Alqalam Journal of Medical and Applied Sciences. 2025;8(3):1279-1285
https://doi.org/10.54361/ajmas.258304

Original article

Design a Ku-band Rectangular Waveguide for Microwaves using HFSS

Mabroka Bobreeg*[1], Fathia Adwep[2]

[1]*Department of Electrical and Electronic Engineering, Omar Al-Mukhtar University, Libya.*
[2]*Department of Electrical and Computer Engineering, Garaboulli Faculty of Engineering, Elmergib University, Libya.*
Corresponding email. mabroka.boobreg@omu.edu.ly

Abstract
Using HFSS software, rectangular waveguides, the first transmission line type utilized for small systems like radars and equipment shelters, have been examined. This study computes the characteristics and field distribution for various modes of air-filled and Teflon–filled rectangular waveguides in free space, focusing on electric and magnetic field strengths. The simulation analysis is conducted for the Ku-band with an operating frequency of 15 GHz. Theoretical analyses of two waveguides were performed and compared with the simulation results to verify accuracy. Additionally, the cutoff frequencies were determined and compared with theoretical values. The mean difference between the two waveguides was also realized, and its importance in fabricating real-world components was highlighted, making the manufacturing process easier.
Keywords. Ku-band, TE modes, HFSS, Rectangular Waveguide, and Patterns in the Field.

Introduction

The purpose of rectangular waveguides is to effectively move electromagnetic energy from one location to another. Radars, attenuators, isolators, and slotted lines are just a few of the various applications for them. A conducting shape is frequently used to encapsulate an open-ended rectangular waveguide [1,2]. The transmission medium is generally air. The waveguide walls must be conductive for proper operation. These waveguides can support multiple electromagnetic wave modes, encompassing Transverse Magnetic (TM) and Transverse Electric (TE), but cannot support the Transverse Electromagnetic (TEM) mode because there is no second conductor to define a unique voltage. Furthermore, below a certain frequency, referred to as the cutoff frequency, rectangular waveguides are unable to propagate. A rectangular waveguide's dominant mode, the TE10 mode, has the lowest cutoff frequency [3-5].

In the simulation analysis, the Ku-band—the part of the radio spectrum that falls between 12 and 18 GHz—is examined. Ku-band is mainly utilized for satellite communication and specialized purposes. NASA's Tracking and Data Relay Satellites (TDRS), which are utilized for communication with the International Space Station (ISS), and SpaceX's Starlink satellites are two examples.

HFSS 13.0 simulation software is utilized to evaluate the parameters of the rectangular waveguide, using the Finite Element Method to simulate intricate 3D structure and investigate the electrical performance of components at high frequencies and speeds Electrical performance is accurately described, according to HFSS, which also successfully assesses a variety of factors, including the S parameters, radiation patterns, input impedance, and propagation constants. As a powerful post-processor, HFSS offers exceptional insights into electrical performance, ensuring more accurate and valuable results before designing components.

This study investigates the properties of the rectangular waveguide through simulation performed with HFSS. Using this software, the analysis includes several other near-field patterns, the radiation pattern, and the cutoff frequency [8-11].

Mathematical modelling

In a rectangular coordinate system, a hollow rectangular waveguide is taken into consideration. Its length runs down the x-axis and its width along the y-axis, as shown in Figure 1, with interior dimensions of a×b (where a > b). a = 2 cm and b = 1 cm in this scenario. Within the waveguide, the dielectric media are Teflon and air, respectively.

Both the magnetic and electric fields are contained within a rectangular waveguide. Since electromagnetic waves travel in a z-direction, energy transmission through the waveguide requires the presence of the magnetic field's z-component or Hz. An endless number of modes, or field patterns, can be supported by the waveguide. To enable energy transmission in the mode of TEmn, which is defined using Ez=0, the magnetic field's Hz component needs to be non-zero. On the other hand, the TMmn mode, which is identified by Hz=0H, implies that energy transmission in the waveguide requires the presence of the electric field's z-component, $Ez \neq 0$.

