ECNG 4402 - Electromagnetic Waves

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Rectangular Waveguide Across Different Modes Design and Simulation

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Objective of the project using HFSS simulation:

The objective of this project is to use the Ansys Electronics (HFSS) software to model a rectangular waveguide and analyze various outcomes for different modes of the waveguide at different frequencies. The dimensions of the rectangular waveguide are determined by the cutoff frequency for the fundamental mode, and the cutoff frequencies for other modes are also examined. The findings for the attenuation and propagation constants are evaluated for three frequencies that fall between modes. These simulation results will be compared with theoretical results.

Theoretical Analysis:

To conduct our simulation, we opted to utilize a cutoff frequency of 3.00 GHz to determine the dimensions of the rectangular waveguide. The cutoff frequency is the lowest frequency at which a waveguide can support a particular mode of electromagnetic wave propagation. By selecting a cutoff frequency, the dimensions of the waveguide can be determined based on the desired mode of propagation. As a result, we calculated that the length of the waveguide would be approximately 49.8 ~= 50 mm. the process of selecting a cutoff frequency and calculating the dimensions of the waveguide is an important step in simulating the behavior of electromagnetic waves in a waveguide and understanding the characteristics of the waveguide. The following theoretical analysis was carried out to establish the length and width of the rectangular waveguide:

Theoretical Analysis & proof

- Fundamental mode cutoff frequency has been selected to be 3.00 GHz.

- Finding the dimensions (a, b & c) of the rectangular waveguide

Then, we will calculate those diminsions using the cutoff frequency equation:-

$$f_{c(m,n)} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2}$$

For TE_{10} fundamental mode,

$$f_{c_{10}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{\pi}{a}\right)^2+0^2} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\left(\frac{\pi}{a}\right)$$

Since our selected frequncy is 3 GHz

$$\therefore 3.00\ GHz = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\left(\frac{\pi}{a}\right)$$

$$= \frac{1}{2\pi\sqrt{(4\pi\times10^{-7})(8.85418\times10^{-12})}}\left(\frac{\pi}{a}\right)$$

$$\therefore a = 0.04996\ m. = 49.96\ mm. \simeq 50\ mm.$$

To find the b dimension, we will create a rectangular waveguide whereas $b = \frac{a}{2}$

$$\therefore \ b = \frac{50\text{mm}}{2} = 25 \text{ mm}.$$

Therefore, c dimension should be significantly larger than a & b. we have selected **c** at a value of 0.5 m = 500mm.

* As we have our dimensions calculated, then we could find the cutoff frequencies for TE_{01} & TE_{20}

$$\therefore \ f_{c_{01}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{(0)^2 + \left(\frac{\pi}{b}\right)^2}$$

$$= \frac{1}{2\pi\sqrt{(4\pi \times 10^{-7}) \times (8.85418 \times 10^{-12})}} \left(\frac{\pi}{25 \times 10^{-3}}\right)$$

$$f_{c_{01}} = 5.996 \text{ GHZ}$$

$$f_{c_{20}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{2\pi}{a}\right)^2 + 0^2}$$

$$= \frac{1}{2\pi\sqrt{4\pi \times 10^{-7} \times 8.85418 \times 10^{-12}}} \left(\frac{2\pi}{50 \times 10^{-3}}\right)$$

$$= 5.996 \text{ GHz}.$$

β value verification :-

$$\because \quad \beta = \sqrt{K^2 - K_c^2}$$

whereas $K = \dfrac{\omega}{c_o} = \dfrac{2\pi f}{c_o}$ & $K_c = \dfrac{m\pi}{a}$

* At 3.0 GHz :-

For TE_{10}

$$K = \frac{2\pi(3\times10^9)}{3\times10^8} = 62.831$$

$$K_c = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} = 62.831$$

$\therefore \beta\Big|_{3GHz} = \emptyset$ (similar to the output on the simulation).

As there is no propagation

$\therefore$ At $f = 5.996$ GHz

$\beta = \sqrt{K^2 - K_c^2}$ #, $K = \dfrac{2\pi f}{C_o} = 125.58$

& $K_c = \dfrac{\pi}{a} = \dfrac{\pi}{0.05} = 62.831$

$\boxed{\therefore \beta = 108.73}$ whereas On HFSS $\boxed{\beta = 108.76}$

* For TE_{01} & TE_{20} :-

Both modes will be having the same cutoff.

