# Lab 4: Rectangular waveguide

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## Introduction

### Experimental objective

The purpose of this experiment is to acquire fundamental knowledge about rectangular waveguides, and to comprehend and master the modeling and simulation using HFSS software, thereby deepen our understanding about the knowledge about waveguides. Moreover, we will use HFSS to observe the electric field distribution, and our primary focus will be on studying and simulating four modes of the rectangular waveguide: TE10 mode, TE20 mode, TE01 mode, and TE11 mode. We will analyze the results using S-parameter plots.

### Waveguides

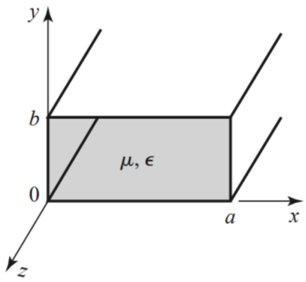
A waveguide is a guiding structure for electromagnetic waves, typically defined by spatial boundaries between conductive surfaces. Its fundamental design allows the propagation of electromagnetic waves, with the electric and magnetic fields constrained by the geometry and electromagnetic properties of the waveguide. Waveguides find extensive applications in wireless communication, radar systems, microwave engineering, and fiber optics.

One common type of waveguide is the rectangular waveguide, characterized by a rectangular cross-section. A rectangular waveguide consists of a rectangular conduit formed by four boundaries (two wide sides and two narrow sides). Electromagnetic waves propagate through this conduit via reflection and refraction. Rectangular waveguides support various modes, with the most fundamental being TE (Transverse Electric) and TM (Transverse Magnetic) modes. These modes describe the distribution of the electromagnetic field with respect to the geometry of the waveguide. And it can offer several advantages over other waveguide structures. One notable advantage is their ease of fabrication, as the rectangular cross-section simplifies manufacturing and installation. Additionally, rectangular waveguides are versatile in supporting multiple modes, providing flexibility and performance advantages. Rectangular waveguides are widely used in communication, radar, antenna systems, and other fields, especially in the microwave and millimeter-wave frequency ranges. Their structure and performance make them an ideal transmission medium in specific frequency bands.

Therefore, the rectangular waveguide is a significant waveguide structure with distinct advantages, making it well-suited for specific applications. In the context of learning and simulation, tools like HFSS enable a better understanding and optimization of the performance of rectangular waveguides.

### Four Modes of Waveguide

For a given cross-sectional waveguide or transmission line, there is a series of solutions at specific frequencies that satisfy the corresponding boundary conditions and Maxwell's equations. Each solution is referred to as a mode. Typically, modes are named based on the presence or absence of components of the electric and magnetic fields along the direction of propagation in the waveguide system. Assuming the waveguide system is placed along the $z$-axis, these components refer to the $Ez$ electric field component and the $Hz$ magnetic field component along the $z$ direction.




According to the presence or absence of components of the electric and magnetic fields along the direction of propagation in the waveguide system, there are primarily three modes:

1. **TEM Mode:** This mode corresponds to cases where $Ez$ = 0 and $Hz$ = 0, and it is known as Transverse Electromagnetic (TEM) wave.
2. **TE Mode:** In this mode, $Ez$ = 0 and $Hz$ $\neq$ 0, and it is referred to as Transverse Electric (TE) mode.
3. **TM Mode:** This mode corresponds to cases where $Ez$ $\neq$ 0 and $Hz$ = 0, and it is known as Transverse Magnetic (TM) mode.

We will mainly focus on the TE mode,

$$H_z = H_0 \cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

$$H_x = \frac{j\beta}{K_c^2}\left(\frac{m\pi}{a}\right)H_0 \sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

$$H_y = \frac{j\beta}{K_c^2}\left(\frac{n\pi}{b}\right)H_0 \cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

$$E_x = \frac{j\omega\mu}{K_c^2}\left(\frac{n\pi}{b}\right)H_0 \cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

$$E_y = -\frac{j\omega\mu}{K_c^2}\left(\frac{m\pi}{a}\right)H_0 \sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

We can set different values of m and n, which correspond to different modes, for example, if m = 1 and n = 0, it is the TE10 mode and other modes are similar.