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

https://doi.org/10.54361/ajmas.258304

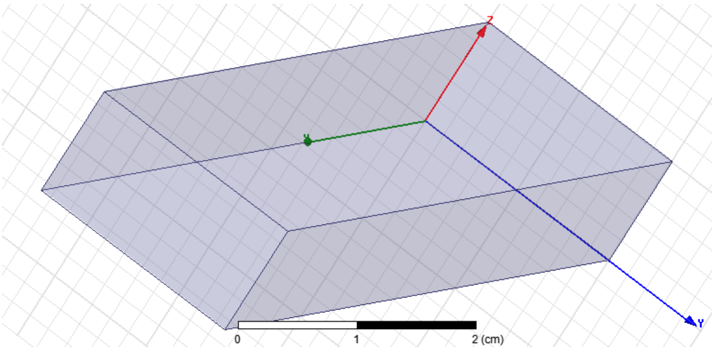

Figure 1: Rectangular Waveguide

The wave equations for waves moving in the z direction are as follows: [4,5].

$\nabla^2 H = -\omega^2 \mu\mathcal{E}$ **Hz** for TE wave (Ez =0) (1)

$\nabla^2 E = -\omega^2 \mu\mathcal{E}$ **Ez** for TM waves (**Hz** =0) (2)

The elements of the TE and TM waves, electric and magnetic fields along the z-direction, are denoted by the letters Ez and Hz, respectively. In a given waveguide with dimensions a > b, the mode with the lowest cutoff frequency is the dominant mode (TE10 mode). It is especially used in the rectangular waveguide for all electromagnetic transmission. While higher modes result in severe power loss and undesired harmonic distortion, the dominant mode usually guarantees low loss and distortion-free transmission.

The following provides the TEmn mode cutoff frequency: [4] -[5]

$$f_C = \frac{1}{2\sqrt{\mu\mathcal{E}}}\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right]^2 \quad (3)$$

Where m=n=0, 1, 2...

. But m=n≠ 0

The following provides the propagation constant: [4]-[5]

$$\gamma = \alpha + j\beta \quad (4)$$

Here γ = *Propagation constant*, α = *Attenuation Constant*

β = phase constant

$\gamma mn = j\beta mn$

$$\beta = \omega\sqrt{\mu\mathcal{E}\left(1 - \left(\frac{f_C}{f}\right)^2\right.} \quad \text{for f>fc} \quad (5)$$

Higher than the cutoff frequency is the operational frequency, f>fc, the wave moves through the waveguide. At the point of the real-to-imaginary transition of the propagation constant is known as the frequency of cutoff.

The characteristic impedance is provided by: [4,5]

$$Z = \frac{\eta}{\sqrt{1-\left(\frac{f_C}{f}\right)^2}} \quad \text{for TE wave} \quad (6)$$

$$Z = \eta\sqrt{1-\left(\frac{f_C}{f}\right)^2} \quad \text{for TM wave} \quad (7)$$

Here $\eta = \frac{1}{\sqrt{\mu\mathcal{E}}}$ *is the interinsic impedance*

Numerical analysis

Electric field strength

According to the inverse square law, A source charge Q's electric field strength is inversely proportional to the square of the source's distance, the electric field strength drops by a factor of 16 (4^2) as the separation

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

distance increases by a factor of 4 and the electric field intensity increases by a factor of 4 (2^2) if the separation distance falls by a factor of 2. The following is the equation: [4,5].

$$E=\frac{K.Q}{d^2} \quad (8)$$

Here Q =source charge
d =distance

Figures 2 and 3 illustrate the electric field strength in both waveguides. As shown, As the relative permittivity falls, the electric field rises.