At frequency = 5.0 GHz

TE_{01} :- $\beta = \sqrt{k^2 - k_c^2}$, $k = \frac{2\pi \times 5 \times 10^9}{3 \times 10^8} = 104.719$

$k_c = \frac{n\pi}{b} = 125.66 > k$

$\therefore$ no propagation at freq < f_c of 5.996 GHz for TE_{01} mode

Same for TE_{20} mode as $\boxed{b = \frac{a}{2}}$

* at freq. = 6.5 GHz

TE_{10} :- $k = \frac{2\pi \times 6.5 \times 10^9}{3 \times 10^8} = 136.136$

$k_c = \frac{m\pi}{a} = 62.832$

$\therefore$ $k > k_c$ $\Rightarrow$ propagation occurs.

$\beta = \sqrt{k^2 - k_c^2} = \boxed{120.769}$

for HFSS $\rightarrow \beta = \boxed{120.8}$

for TE_{01} & TE_{20} :-

$k = \frac{2\pi \; 6.5 \times 10^9}{3 \times 10^8} = 136.136$

TE_{01} : $k_c = \frac{n\pi}{b} = 125.66$

$\therefore$ $\beta = \sqrt{k^2 - k_c^2} = \boxed{52.36}$

HFSS $\rightarrow \boxed{\beta = 52.711}$

Same for TE_{20} mode.

The theoretical analysis shows that the results are reasonable. The length of side (b) of the rectangular waveguide is equal to half the length of side (a), indicating that the frequency of mode TE20 will be equal to the frequency of mode TE01. Consequently, we determined that the frequencies of the TE10, TE01, and TE20 modes are 3.0 GHz and 5.996 GHz, respectively. In addition to examining different frequencies, we will also evaluate the gamma for each mode. The gamma value is expressed using the equation: $\boldsymbol{\Gamma = \alpha + j\beta}$.

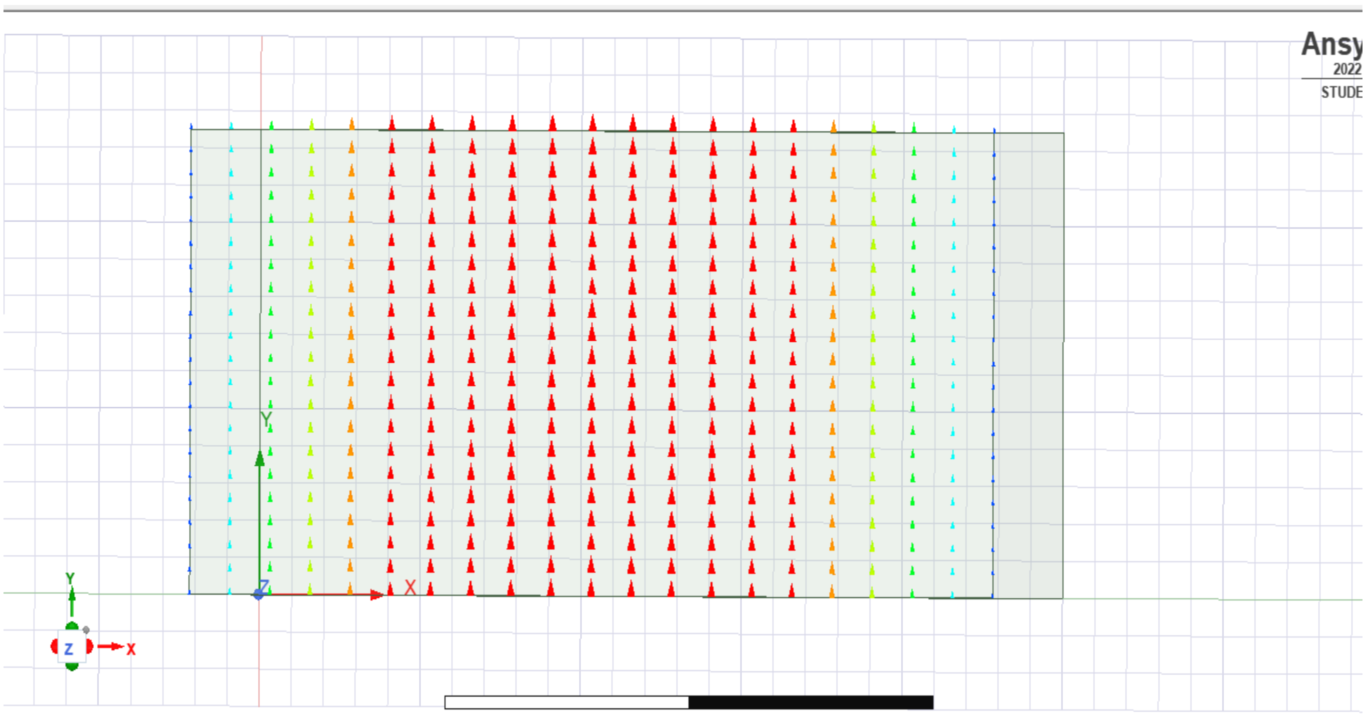
As the attenuation constant (represented by α) and propagation constant (represented by β). These values help to determine whether an electromagnetic wave has propagated through the waveguide. When the attenuation constant is large and the propagation constant is close to zero, it indicates that the wave's frequency is lower than the cutoff frequency, and thus, the wave has not propagated through the waveguide. Conversely, when the attenuation constant is approximately zero and the propagation constant is large, it indicates that the wave's frequency is higher than the cutoff frequency, and therefore, the wave has propagated through the waveguide.