## Cutoff Frequency

Each mode has a cutoff frequency $f_c$ given by:

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

The mode with the lowest cutoff frequency is called the dominant mode because the rectangular waveguide we simulate satisfies $a > b$, so the lowest cutoff frequency occurs for the $TE10$ mode.

At a given operating frequency $f$, only those modes with $f > f_c$ can propagate and modes with $f < f_c$ will lead to an imaginary $\beta$ (or real $\alpha$), meaning that all field components will decay exponentially away from the source of excitation.

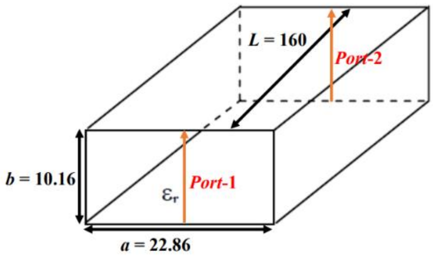
For this experiment, the dimension of the air-filled WR-90 waveguide is $a$ = 22.86 mm, $b$ = 10.16 mm, we can calculate the $f_c$ for each mode as below:

1) $TE10$ mode, $f_c$ = 6.557 $GHz$
2) $TE20$ mode, $f_c$ = 13.114 $GHz$
3) $TE01$ mode, $f_c$ = 14.754 $GHz$
4) $TE11$ mode, $f_c$ = 16.144 $GHz$

# Lab results & Analysis：

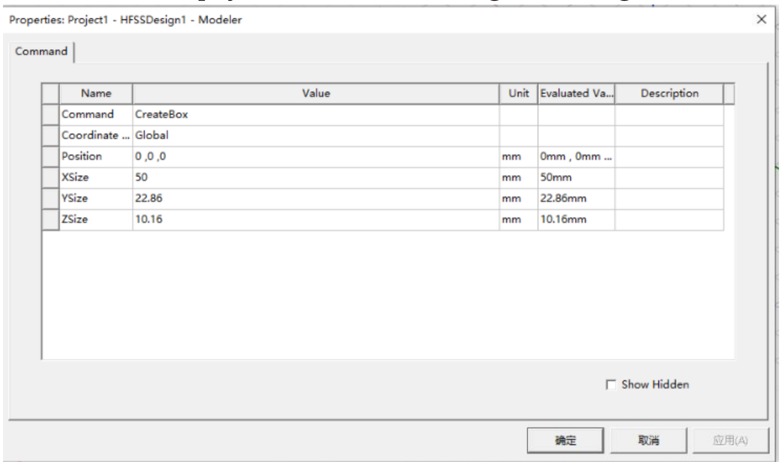
## Objective

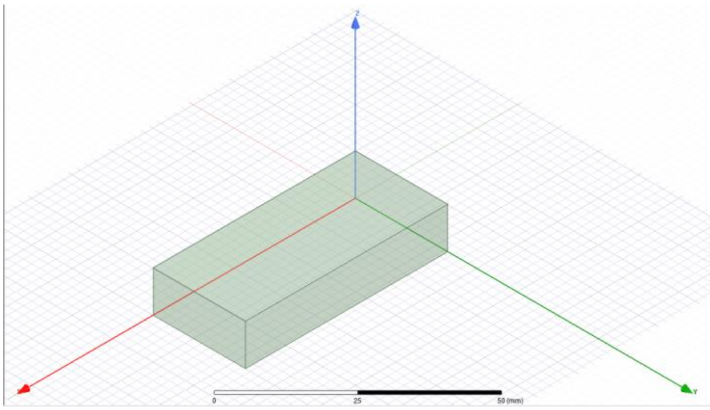
• Using HFSS, simulate an air-filled WR-90 waveguide.
• To obtain the Field patterns, propagation constant for the 3 modes (TE10, TE20, TE01, modes).
• Generate a graph for β vs. frequency for each mode using HFSS

