Case Study

Design and Simulation of Circular Waveguides using Ansys HFSS

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Summary

This case study discusses one of the most basic forms of waveguides, the circular waveguide. The name of this kind of waveguide is derived from the shape of the cross-section of the waveguide. In the different sections of the case study, a basic introduction to the circular waveguide and its modeling has been presented. To aid understanding, basics steps involved towards design and simulation of a circular waveguide and visualizations of the fields of the propagating modes inside the waveguide have been presented. Additionally, the influence of change of the radius of the circular waveguide and the dielectric material inside the waveguide have been illustrated with the help of simulations. These kinds of investigations are quite involved, if not impossible, to model with analytical methods and hence, intensify the need for simulations even for simple structures like the circular waveguides.

The Ansys Electronics Desktop (AEDT) is a platform that enables true electronics system design. AEDT provides access to the Ansys gold-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 circular waveguide (CW) is one of the basic forms of waveguides along with the parallel plate waveguide (PPW) and the rectangular waveguide (RW). The name of this waveguide is derived from the circular shape of the cross-section of the cavity which runs uniformly along the axis of the waveguide. It is formed by a hollow cylindrical metallic conductor, of radius “a” as shown in Fig. 1 below. The hollow cavity inside the waveguide may be empty or filled with a dielectric material. Since the CW is made up of a single conductor like the RW, it can support Transverse Magnetic (TM) and Transverse Electric (TE) modes and but cannot support a Transverse Electro-Magnetic (TEM) mode. The understanding of the analysis of the CW forms the basis for modeling a circular transmission line such as the coaxial conductor transmission lines which find widespread use in lot of applications.

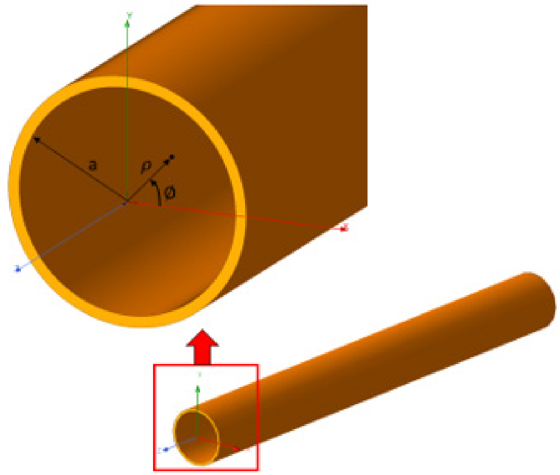

Fig 1: Basic Geometry of a PPW

Due to its geometry, the polar coordinates are naturally conducive for use in analysis of circular waveguides. The different modes of the electromagnetic fields inside the circular waveguide are obtained as general solution to Maxwell’s equations for the specific cases of TE and TM wave propagation in a cylindrical waveguide. The circular waveguide is assumed to be uniform in shape and dimension along the z-axis. For time harmonic electromagnetic fields with an $e^{j\omega t}$ dependence and propagating along the z-axis inside the circular waveguide, the electric and magnetic field can be expressed as:

$$E_\rho = -\frac{j}{k_c^2}\left(\beta\frac{dE_z}{d\rho} + \frac{\omega\mu}{\rho}\frac{dH_z}{d\Phi}\right) \tag{1}$$

$$E_\Phi = -\frac{j}{k_c^2}\left(\frac{\beta}{\rho}\frac{dE_z}{d\Phi} - \omega\mu\frac{dH_z}{d\rho}\right) \tag{2}$$

$$H_\rho = \frac{j}{k_c^2}\left(\frac{\omega\mu}{\rho}\frac{dE_z}{d\Phi} - \beta\frac{dH_z}{d\rho}\right) \tag{3}$$

$$H_\Phi = -\frac{j}{k_c^2}\left(\omega\epsilon\frac{dE_z}{d\rho} + \frac{\beta}{\rho}\frac{dH_z}{d\Phi}\right) \tag{4}$$

where, $k_c^2 = k^2 - \beta$ and $e^{-j\beta z}$ propagation has been assumed. Since the conductor of the circular waveguide is assumed to be perfectly conducting and the dielectric inside the waveguide is assumed to be lossless with a dielectric constant of ϵ and a permeability μ, the propagation constant can be assumed to be $j\beta$. For a lossy propagation, $j\beta$ should be replaced with $\gamma = \alpha + j\beta$, where α is the attenuation constant. A detailed explanation on the method of derivation of the above expressions from the Maxwell's equations can be found in [1].