Results:

According to the theoretical analysis, the rectangular waveguide was created with dimensions of a = 50 mm and b = a/2 = 25 mm. and choosing c dimension to be 0.5 m. The attenuation and propagation constants were determined by analyzing the results of three frequencies, which were selected to be just below the next cutoff frequency for each mode and slightly higher than the previous mode. The values of alpha and beta were calculated, and the outcomes are presented below.

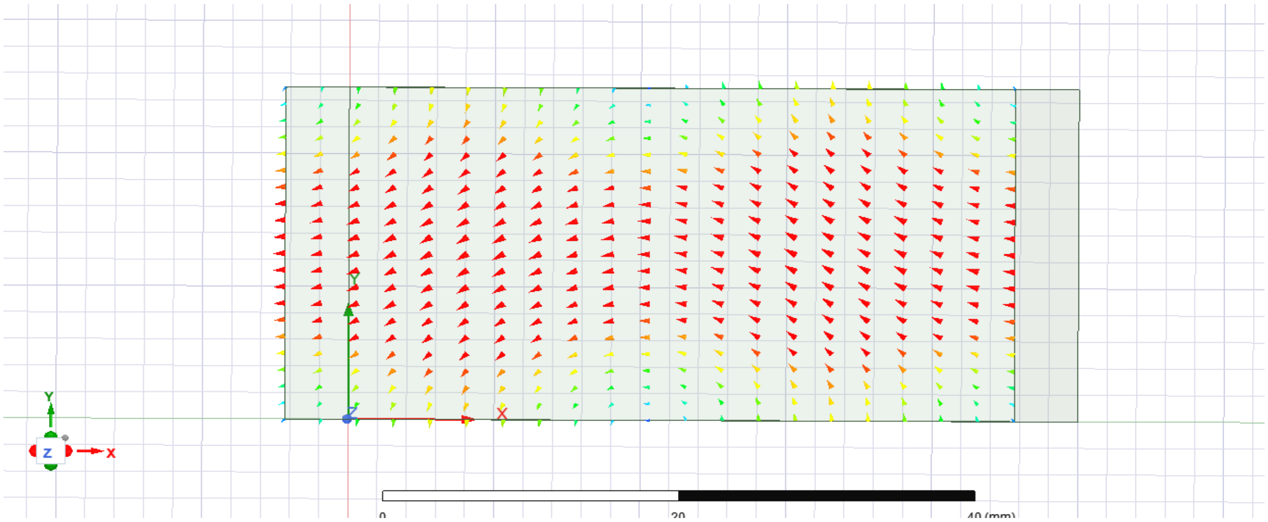
Starting with the field patterns of the modes TE10, TE01, and TE20 respectively.