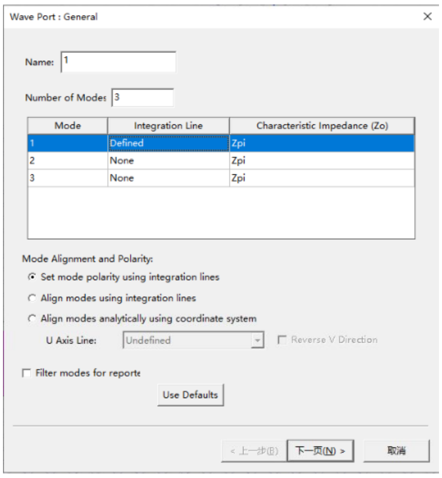


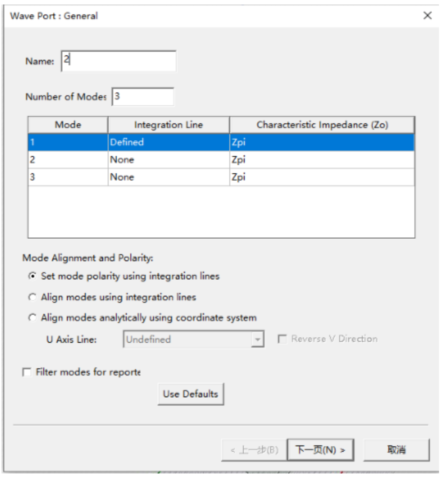

## Waveguide model construct

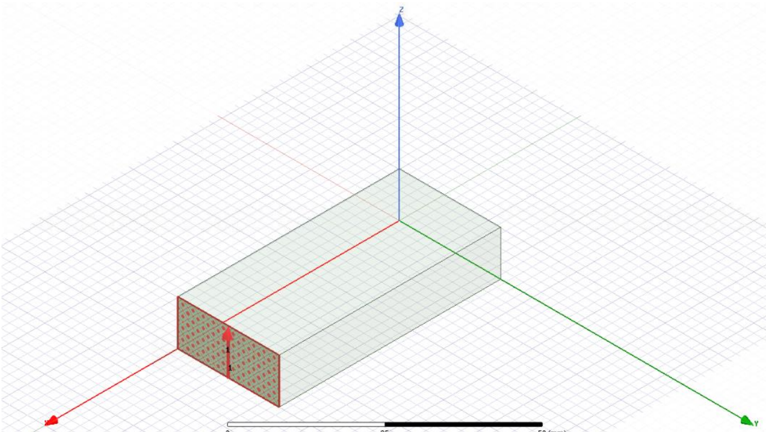
First, we should construct the physical model of rectangular waveguide in HFSS.





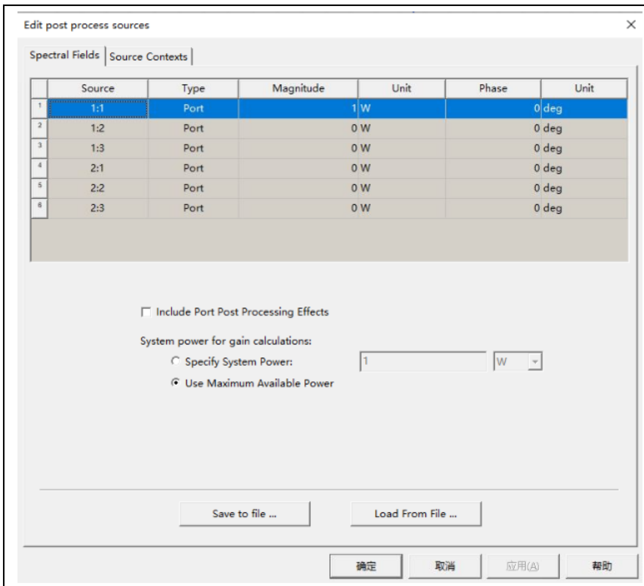



And then we choose different modes:

For TE10: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1:2 Port 0 W 0 deg
1:3 Port 0 W 0 deg
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2:2 Port 0 W 0 deg
2:3 Port 0 W 0 deg
Include Port Post Processing Effects
System power for gain calculations:
Specify System Power:
Use Maximum Available Power
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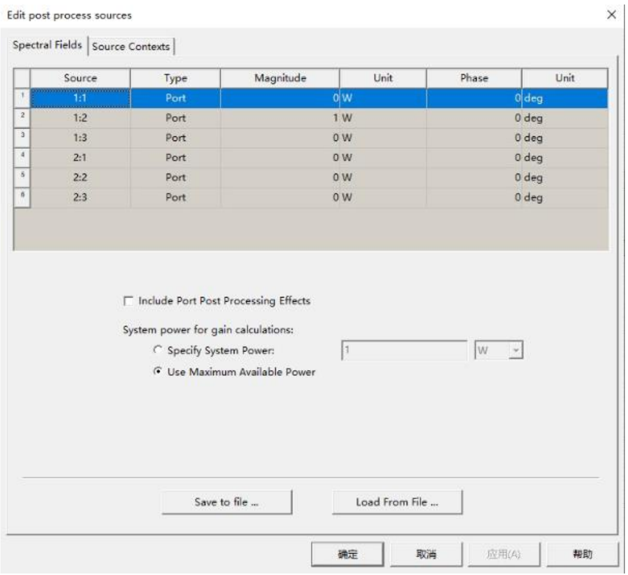
确定
取消
应用(A)
帮助