By applying field assumptions of TE and TM modes to the equations (1)-(4), one can derive the following expressions shown in Table 1 below, as presented in [1]:

Table 1: Summary of TE and TM mode expressions in a Circular Waveguide

Quantity	***TE_{mn} Mode***	***TM_{mn} Mode***
Wavenumber, k	$\omega\sqrt{\mu\epsilon}$	$\omega\sqrt{\mu\epsilon}$
Cut-off frequency, $f_{c.mn}$	$\frac{p'_{mn}}{2\pi a\sqrt{\mu\epsilon}}$	$\frac{p_{mn}}{2\pi a\sqrt{\mu\epsilon}}$
Phase constant, β	$\frac{2\pi}{k_c}$	$\frac{2\pi}{k_c}$
Cut-off wavelength, λ_c	$\sqrt{k^2 - k_c^2}$	$\sqrt{k^2 - k_c^2}$
Guide wavelength, λ_g	$\frac{2\pi}{\beta}$	$\frac{2\pi}{\beta}$
Phase velocity, v_p	$\frac{\omega}{\beta}$	$\frac{\omega}{\beta}$
Attenuation constant due to dielectric loss, α_d	$\frac{k^2 \tan\delta}{2\beta}$	$\frac{k^2 \tan\delta}{2\beta}$
E_z	0	$(A\sin n\Phi + B\cos n\Phi)J_n(k_c\rho)e^{-j\beta z}$
H_z	$(A\sin n\Phi + B\cos n\Phi)J_n(k_c\rho)e^{-j\beta z}$	0
Wave impedance, Z	$Z_{TE} = \frac{k\eta}{\beta}$	$Z_{TM} = \frac{\beta\eta}{k}$

Where m and n are the indices for the various modes in the waveguide and meanings of the other terms can be found in [1]. Also, using the expressions for E_z and H_z in equations (1)-(4) above, the expressions for the other filed components can be derived.

In the next section, simulation of a circular waveguide shall be discussed wherein the cut-off frequencies of propagating modes shall be determined from simulations.

2. Simulation of a Circular Waveguide

For the purpose of this simulation, High Frequency Structure Simulator (HFSS) inside the Ansys Electronic Desktop framework is used. As an illustrative simulation of a circular waveguide, the geometry described in Example 3.2 of [1] is used for simulation. The geometry is a Teflon (ϵ=2.1, tanδ=0.0004) filled circular waveguide with radius, a=0.5 cm and length, L=5 cm, as shown in Fig. 2 below:

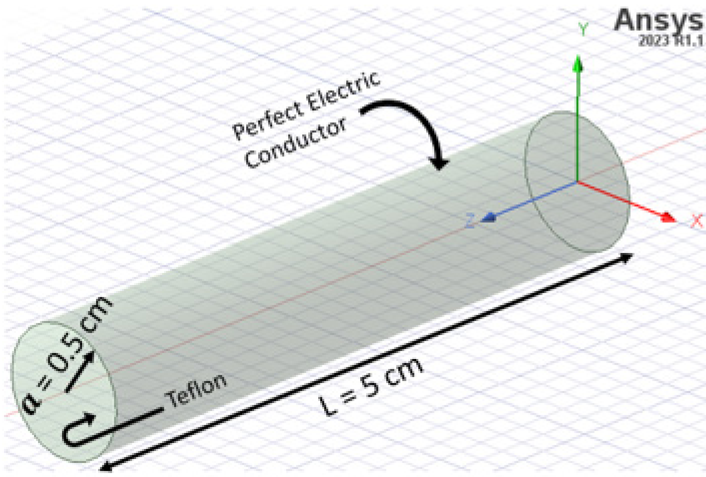

Fig 2: Simulation Model of a Circular waveguide

For feeding electromagnetic energy into the model, wave ports on both circular faces of the waveguide are defined as shown in Fig. 3. The example in [1] requires calculation of cut-off frequencies for the first 2 propagating modes in the above waveguide. Hence, for the present simulation, 5 propagating modes were used. The user may choose to define their own integration line wherein the mode polarity would then be aligned with the integration line as per the selected setting.