TE10 mode



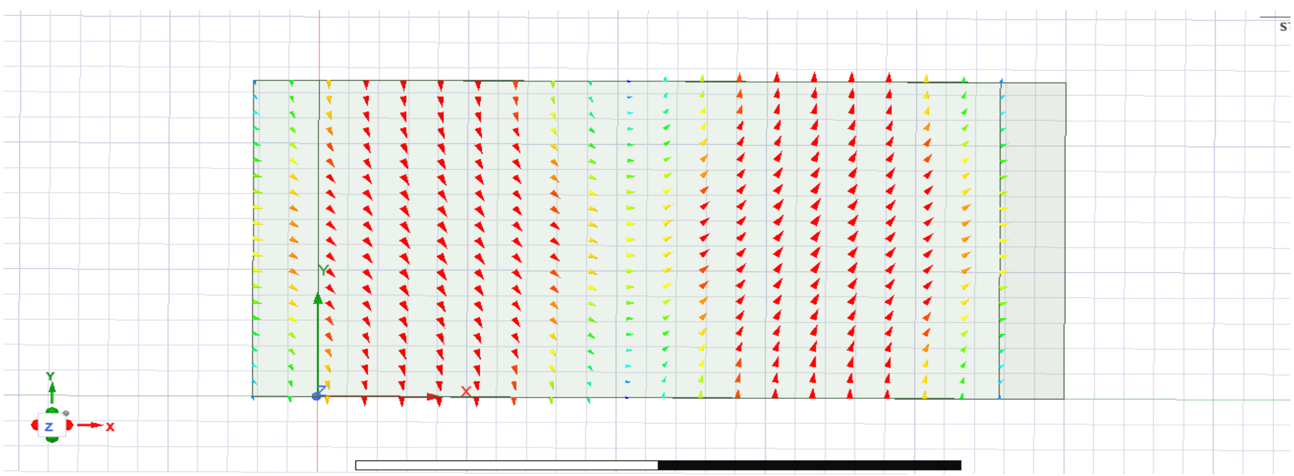
The TE10 mode is the fundamental mode of the rectangular waveguide, and it refers to the transverse electric field having one maximum and zero points on the perpendicular electric field. The field pattern of the TE10 mode is expected to be a positive half sinusoidal wave that peaks at the center of the rectangular waveguide before descending again.

