Case Study

Design and Simulation of Rectangular Waveguides using Ansys HFSS

Mrinmoy Bharadwaj (ACE Electronics)

Edited by Madhumita Saravana Kumar, Ansys Academic Development Team

education@ansys.com

Summary

In this case study, the basic steps involved in designing and simulating one of the simplest forms of waveguide, the rectangular waveguide, are explored using Ansys HFSS. Emphasis is given on how to visualize the fields of different propagating modes inside the waveguide. Additionally, two interesting variations of waveguide parameters and the impact these variations have on the modes of the rectangular waveguide have also been illustrated.

The Ansys Electronics Desktop (AEDT) is a platform that enables true electronics system design. AEDT provides access to the Ansys industry-standard electromagnetics simulation solutions such as Ansys HFSS, Ansys Maxwell, Ansys Q3D Extractor, Ansys SIwave, and Ansys Icepak using electrical CAD (ECAD) and mechanical CAD (MCAD) workflows. In addition, it also includes direct links to the complete Ansys portfolio of thermal, fluid, and mechanical solvers for comprehensive Multiphysics analysis. Tight integration among these solutions provides the user with unprecedented ease of use for setup and faster resolution of complex simulations for design and optimization.

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1. Introduction

A waveguide is a device that is used to transfer electromagnetic energy from one point to another. There are several different types of waveguides. The parallel plate waveguide (PPW) is the most basic and the simplest type of waveguide. It has a very simple geometry formed by two parallel flat conducting metal plates, of width "W", having a hollow space in the middle, of height "d", as illustrated in figure (Figure 1) below. PPW can support Transverse Magnetic (TM) and Transverse Electric (TE) modes and can also support a Transverse Electro-Magnetic (TEM) mode due to its geometry. The understanding of the analysis of a parallel plate waveguide can be useful for modeling many other waveguides and also for modeling the propagation of higher order modes in a strip line.

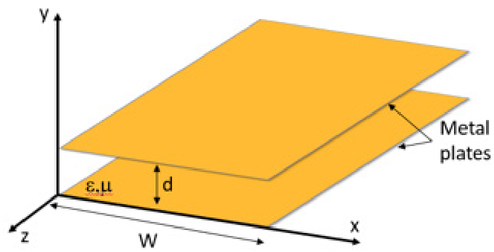

Figure 1: Basic Geometry of a PPW

Conventionally, 'W' is assumed to be much greater than the separation 'd' so that the effect of fringing fields and any variations along x-direction can be ignored in the analysis. ε and μ are assumed to be the relative permittivity and relative permeability of the medium filling the region between the two metal plates[1].

If the region between the plates of a parallel plate waveguide is terminated by two vertical metallic planes (one on either lateral side) we get the next basic form of a waveguide called the rectangular waveguide (RW)[2]. In other words, a rectangular waveguide is a hollow metallic tube with a rectangular cross-section formed by width "a" and height "b", filled with a dielectric medium with permittivity ε and permeability μ. The name of the waveguide is derived from the shape of the cross-section as shown in Figure 2 below:

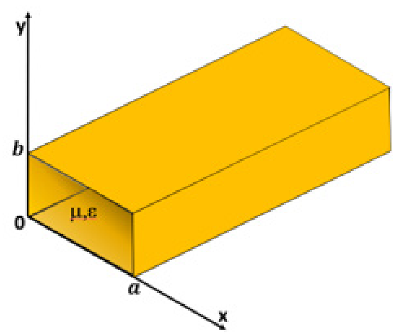

Figure 2: Basic Geometry of a Rectangular Waveguide

1 M. Bharadwaj, Ansys Education Resource – "Case Study: Design and Simulation of a Parallel Plate Waveguide using Ansys HFSS", Case Study: Design and Simulation of a Parallel Plate Waveguide using Ansys HFSS

2 Pozar, David M. (2012), "Microwave engineering," John Wiley & Sons, 2011. NJ :Wiley, Ch. 3, pg. 110

Conventionally, the longer dimension of a RW is aligned with the x-axis *i.e.* a > b. The closed geometry of the RW confines the fields within the waveguide allowing no interference from external fields. Therefore, RW can be designed to be having large bandwidths and low loss. Since the RW is a single conductor transmission line structure, it does not support a pure TEM mode of propagation. Only TE_{mn} and TM_{mn} modes are supported in a RW, where the subscripts 'm' and 'n' are positive integers and represent the indices to specific modes in the waveguide. Both TE_{mn} and TM_{mn} modes have cut-off frequencies determined by the dimensions of the waveguide. Wave propagation in the waveguide is not possible below these cut-off frequencies. This behavior of the waveguide resembles the function of a high-pass filter.