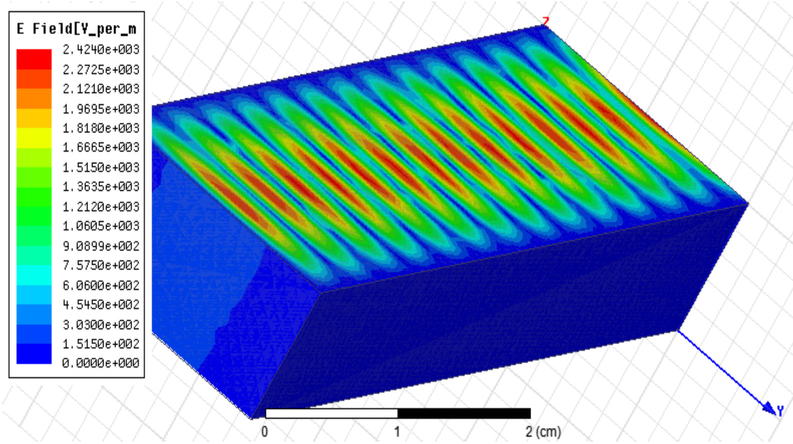

Figure 2. Electric Field Strength in Teflon-filled rectangular waveguide

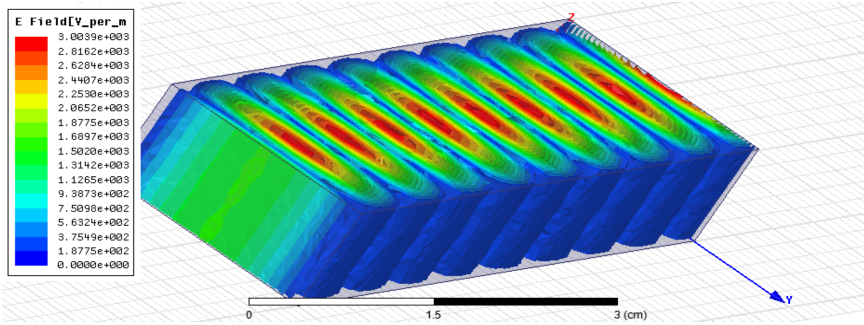

Figure 3. Electric Field Strength in Air-filled Rectangular Waveguide

Magnetic field strength

Any field that exerts a magnetic force and can cause magnetization in a substance is referred to as a magnetic field. The formula is provided by:

$$B=\frac{\mu_0 m}{4\Pi d^2} \quad (8)$$

Where B = *magnetic field*

$\mu_0 = 4\pi \times 10^{-7}\ Hm^{-1}$

Figures 4 and 5 illustrate the magnetic field strength in both waveguides. As shown, the magnetic field increases as the relative permittivity increases.

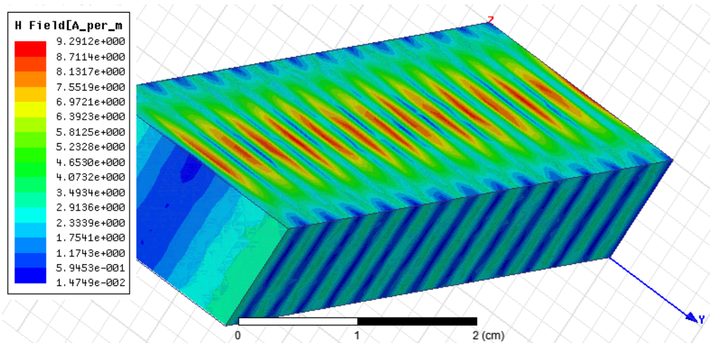

Figure 4. Magnetic Field Strength in Teflon–filled Rectangular Waveguide

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

https://doi.org/10.54361/ajmas.258304

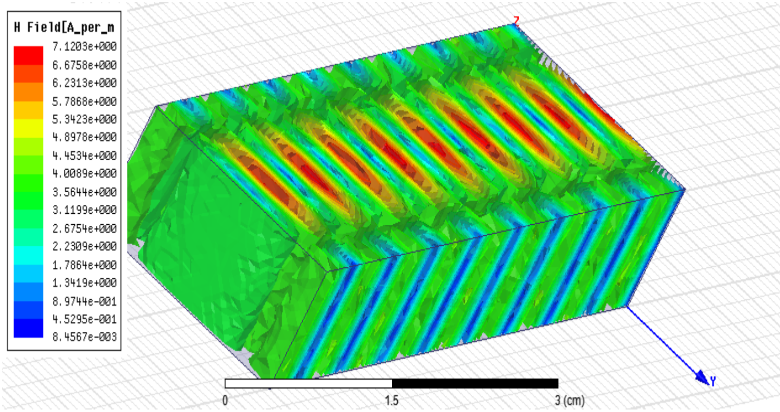

Figure 5. Strength of Magnetic Field in Air-Filled Rectangular Waveguide

Propagation constant

Figures 6 and 7 illustrate the propagation constant of a Teflon-filled rectangular waveguide and an Air-filled rectangular waveguide. It has been noted that the propagation constant rises in tandem with frequency. The frequency and the propagation constant are proportional.