TE01 mode

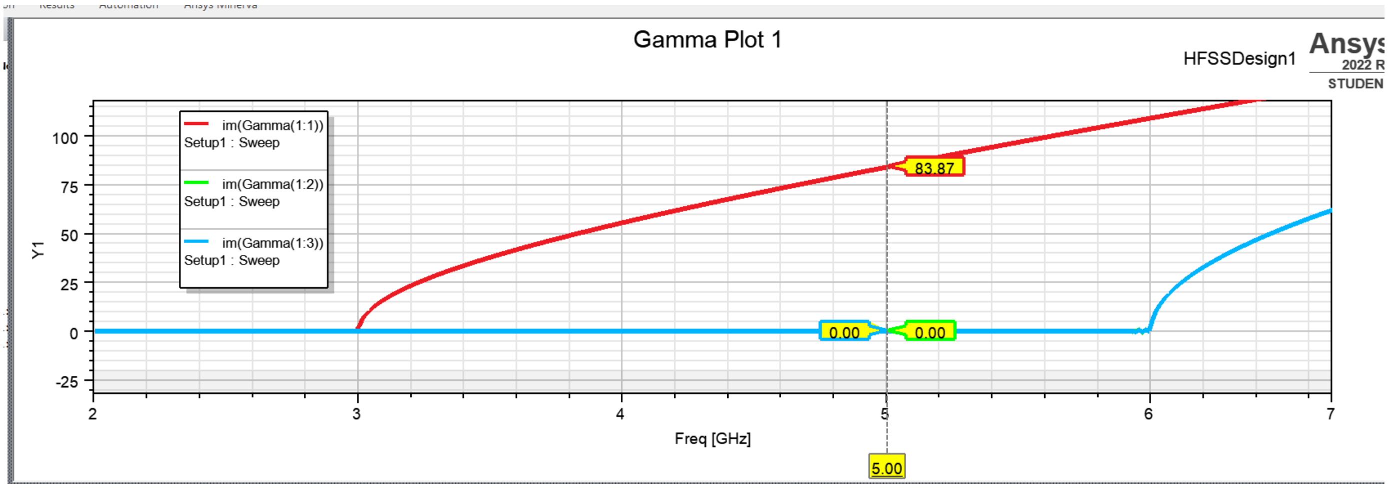


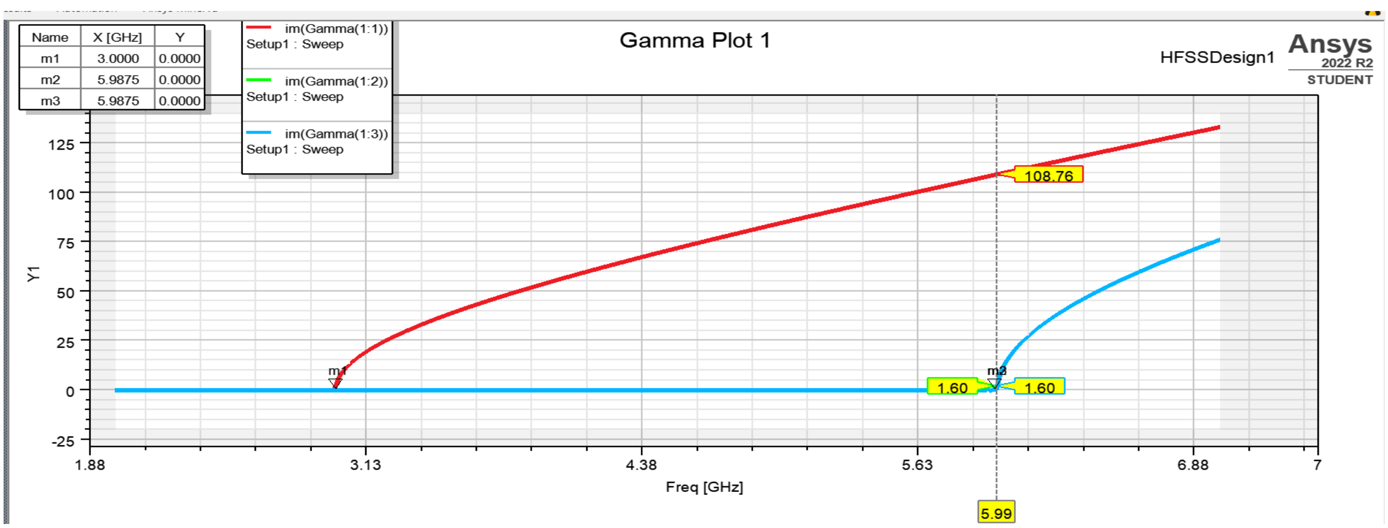
The observed field pattern corresponds to the TE01 mode as expected. The pattern is also a positive half sinusoidal wave, but it begins at the b-side of the rectangular waveguide, unlike the TE10 mode, which starts at the a-side. This observation aligns with the theoretical analysis and is therefore considered reliable.