The values of 'm' and 'n' signify different modes electromagnetic waves. Modes only above the cut-off frequency can propagate in the waveguide. Note that for a TE mode, either m or n may be equal to zero, but not both. For a TM mode, neither m nor m may be equal to zero. The characteristic impedances, cutoff frequencies, and phase velocities of the various modes on a rectangular waveguide are given by the equations found in Table 1.

Table 1: Equations for Cut-off Wavenumber, Phase Velocity, Cut-off Frequency, and Characteristic Impedance

	TE_{mn}	TM_{mn}
Cut-off Wavenumber	$k_{c,mn} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$	$k_{c,mn} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$
Phase Velocity	$\upsilon_{ph,mn} = \frac{\omega}{\sqrt{k^2 - k_{c,mn}^2}}$	$\upsilon_{ph,mn} = \frac{\omega}{\sqrt{k^2 - k_{c,mn}^2}}$
Cut-off Frequency	$f_{c,mn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$	$f_{c,mn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$
Characteristic Impedance	$Z_{0,mn} = {}^{k\eta}/_{\beta_{mn}}$	$Z_{0,mn} = {}^{\beta_{mn}\eta}/_{k}$

Where:

$$\beta_{mn} = \frac{\omega}{\upsilon_{ph,mn}} \qquad k = \omega\sqrt{\mu_0\mu_r\epsilon_0\epsilon_r} \qquad \eta = \sqrt{\frac{\mu_0\mu_r}{\epsilon_0\epsilon_r}} \qquad c = \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

In the above equations, β_{mn} is the phase constant corresponding to the TE_{mn}/TM_{mn} mode in the waveguide which is traveling with a phase velocity of $\upsilon_{ph,mn}$ inside the waveguide along the direction of propagation. ω is the angular frequency (ω=2πf, f being the frequency), η is the characteristic impedance of the dielectric inside the waveguide which has a relative permittivity of ε_r and a relative permeability of μ_r, and μ_0, ε_0 are the permeability and permittivity of free space.

The above parameters of the RW are obtained by solving the Helmholtz wave equation subjected to the boundary conditions of a rectangular metallic cavity. Rectangular waveguides are one of the most widely used form of waveguides due to its simple geometry and ease of fabrication. Several commercially available waveguides have a rectangular cavity. In the next and the subsequent sections, the design and simulation of an 8 GHz Rectangular waveguide shall be presented. The first four propagating modes of an 8 GHz rectangular waveguide, plot of the cutoff frequencies in terms of real and imaginary parts of the propagation constant gamma shall be illustrated.

2. Design of an 8 GHz Rectangular Waveguide

For the purpose of this simulation, High Frequency Structure Simulator (HFSS) inside the Ansys Electronic Desktop framework shall be used. For building up the simulation model of a basic rectangular waveguide in HFSS, a 4 inch long hollow rectangular aluminum with a = 1 inch and b = 0.2 inch has been used as seen in the Figure 2 below:

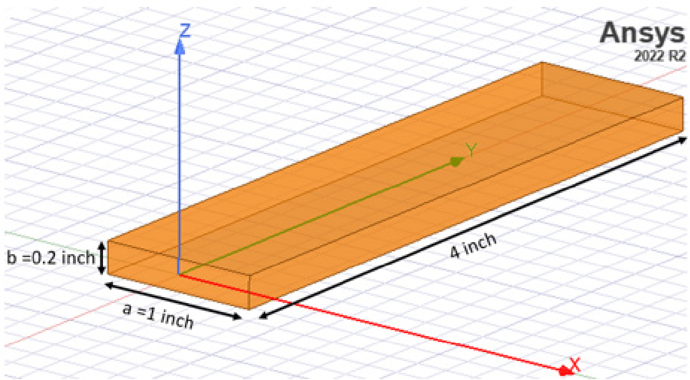

Figure 2: Simulation Model of a RW

The region inside the hollow aluminum structure has been assumed to be vacuum in the model. However, any dielectric material or combination of materials can be assumed. For feeding electromagnetic energy into the model, wave ports on both edge apertures of the structure have been used as shown in the figure below:

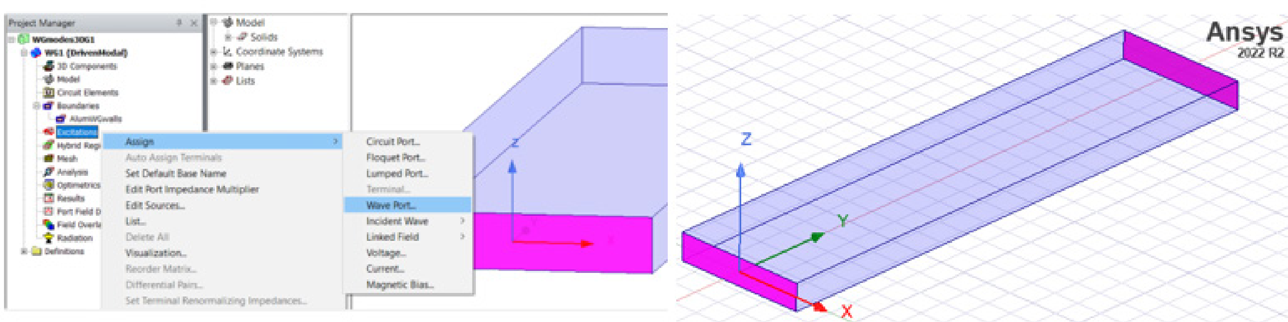

Figure 3: Feed to the RW structure

The number of modes and mode polarities can be chosen to excite the RW structure. In this study, a solution frequency of 20 GHz single mode shall be used for simulations. With a step size of 0.1 GHz, an interpolating-type frequency sweep from 1 GHz to 30 GHz shall be applied.

3. HFSS Solution process

The HFSS solver utilizes Finite Element Method (FEM) for solving geometries. FEM is a volumetric meshing based numerical solution technique. This method creates an initial mesh of the entire solution domain and then refines this initial mesh iteratively to improve the mesh quality. Once the metric for the mesh quality is met, the solver starts solving the frequency points, defined by the user, at each mesh node. In Figure 4, a view of the meshing applied onto the RW is shown for better understanding.

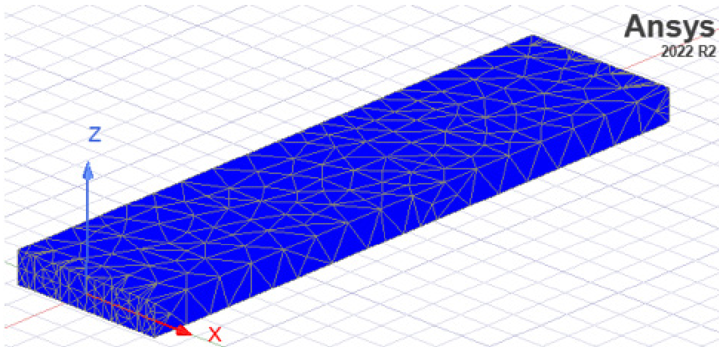

Figure 4: FEM applied to RW

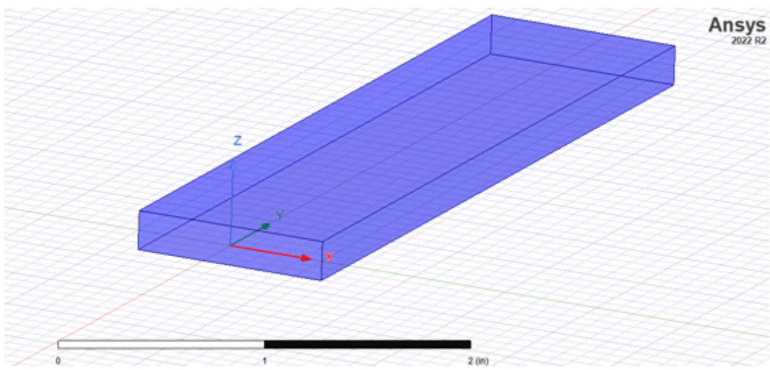

Figure 5: Simulation Model

The entire simulation process consists of the following steps:

- **Geometry and Material:** In this first step the initial physical geometry and the materials to be used are defined. Figure 5 shows the initial geometry used in this case study.
- **Preprocessing:** This step involves defining the feed, the boundary conditions required for the simulations.
- **Solution:** In this step, a solution set-up and an associated frequency sweep is defined. The solution set-up involves specifying the meshing frequency and mesh quality metric.
- **Post-processing:** Once the model is solved, required outputs like s-parameters, electric and magnetic fields, surface currents *etc.* can be evaluated and visualized.
- **Validation:** The last and most important step is to validate the results and outputs and check if they are in line with what is expected.

It important to note that the simulation process shown above might be an iterative process which may require several cycles of repetition before an optimal design can be found. At the end of each iteration, the engineer or designer can see if the changes in geometry and other aspects resulted in an improvement in the overall design or not. Based on this knowledge, further changes can be made to move the results in the required direction.

4. Simulation of a basic RW with Ansys HFSS

In this section the field-plots for 4 modes in the rectangular waveguide and imaginary part of the propagation constant (γ, Gamma) shall be presented. From the basic analytical model of a RW, we know that RW can only support TE and TM modes due to its geometry. The simulation of a RW with a=1 inch, b=0.2 inch had been carried out at 20GHz.

The field plots for 4 of the propagating modes in the RW has been shown below:

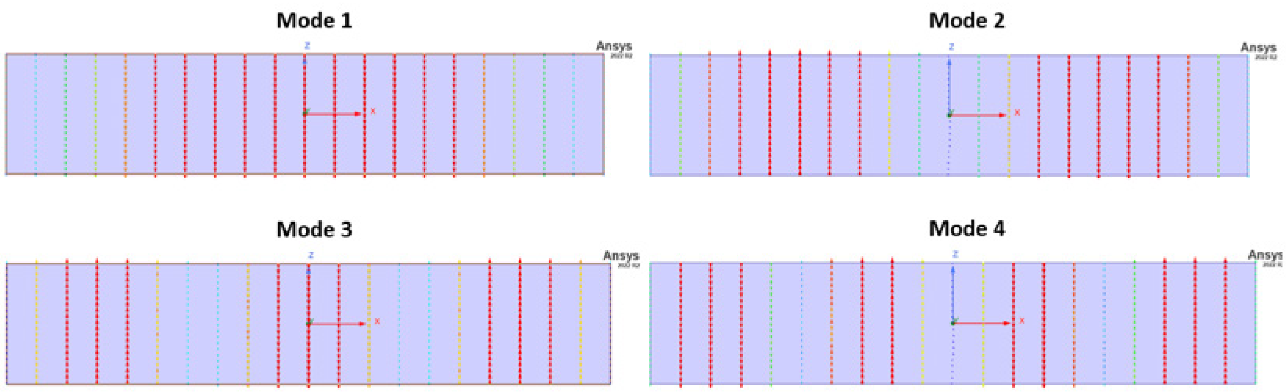

Figure 6: 4 propagating modes in the rectangular waveguide

As the imaginary part of the propagation constant (γ, Gamma) represents phase, the plot below shows the frequency at which Im{γ} comes up from zero which indicates the frequency where the mode begins to propagate.