Seven modes are propagating in the Teflon-filled rectangular waveguide, but only three modes propagate in the air-filled rectangular waveguide, as shown in Figures 6, 7, and Table 1.

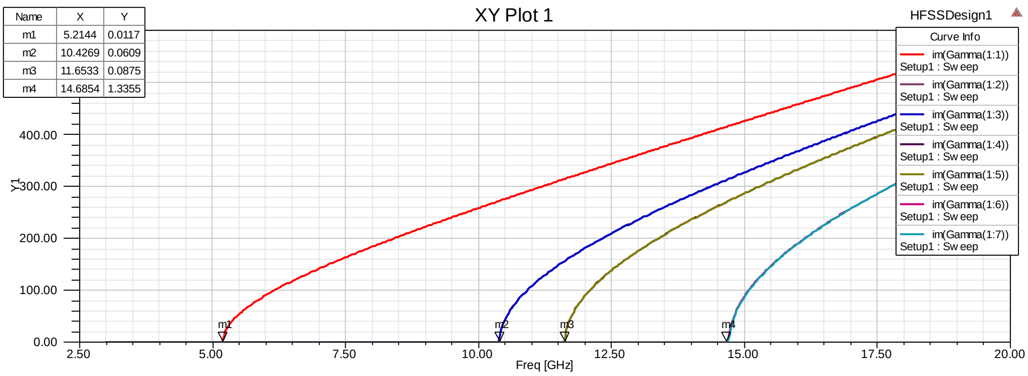

Figure-6. Propagation Constant and Modes of a Teflon–filled Rectangular Waveguide

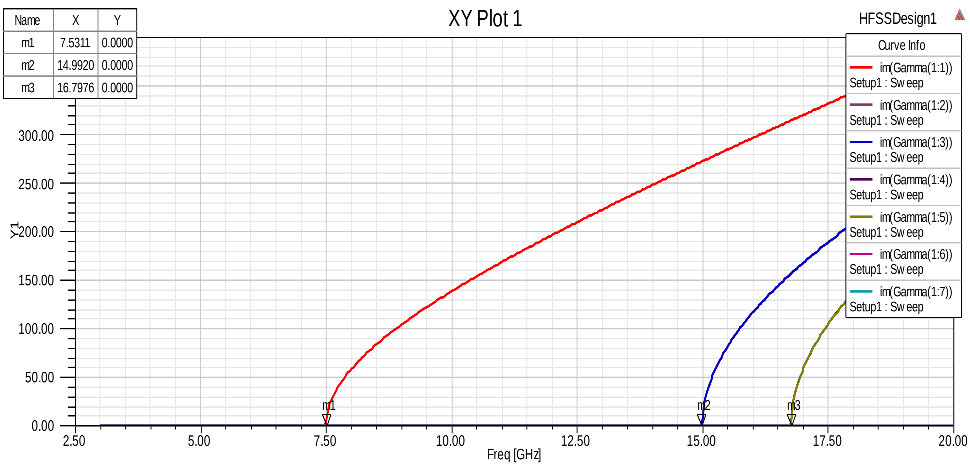

Figure 7: Air-filled Rectangular Waveguide's Propagation Constant and Modes

Impedance

Figures 8 and 9 illustrate the characteristic impedance of an air-filled rectangular waveguide and a Teflon-filled rectangular waveguide. The impedance reaches its maximum value at the cutoff frequency, then decreases and stabilizes at a constant value at higher frequencies.