TE20 mode



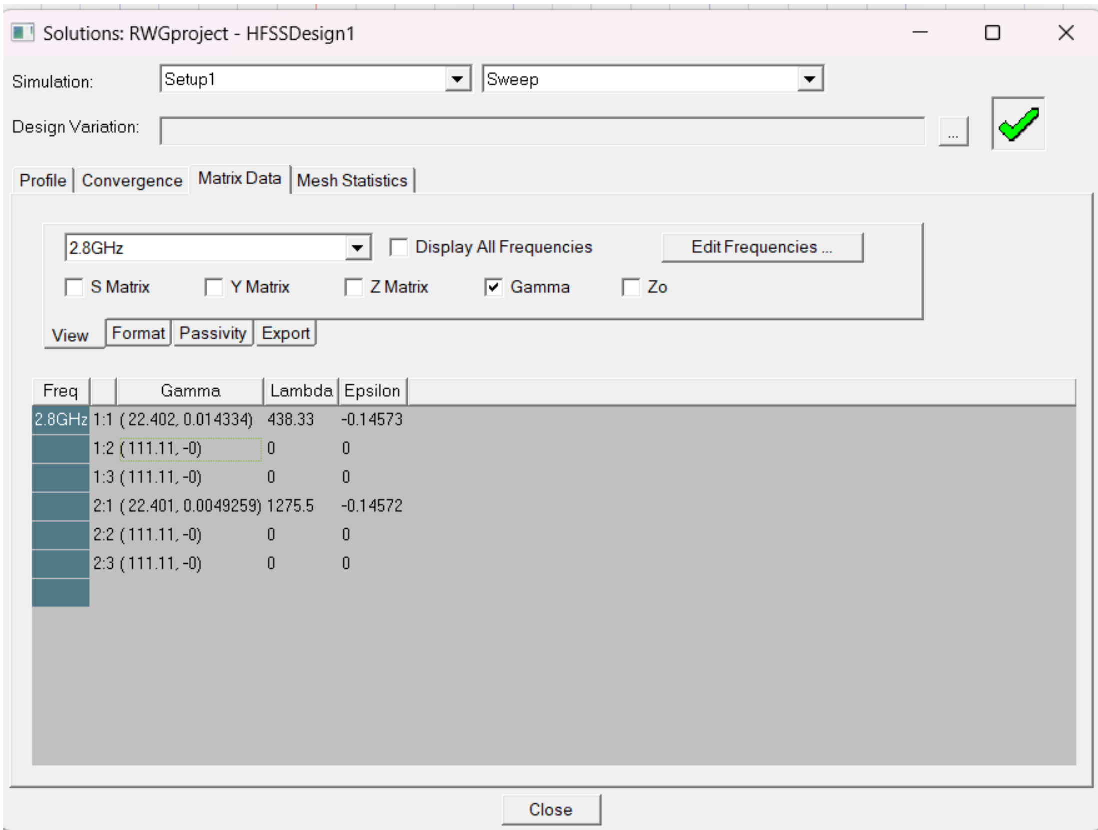
The observed field pattern for the TE20 mode aligns with the theoretical expectations. As predicted, the TE20 mode produces a field pattern that consists of two positive halves of sinusoidal waves occurring consecutively within the rectangular waveguide, and this pattern is accurately reflected in the simulation results.