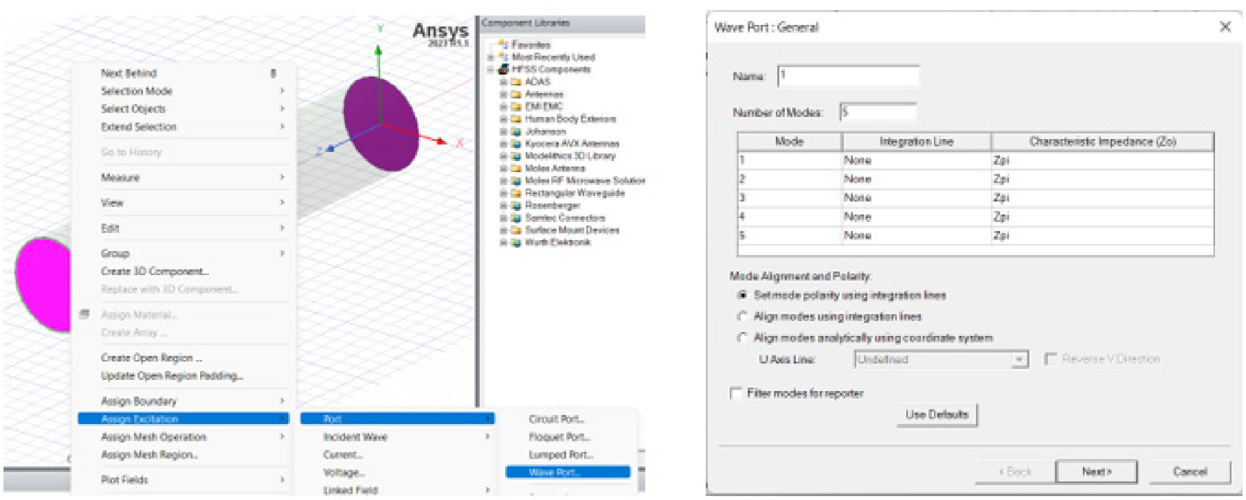

Fig. 3: Feed to the RW structure

Since the frequency of operation of the circular waveguide in [1] is specified to be 14 GHz, a solution frequency of 14 GHz is used for simulations as shown in Fig. 4 below:

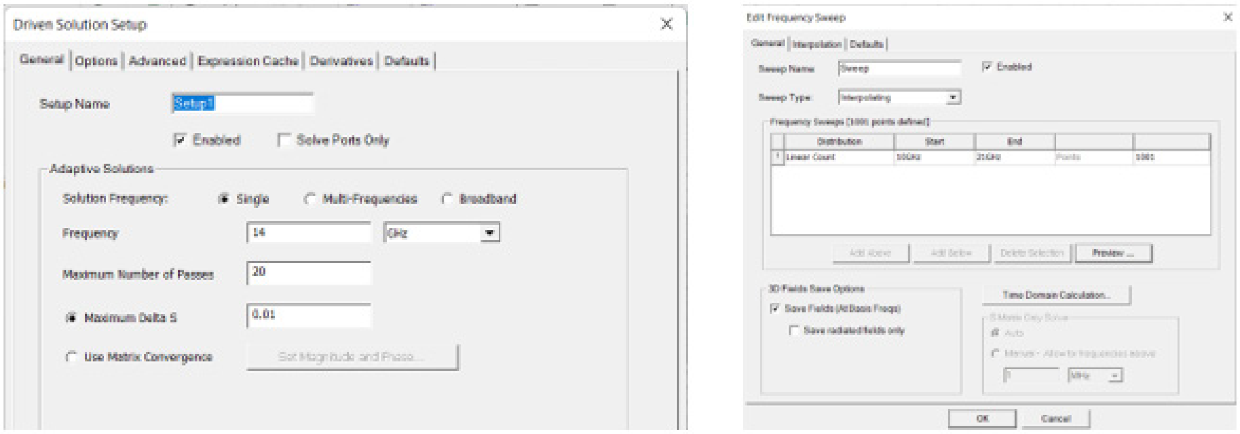

Fig. 4: Analysis set-up and Frequency Sweep

With 1001 sample points, an interpolating-type frequency sweep from 10 GHz to 25 GHz is used in the simulation of the circular waveguide.

