GUI allows input of the relevant geometry, the internal medium (vacuum, ceramic, etc.) and the wall conductivity. The waveguide system geometry is sequentially generated using a series of input screens for various waveguide types. Several types of analysis are supported. These include:

- Scattering Matrix – used for determining transmission or reflection characteristics,
- Resonant Frequency Calculation – determines frequency and Q of non-reentrant cavities,
- Determinant Sweep – searches structure for potential trapped of parasitic modes.

GUI screens are provided for determining the type of analysis, accuracy of the calculation, and frequency range of interest. Execution of a single simulation typically takes only a few seconds.

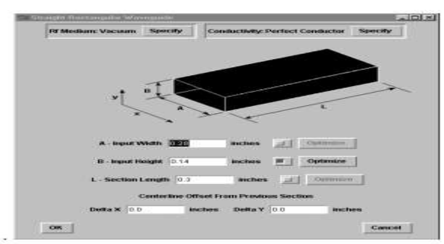


Figure 5. CASCADE software

9. SIMULATION CODE AND RESULTS

9.1 Design Parameters

a_1 = 59 mm, b_1 = 29 mm, L = 30 mm for first rectangular wave guide (WG11A). TE_{10} cut-off frequency = 2.577 GHz

a_2 = 86 mm, b_2 = 43 mm, L = 30 mm for second rectangular wave guide (WG9A). TE_{10} cut off frequency = 1.736 GHz

9.2 Calculation of S parameter of two cascaded rectangular waveguide by using HFSS

Metric Taper Calculations:- If know d, k, and D, one may be calculated. D equals to small diameter plus amount of taper.

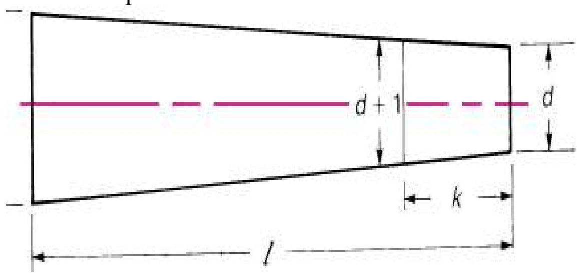


Figure 6.1. Metric Taper

D = d + total taper
D = d + l/k
D = d + total taper
d = small diameter
k = unit length of taper
l = total length of taper
D = large diameter

9.3 Simulation in HFSS

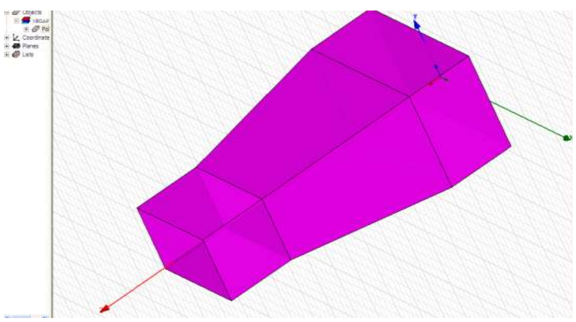


Figure 6.2. Simulation of two cascaded waveguides

9.4 Results in HFSS

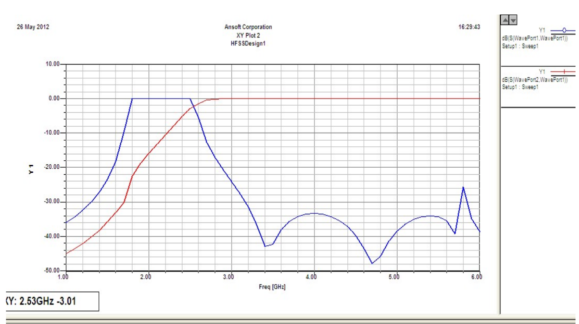


Figure 7. HFSS simulation result

10. CALCULATION OF S PARAMETER OF TWO CASCADED RECTANGULAR WAVEGUIDE BY USING CASCADE SOFTWARE

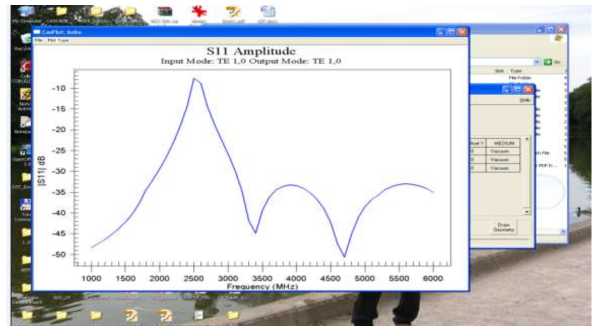


Figure 8.1. S11 plot by CASCADE Software

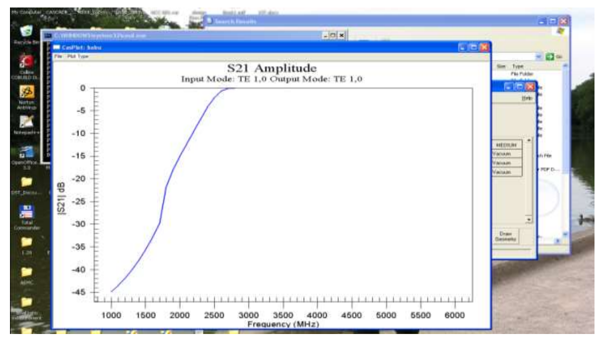


Figure 8.2. S21 plot

11. CONCLUSION

The overall S matrix of two cascaded rectangular waveguide with different dimensions is calculated by using three methods, HFSS, CASCADE and MATLAB. An Excellent agreement among results obtained by using these three software. The sum of reflection and transmission coefficient of a rectangular waveguide discontinuity is approximately one and it works as High pass filter at cut off frequency 2.57GHz.

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