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

https://doi.org/10.54361/ajmas.258304

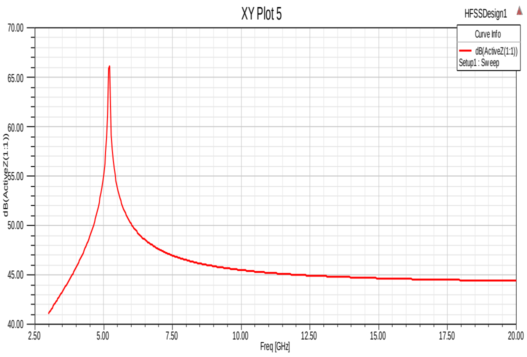

Fig 8. Impedance Matching in a Teflon-Filled Rectangular Waveguide

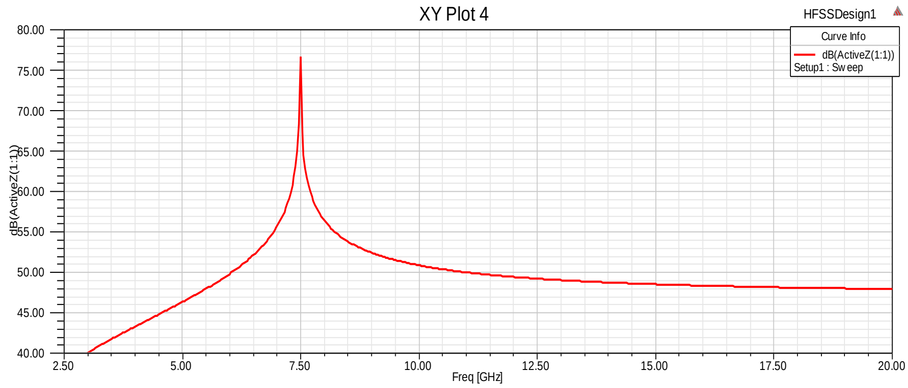

Figure 9. Impedance Matching in an Air-Filled Rectangular Waveguide

Theoretically predicted results

Equation 3 is used to determine the cutoff frequencies for many modes in two waveguides (a rectangular waveguide filled with air and one filled with Teflon). Below are the anticipated outcomes for the various modes. As shown in Table 1, the mathematical analysis of mode cutoff frequencies aligns with the simulation results. Changing the relative permittivity of the rectangular waveguide affects the TE and TM modes' cutoff frequencies; as the relative permittivity decreases, the cutoff frequency increases. In TE and TM arrangements, TE10 and TM11 are the predominant modes, respectively.

Table 1. Cutoff Frequencies for TEm,n, and $TM_{m,n}$ Modes: Mathematical Analysis and Simulation Software (HFSS) with different relative permittivity(εr).

Trever's electric and magnetic modes	**f_o In(GHz)**	**f_c of math analysis when $\varepsilon r = 2.08$ In(GHz)**	**F_c of simulation by hfss $\varepsilon r = 2.08$ (GHz)**	**f_c of math analysis when$\varepsilon r = 1.0006$ (GHz)**	**F_c of simulation by hfss when$\varepsilon r = 1.0006$ (GHz)**
TE_{10}	15	5.2	5.21	7.5	7.53
TE_{01} &TE_{20}	15	10.4	10.42	14.9	14.99
TE_{11} &TM_{11}	15	11.64	11.65	No propagate	16.79> f_o (It will not propagate)
TE_{21} &TM_{21}	15	14.7	14.6	No propagate	No propagate

The following five figures depict the five modes of TE and TM configurations within a Teflon-filled, copper ku-band rectangular waveguide.

.