3. HFSS Solution process

The HFSS solver utilizes Finite Element Method (FEM) for solving any geometry. 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. This technique of iteratively refining the initial mesh to the geometry, until the refinement criterion is met, is known as Adaptive meshing in HFSS which is shown in Fig. 5 below:

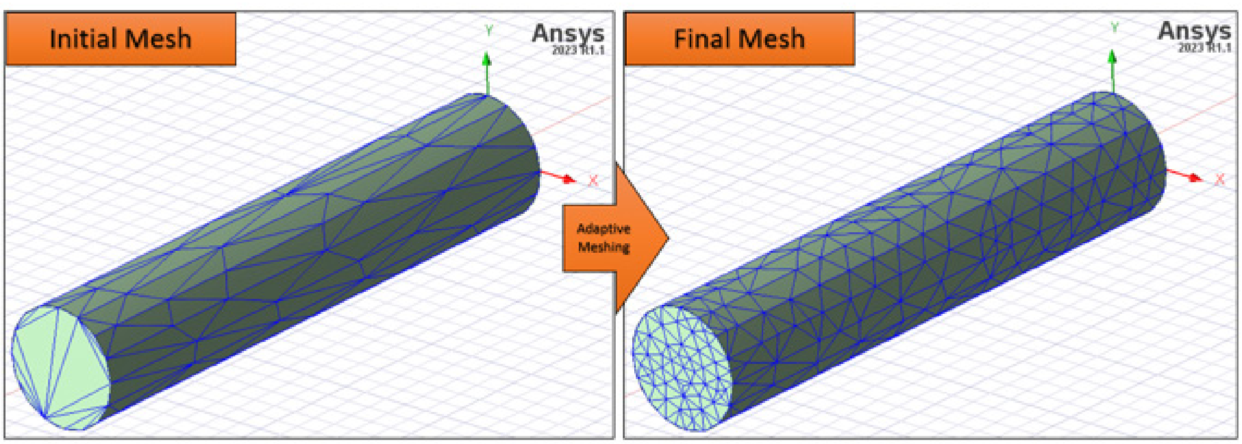

Fig 5: Adaptive Meshing applied to the circular waveguide geometry.

Once the metric for the mesh quality is met, the final mesh is done, the solver starts solving the frequency points, defined by the user, at each mesh node. In the adaptive meshing algorithm, the cylindrical body of the waveguide is approximated closely by a multi-sided polygon as seen in the above Fig. 5. The number of sides required to approximate the cylindrical surface closely can be set by the user as well. The more the number of sides, closer is the approximation. However, increasing the number of sides after a certain number does not lead to any significant gain in the accuracy and rather results in higher simulation time. Therefore, a trade-off between accuracy and simulation time always needs to be established. This is more significant in complex geometries. The adaptive meshing algorithm can analyze that trade-off based on the "Maximum value of Delta S" seen in Fig. 4.

The 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. Fig. 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.
- **Postprocessing:** 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 is 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. Results of Simulation of a basic Circular Waveguide with Ansys HFSS

In this section the field-plots for 5 modes in the circular waveguide and imaginary parts of their corresponding propagation constant (γ, Gamma) shall be presented. From the basic analytical model of a CW, we know that CW can only support TE and TM modes due to its geometry. The field plots for the 5 propagating modes in the CW has been shown below:

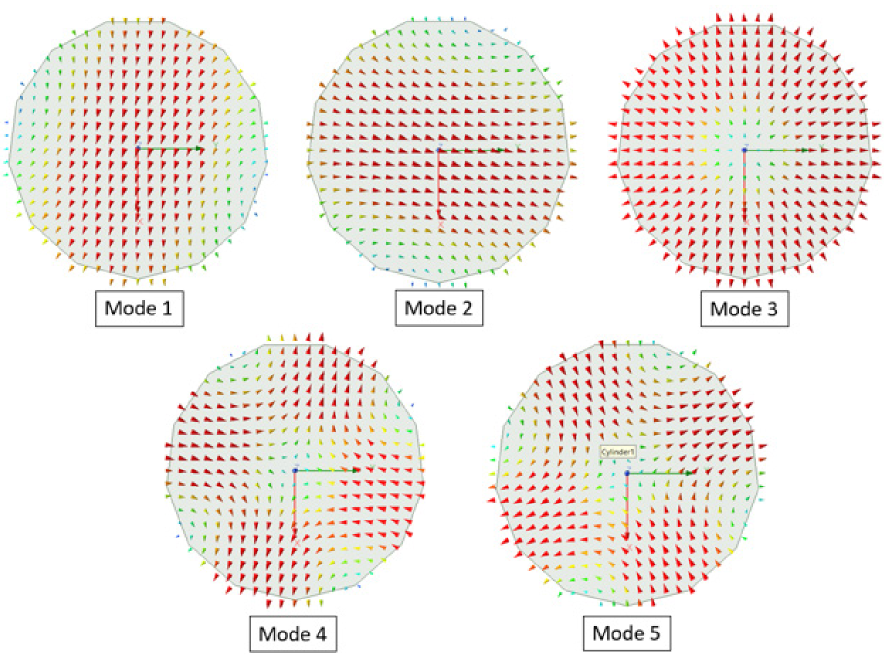

Fig 6: 5 propagating modes in the circular waveguide

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.

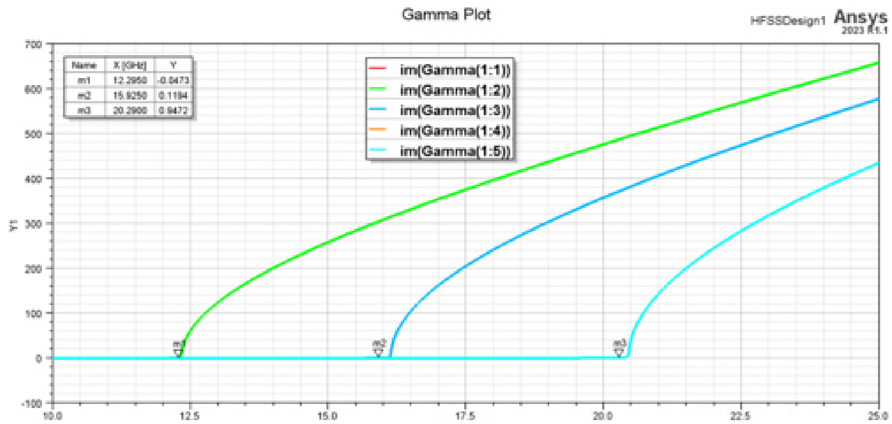

Fig. 7: Plot of the imaginary part of propagation constant in CW for various modes

To identify the mode of propagation of the electromagnetic wave in the waveguide, the electric and magnetic field vectors can be plotted in the interior as well as the face of the circular waveguide. In Fig. 8, this process has been done to identify the TE11 mode in the CW.