TE20: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2:2 Port 0 W 0 deg
2:3 Port 0 W 0 deg
Include Port Post Processing Effects
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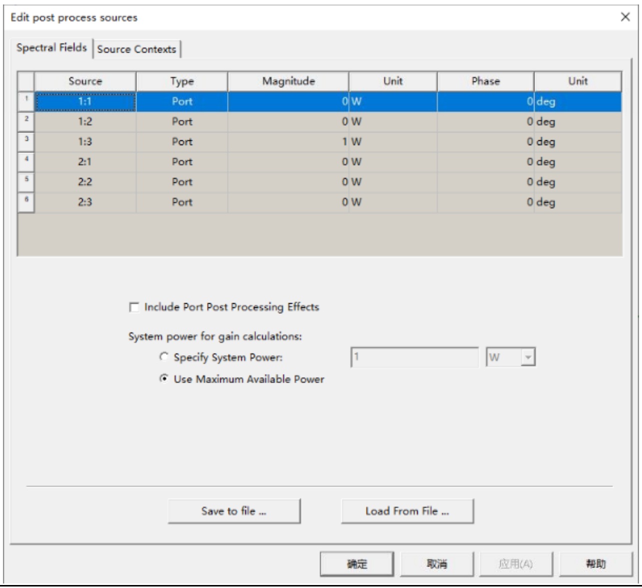
Load From File ...
确定
取消
应用(A)
帮助

TE01: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Source Contexts
Source Type Magnitude Unit Phase Unit
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1:2 Port 0 W 0 deg
1:3 Port 1 W 0 deg
2:1 Port 0 W 0 deg
2:2 Port 0 W 0 deg
2:3 Port 0 W 0 deg
Include Port Post Processing Effects
System power for gain calculations:
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Use Maximum Available Power
Save to file ...
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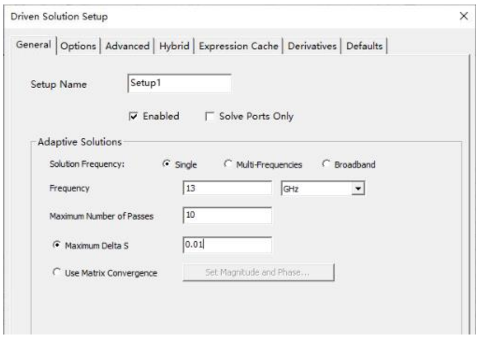
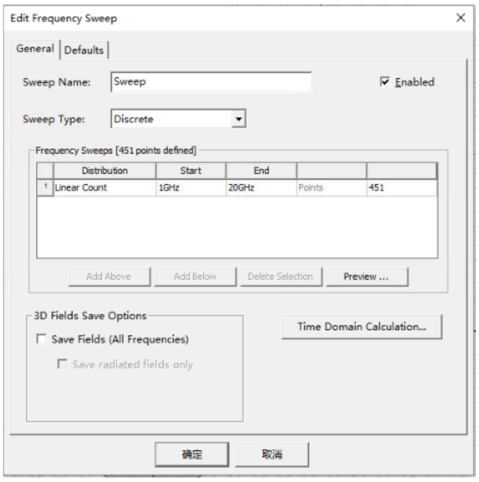
确定
取消
应用(A)
帮助

And we set the setup and frequency sweep.