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

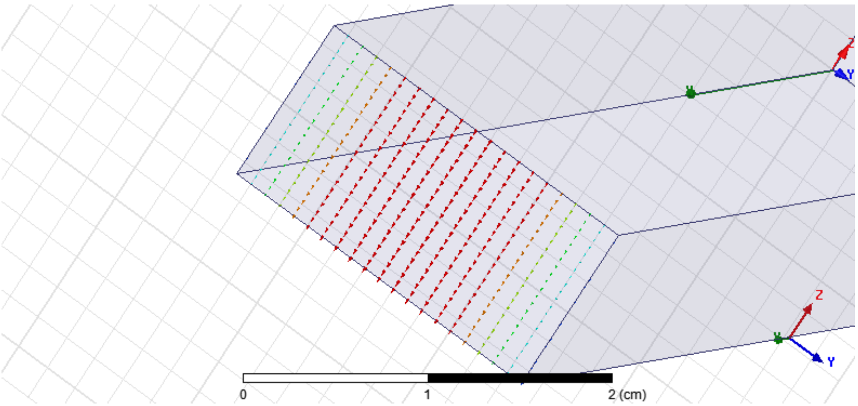

Figure9: TE10 mode

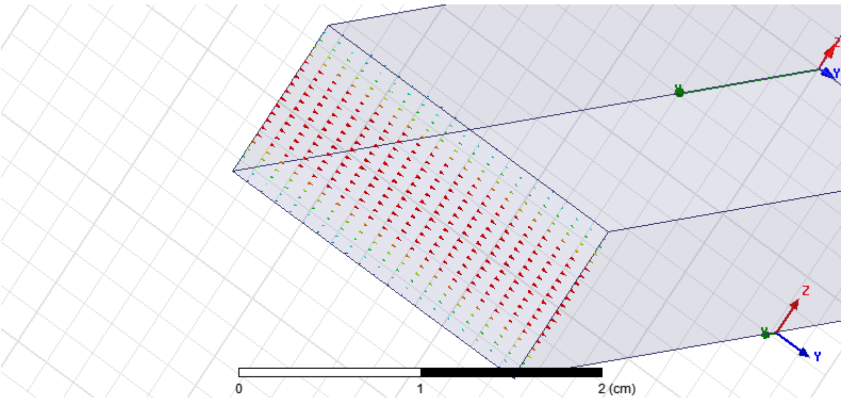

Figure10: TE01 mode

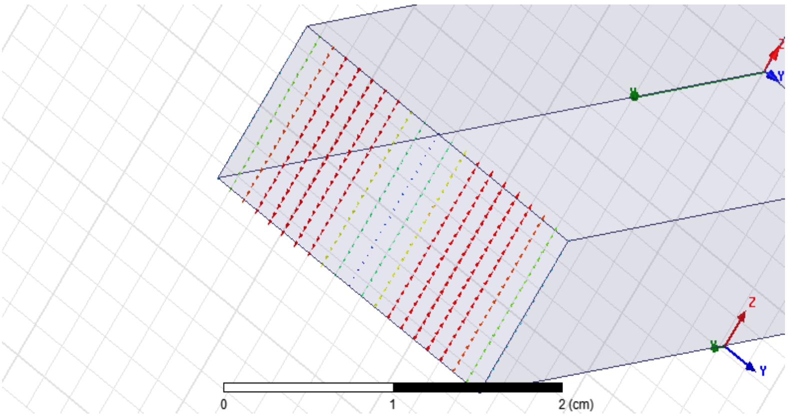

Figure11:TE11mode

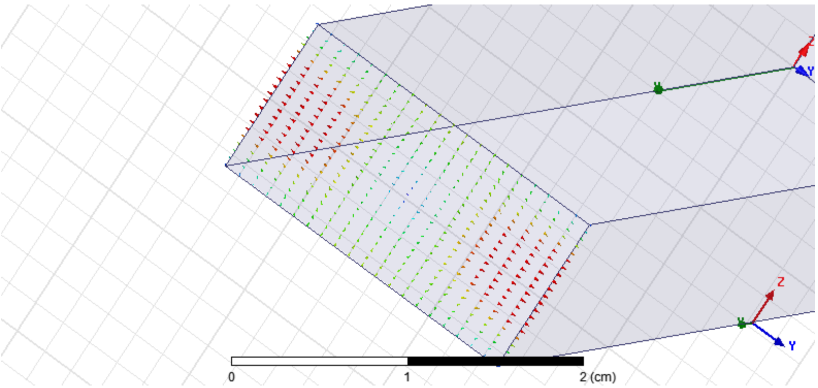

Figure12:TM11 mode

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*

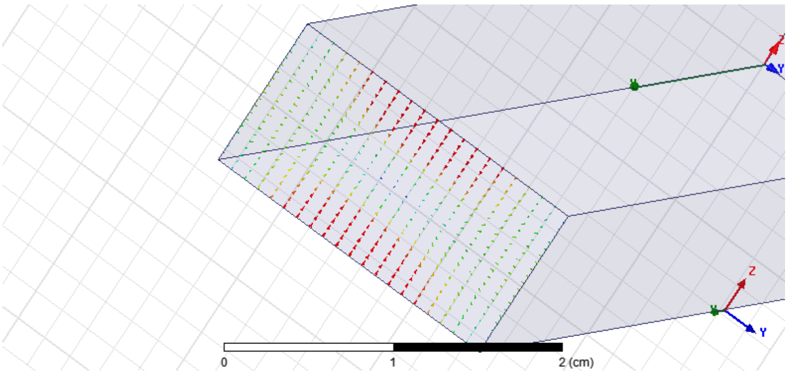

Figure13:TE21 mode

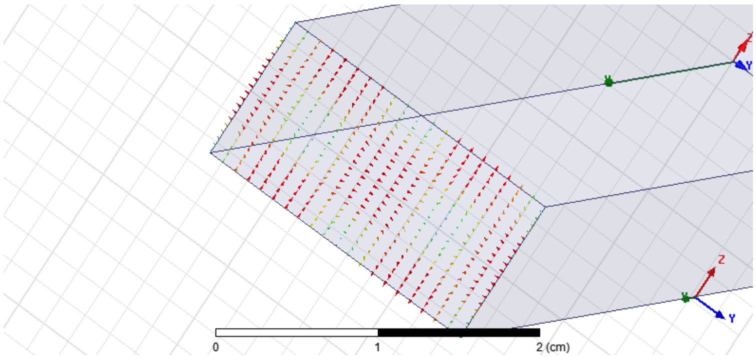

Figure14: TM21 mode

Conclusion

We examined two rectangular waveguides with varying relative permittivity in this research. Here is a comparison of the two waveguides. As the relative permittivity of the waveguide increased, the frequency of the cutoff dropped. This permits the propagation of higher frequencies and produces a good propagation constant. Both waveguides' characteristic impedance dramatically dropped with increasing frequency. This leads to the lossless transmission of information. As the relative permittivity of the waveguide falls, the electric field rises, but as the relative permittivity of the waveguide rises, the magnetic field does as well. The number of propagation modes decreases as the relative permittivity decreases. The two waveguides' theoretically determined cutoff frequencies match those found via simulation. The waveguide properties were used to determine its characteristics. Simulations are a powerful tool for examination through experimentation and can be especially helpful in the design phase of practical elements. The results of the simulations of the Electric and Magnetic Field Patterns are in agreement with the theoretical analysis. Consequently, the various characteristics of the waveguide have been studied, allowing us to select a waveguide with better performance for wave propagation.