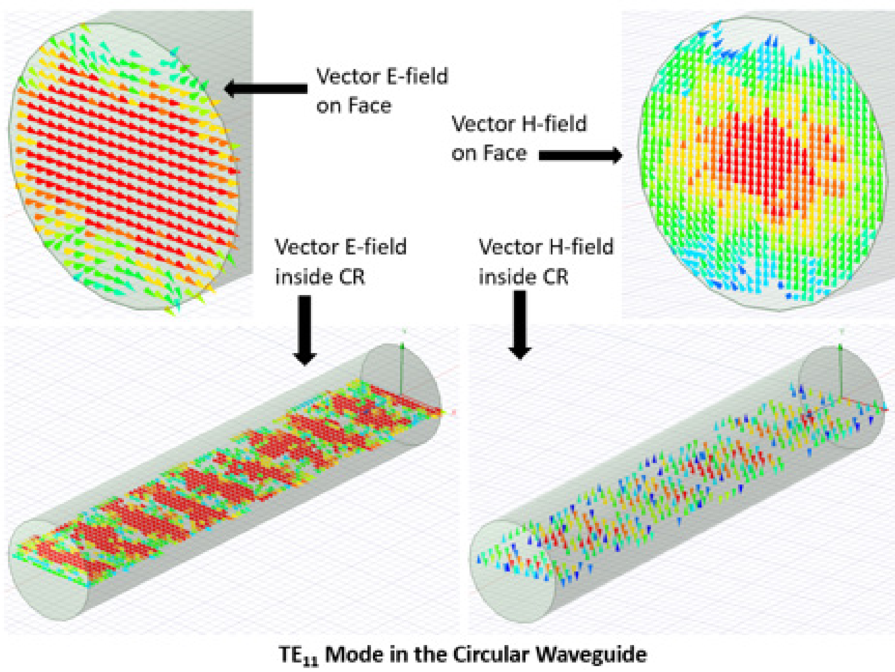

Fig. 8: Electric and Magnetic field vector plots to identify TE11 mode in the CW

This process can be repeated for the other modes in the HFSS project to identify the higher order modes in the waveguide. A representation of a few of the propagating modes with their cut-off frequencies for a circular waveguide relative to the dominant TE11 mode is shown in Fig.9 below.

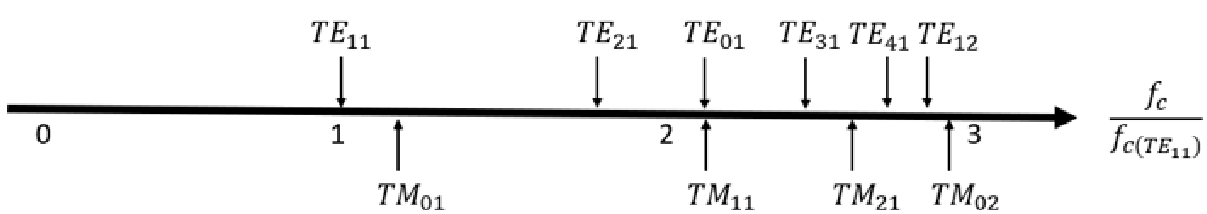

Fig. 9: Cut-off frequencies of the first few TE and TM modes of a circular waveguide relative to the cutoff frequency of the dominant TE11 mode

A detailed plot of the E and H vector field plots of the different propagating modes can be found in [2]. To learn more about using Ansys HFSS for simulations, please visit the Ansys Innovation Courses website.

5. Change of Radius and dielectric material of Circular waveguides

For a circular waveguide, the radius of the waveguide is a critical dimension. Any change in the radius leads to a change in the cut-off frequency as evident in Table 1 above for both TE and TM modes in the waveguide of the waveguide. Along with the radius, the dielectric material inside the waveguide can also influence the propagation characteristics of the electromagnetic fields inside the waveguide. Although to some extent the influence of the changes in the radius and the dielectric material can be modeled analytically, yet for more complex variations and perturbations to the geometry and the dielectric configurations in the waveguide, the complete understanding of the impact of such changes is difficult to be tracked analytical. This difficulty can be solved with the help of simulations. In simulations, all possible variations and changes can be visualized and implemented, and the impact of the changes can be readily seen in the characteristics of the waveguide.
In this section, simulation of the above circular waveguide for varying radius and relative permittivity of the dielectric inside the circular waveguide have been simulated as seen in Fig. 10 below:

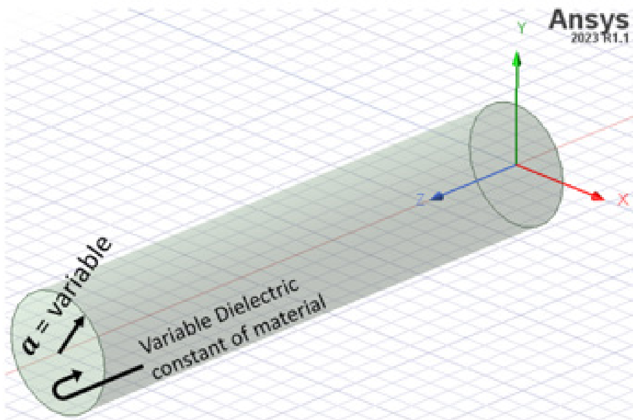

Fig. 10: Representation of the variable quantities assumed for investigations via simulations.