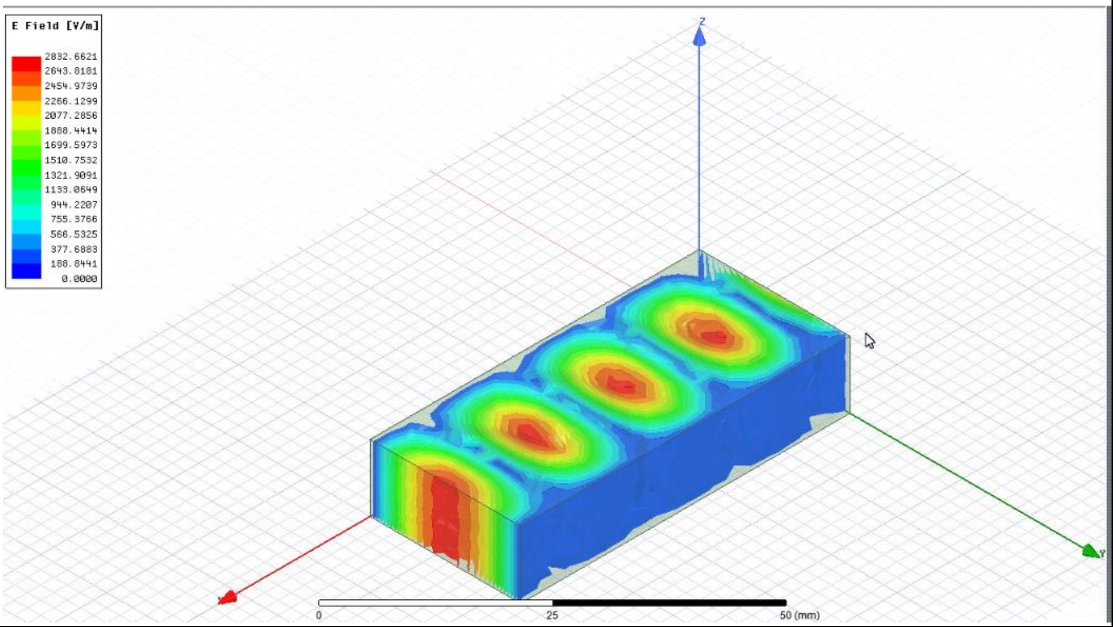


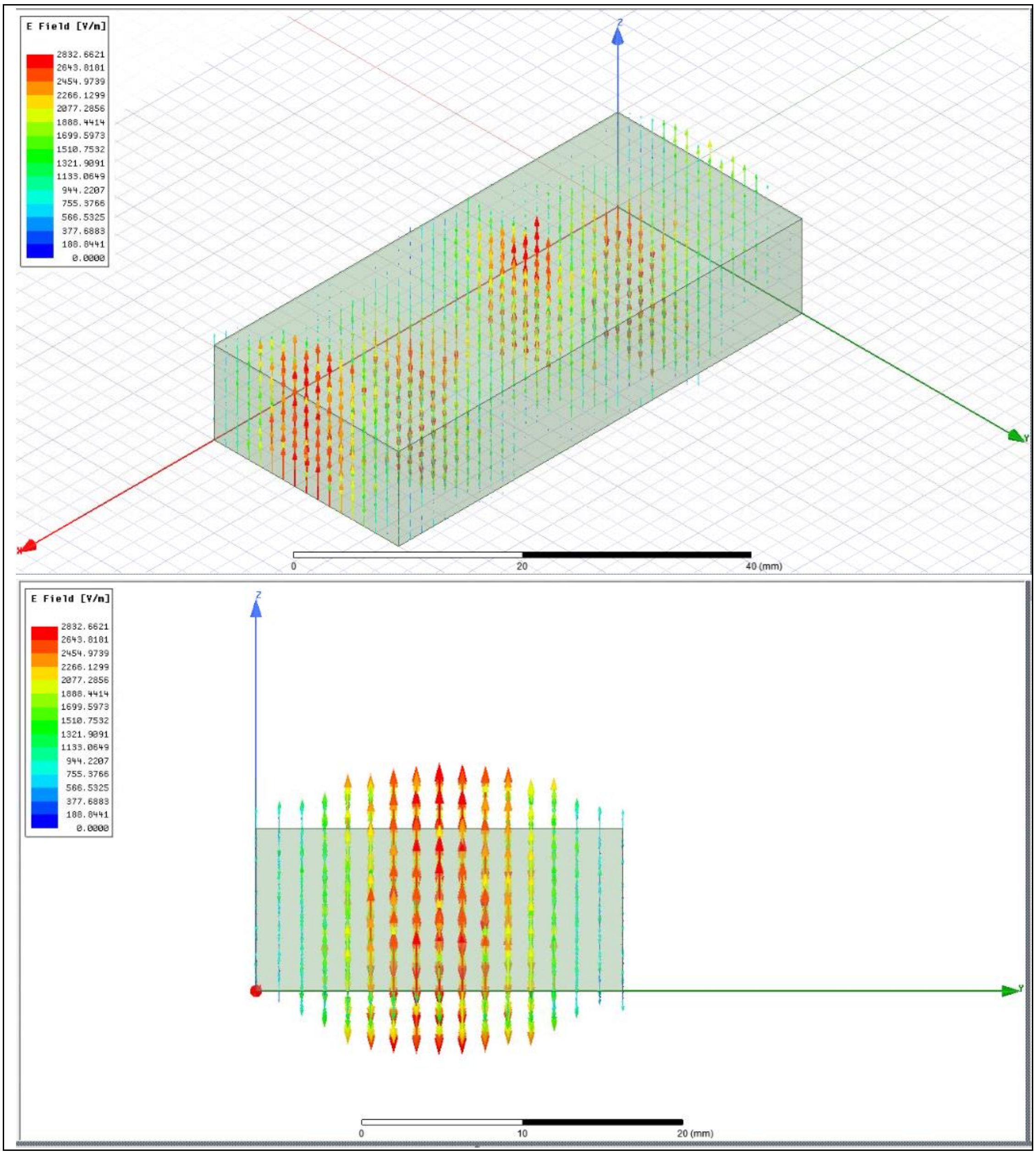




## Electric Field and Magnetic field distribution