Conflict of interest. Nil

References

1. Paramesha S, Chakraborty A. Waveguide as a near-field measuring probe of the two-element array radiator. Prog Electromagn Res B. 2008;7:245-55.
2. Jiao CQ. Selective suppression of electromagnetic modes in a rectangular waveguide by distributed wall losses. Prog Electromagn Res Lett. 2011;22:119-28.
3. Lee CS, Lee SW, Chuang SL. Plot of modal field distribution in rectangular and circular waveguides. IEEE Trans Microw Theory Tech. 1985;33:271-4.
4. Sadiku MNO. Elements of electromagnetics. 4th ed. New York: Oxford University Press; 2015.
5. Liao SY. Microwave devices and circuits. 3rd ed. Upper Saddle River (NJ): Pearson Prentice Hall; 2008.
6. Wikipedia contributors. Ku band [Internet]. Wikipedia, The Free Encyclopedia; [cited year month day]. Available from: https://en.wikipedia.org/wiki/Ku_band
7. SATMODO. Ku band and its use in satellite communications [Internet]. 2019 Nov 25 [cited year month day]. Available from: https://www.satmodo.com/blog/2019/11/25/ku-band-and-its-use-in-satellite-communications/
8. Harrington RF. Time harmonic electromagnetic fields. New York: McGraw-Hill; 1961.
9. Balanis CA. Advanced engineering electromagnetics. New York: John Wiley & Sons; 1989.
10. Collin RE. Foundations for microwave engineering. 2nd ed. New York: McGraw-Hill; 1992.
11. Baudrand H, Tao JW, Atechian J. Study of radiating properties of open-ended rectangular waveguides. IEEE Trans Antennas Propag. 1988;36(8):1071-7.

***Received**: 28-02-2025 - **Accepted**: 09-04-2025 - **Published**: 16-04-2025*