The influence of these changes on the cut-off frequency of the waveguide have also been illustrated with plots as seen in Fig. 11 and 12 below.

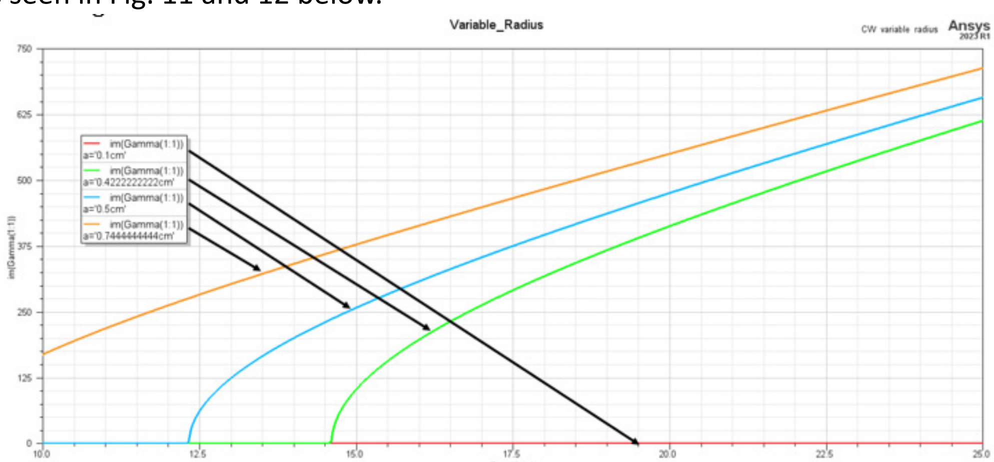

Fig 11: Plot of the imaginary part of propagation constant in CW with varying radius

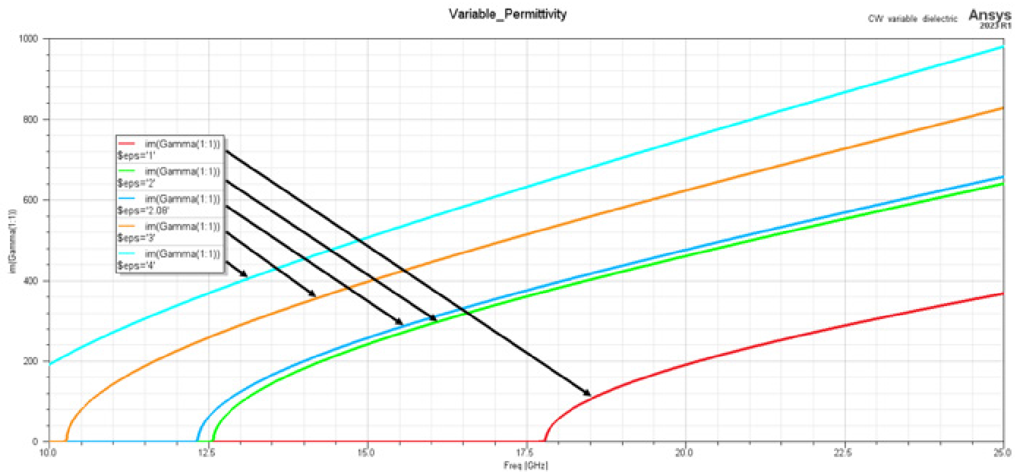

Fig. 12: Plot of the imaginary part of propagation constant for various dielectric constants

As seen in Fig. 11, the cut-off frequency increases as the radius decreases and decreases when the radius increases. Similarly, in Fig. 12 we observe that, at the same radius, a higher dielectric constant material would increase the cut-off frequency of the circular waveguide.

6. 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 circular waveguide. The FEM based solver allows for a gold standard accurate solution of the electric and magnetic fields inside the CW geometry and carries 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 on 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.

7. References

[1] Pozar, David M. (2012), "Microwave engineering," John Wiley & Sons, 2011. NJ :Wiley, Ch. 3, pg. 122

[2] Ansys Innovation Courses: Circular Waveguide Simulation Circular Waveguide Simulation | Ansys Innovation Courses

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