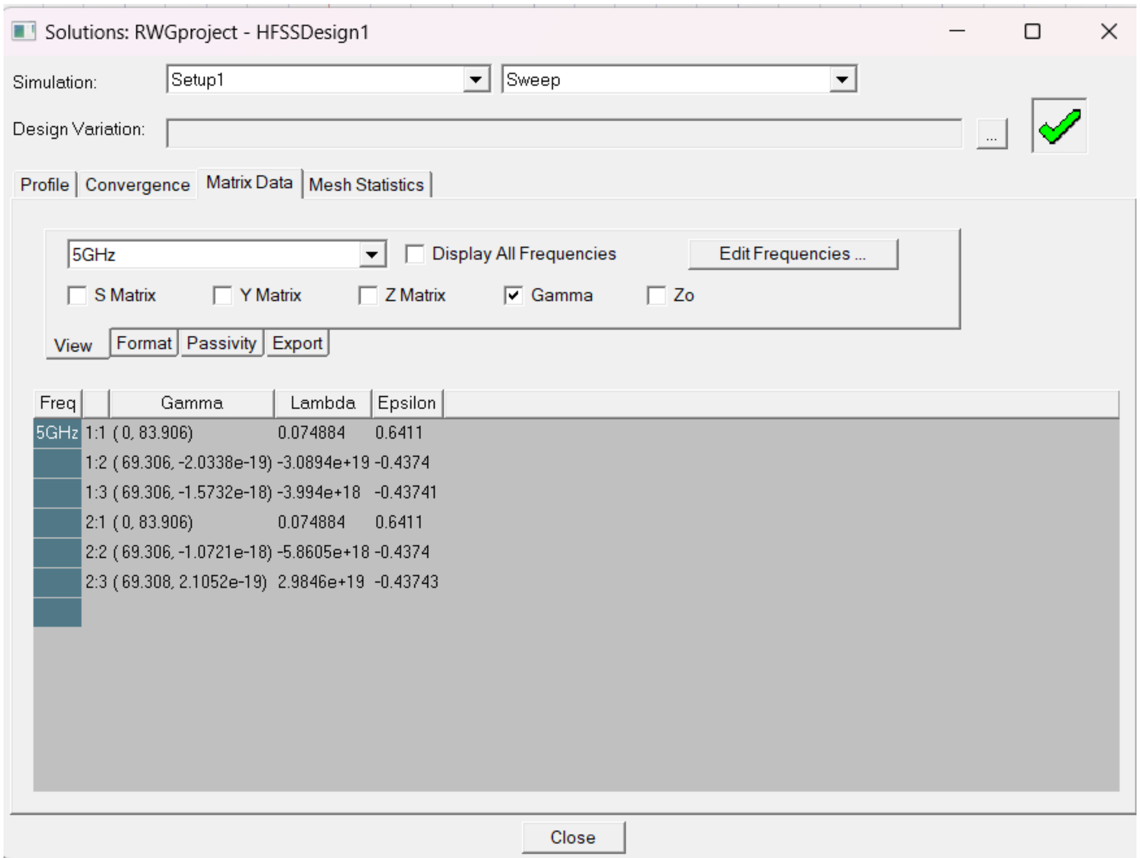


The simulation results indicate that the frequency cutoffs for each mode are m1 = 3.00 GHz for Waveport1:1 (TE10), m2 = 5.9675 GHz for Waveport1:2 (TE01), and m3 = 5.9675 for Waveport1:3 (TE20).

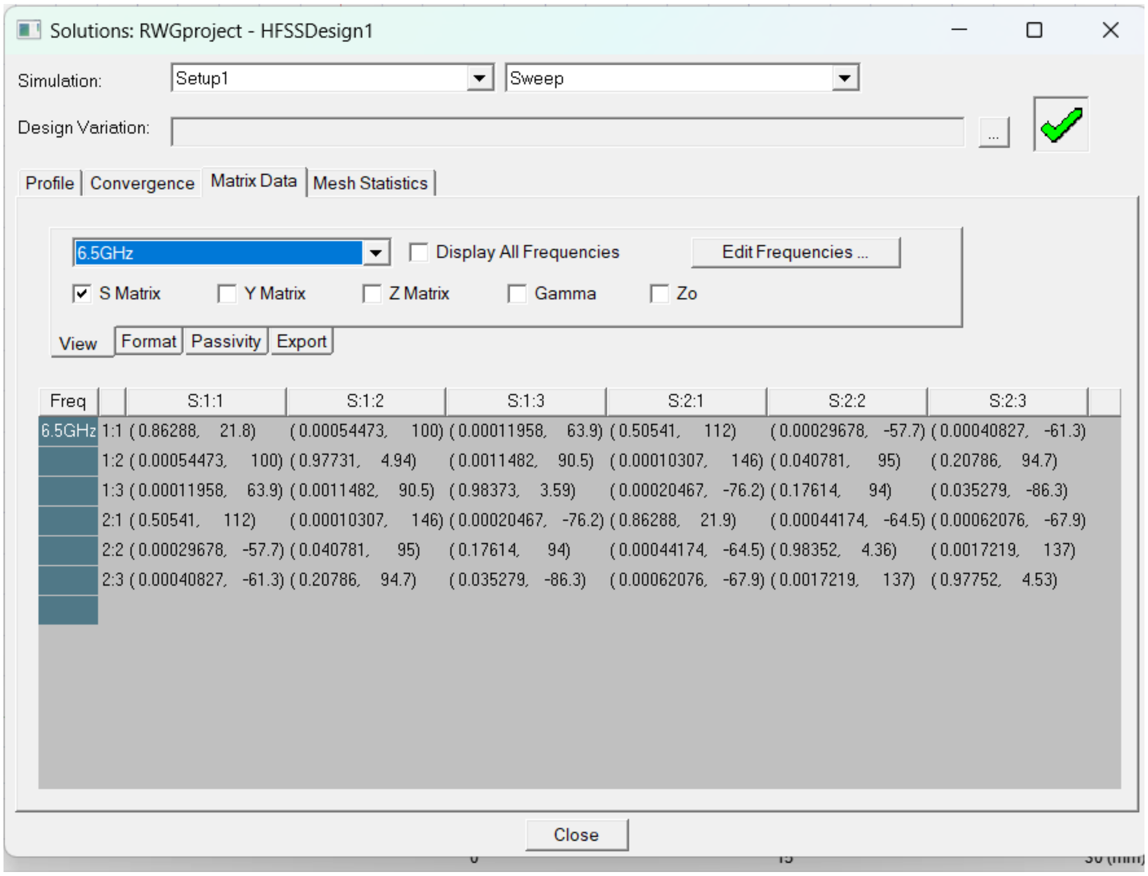
To analyze the alpha and beta values at suitable frequencies, we selected four frequencies for evaluation: 2.80 GHz, 5.00 GHz, 6.5 GHz. The simulation results for the alpha and beta values at each of these frequencies are presented below.