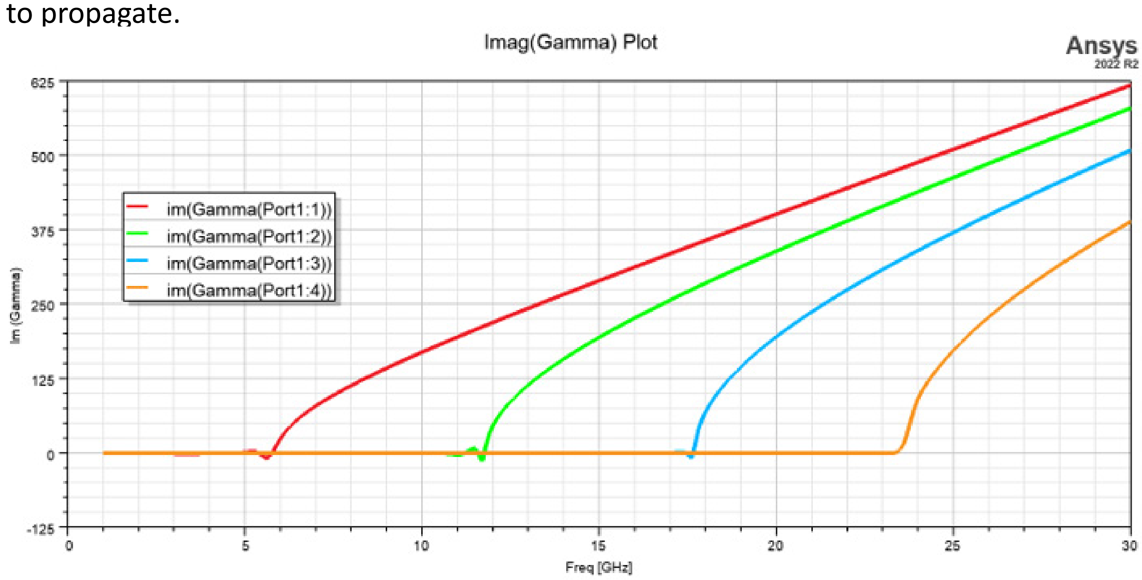

Figure 7: Plot of the imaginary part of propagation constant in RW

To learn more about using Ansys HFSS for simulations, please visit the Ansys Innovation Courses website.

5. RW with equal dimensions

In this section, simulation with a=b=1 inch in the RW has been carried out and the results are presented. The hollow region is still filled with vacuum. The geometry of the PPW is shown in Figure 8 below:

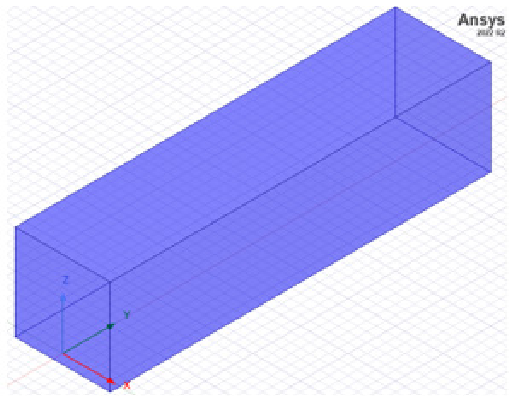

Figure 8: Geometry of equal-dimensional RW

The mode plots for the 4 modes are given below:

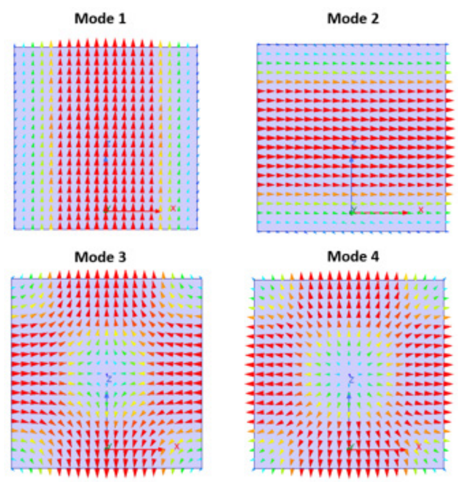

Figure 9: Mode plots for the equal-dimensional RW

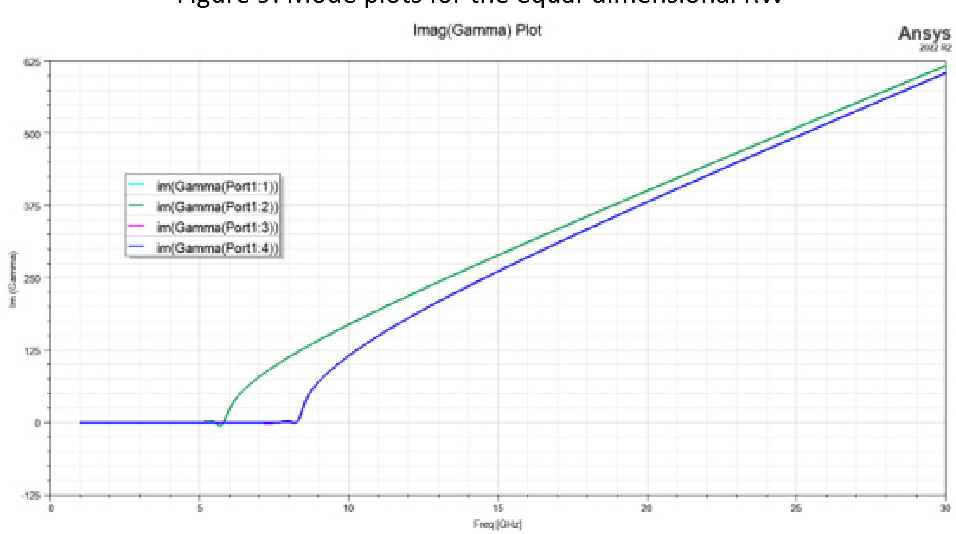

Figure 10: Plot of the imaginary part of propagation constant for equal-dimensional PPW

As expected, it is evident in the mode plots, due to the two dimensions becoming equal, the modes 1,2 and 3,4 become degenerate, *i.e.* it is hard to differentiate between the two modes leading to a lower mode purity or a higher mode conversion loss. This is also evident in the plot of the imaginary part of the propagation constant Im{γ} wherein the phase starts from zero at the same frequency points for the degenerate modes. Since practical applications demand high mode purity, such waveguides are not used in practice.

6. Partially filled RW

The basic geometry of a RW has the same dielectric material filling the entire hollow space inside the waveguide. However, it is worthwhile investigating the impact of partial filling of a RW with different dielectric materials. The geometry of a partially filled RW is shown in Figure 11 below:

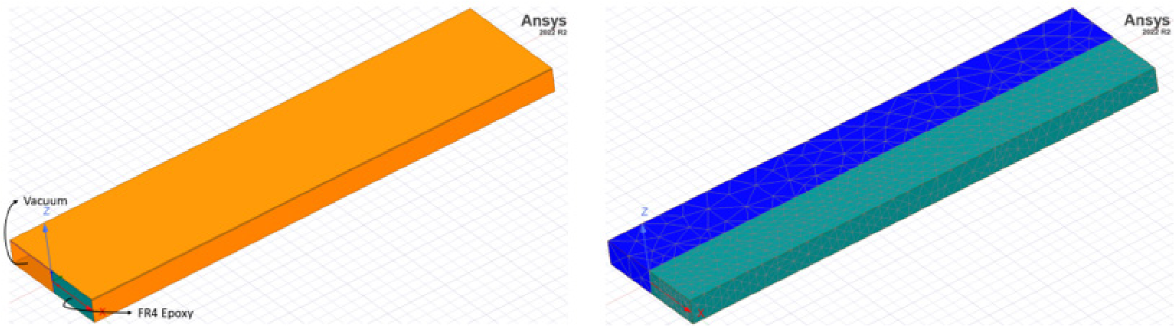

Figure 11: Geometry and Mesh details of partially filled RW

For the purpose of this simulation the filling is 50% with FR4 Epoxy (ε_r=4.4, μ_r=1, tanδ=0.02) and the rest empty space is vacuum. The choice of the fill percentage and the dielectric material is purely arbitrary here. From the basic definition of dielectric constant, electric fields are more confined in the material with the higher dielectric constant. In this case, this effect is evident in the mode plots shown in Figure 12 below:

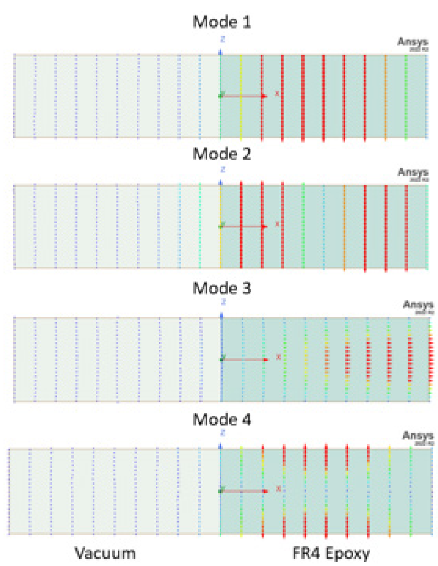

Figure 12: Mode plots in a partially filled RW

The plot of the imaginary part of the propagation constant, Im{γ}, for the partially filled RW is provided in Figure 13 below. One interesting thing to note in the plot is that the higher order modes have very close/overlapping values of Im{γ} which can mean a lower mode purity for these kind of geometries.

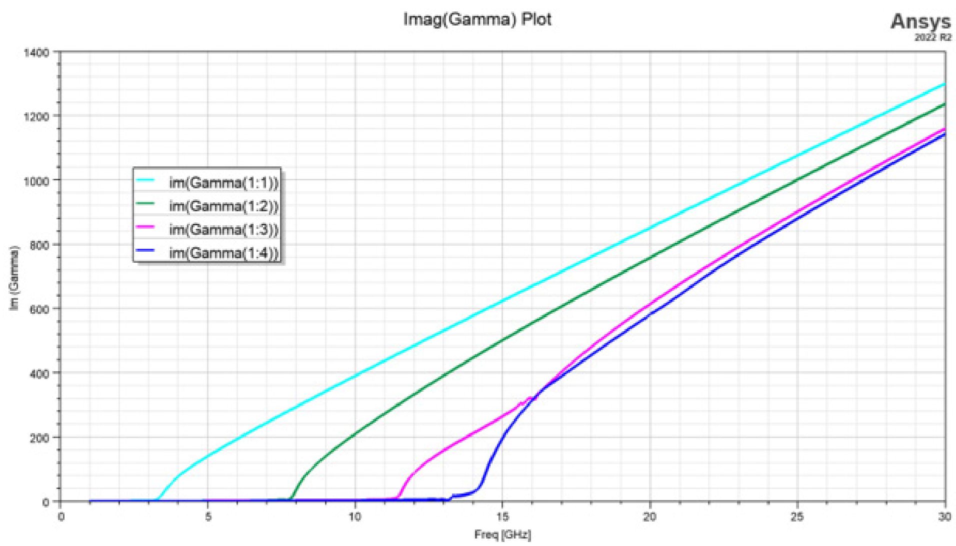

Figure 13: Plot of the imaginary part of propagation constant for partially filled PPW

7. Further possibilities of investigations

The simulation-driven design and analysis process is an iterative one, often involving iterative modifications to the existing design to arrive at a more optimized design. In the case of the RW, one can alter several variables in the design such as:

- Width and height of the metallic cavity to see its impact on cut-off frequencies and mode field distributions
- Dielectric material and its properties, and the variations in the filling geometries to understand the impact caused on the fields as a result of the variations.
- Number of modes excited into the structure to see which mode is sustained and which is attenuated.
- Variations in the geometrical shape of the metallic cavity to identify the impact on the field distributions inside the structure. This will lead to newer shapes of waveguides that are found commercially.

8. What does Ansys HFSS bring to the understanding?

In this case study, Ansys HFSS helps the educator illustrate the design and simulation process of one of the basic forms of a waveguide, which is also seen widely commercially available, namely the rectangular waveguide. The FEM based solver allows for a highly-accurate solution of the electric and magnetic fields inside the RW geometry and carry out several other simulations which would be rather impossible to describe with analytical models. Ansys HFSS solution process helps to explain how the numerical solution of the Maxwell's equations are carried out using FEM. The tool illustrates that the design process is iterative and can take up to several cycles to reach the required optimal design. From a more practical perspective, the tools help to highlight and emphasize the fundamental benefits of a simulation-driven design process by illustrating how simulation helps speed up the design process and decrease cost as it lowers the need for expensive experiments and prototypes.

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ANSYS, Inc.
Southepointe
2600 Ansys Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com