These findings indicate that the attenuation constant for all three modes, TE10 (Waveport 1:1), TE01 (Waveport 1:2), and TE20 (Waveport 1:3), remains high. The propagation constant is very small for all three modes because the frequency being analyzed is lower than the cutoff frequency for all three modes, indicating that the wave cannot propagate in the waveguide.



At a frequency of 5.00 GHz, the attenuation constant for the TE10 mode (Wave port 1:1) is no longer high. This is because, at 5 GHz, the frequency is higher than the calculated and tested cutoff frequency for the TE10 mode, which is 3.00 GHz. However, the propagation constant for TE10 mode is now high, indicating that the wave has propagated through the waveguide. For the other two modes, the frequency is still lower than their respective cutoff frequencies, and therefore, there is no propagation in those modes.



At a frequency of 6.5 GHz, it is observed that the wave can pass through both Wave port 1:1 (TE10), Waveport1:2 (TE01), and Waveport1:3 (TE20) modes, as this frequency is higher than the cutoff frequency for the three modes. Consequently, the attenuation constant for both modes is almost zero, while the propagation constant is relatively high.

Discussion

The results obtained from the simulation indicate that the rectangular waveguide has been successfully implemented within the desired parameters. The theoretical analysis closely matches the simulated waveguide, and the cutoff frequencies for the three modes (TE10, TE01, and TE20) are like those calculated by hand. The analysis of different frequencies swept through the waveguide reveals reasonable values for their attenuation and propagation constants. For instance, frequencies such as 2.9 GHz have a higher attenuation constant in all three modes compared to later frequencies such as 5 GHz and 6.5 GHz, which can progressively propagate through the TE10 and all three modes (TE10, TE01, and TE20) respectively.

Additionally, the field patterns of the different modes are found to be accurate to what is expected theoretically. The TE10 mode's field pattern shows a positive half of a sinusoidal wave rising from the a-side of the rectangular waveguide, which is in line with the theoretical drawing of the field pattern. Similarly, the TE01 mode's field pattern is shown to be a positive half of the sinusoidal wave rising from the b-side, which is as expected theoretically. Finally, the TE20 mode is accurately simulated as two positive halves of sine waves adjacent to each other, rising from the a-side. These results match those found or expected theoretically, indicating that the design of the rectangular waveguide is successful.

Conclusion

We have successfully designed a rectangular waveguide that meets the given assumptions and simulated it. The simulation results accurately match the theoretical calculations, thereby confirming the success of the waveguide's design. The analysis of the different frequencies swept through the waveguide shows that lower frequencies such as 2.8 GHz have high attenuation constants across all three modes and low propagation constants, indicating that they cannot propagate. As the frequency increases, certain modes begin to propagate while others do not until the frequency surpasses their cutoff frequency.

The results obtained from the simulation for the waveguide's frequency cutoffs are consistent with the theoretical analysis. The fundamental mode, TE10, has the lowest cutoff frequency, while the TE20 and TE01 modes have a higher cutoff frequency and are equal because the length of side b is equal to half of the length of side a. The field patterns of the different modes are also consistent with the theoretical expectations, with the TE10 mode showing a positive half sinusoidal wave rising from side a, the TE01 mode showing a positive half sinusoidal wave from side b, and the TE20 mode showing two positive halves of the sinusoidal wave. These results matching what was expected theoretically confirm the success of the project.