### TE10:

Center frequency: 13GHZ




E Field [V/m]
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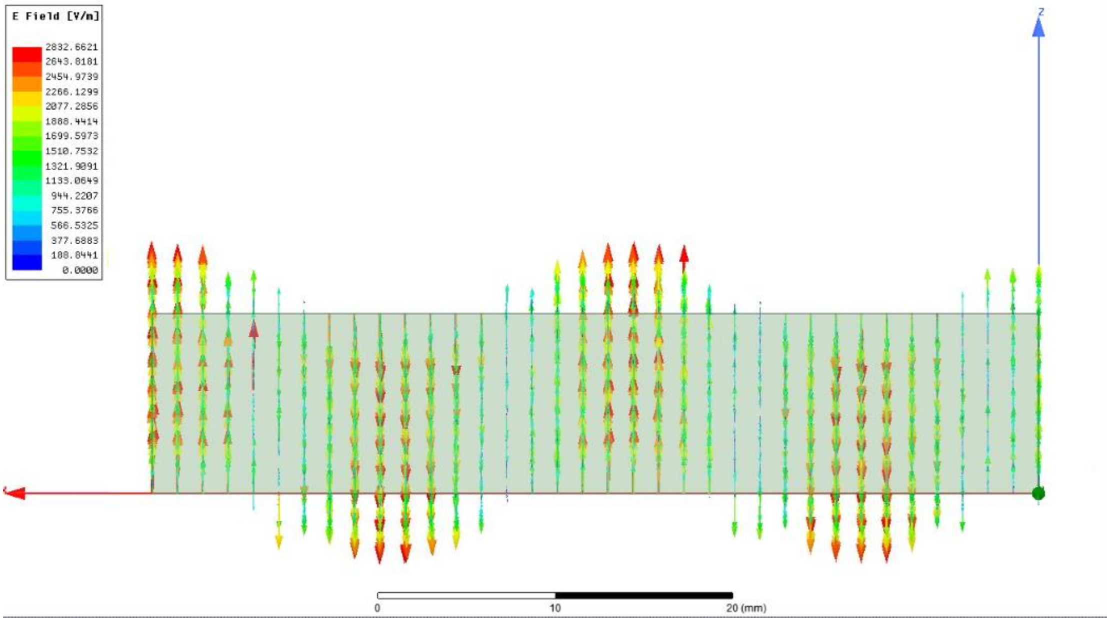
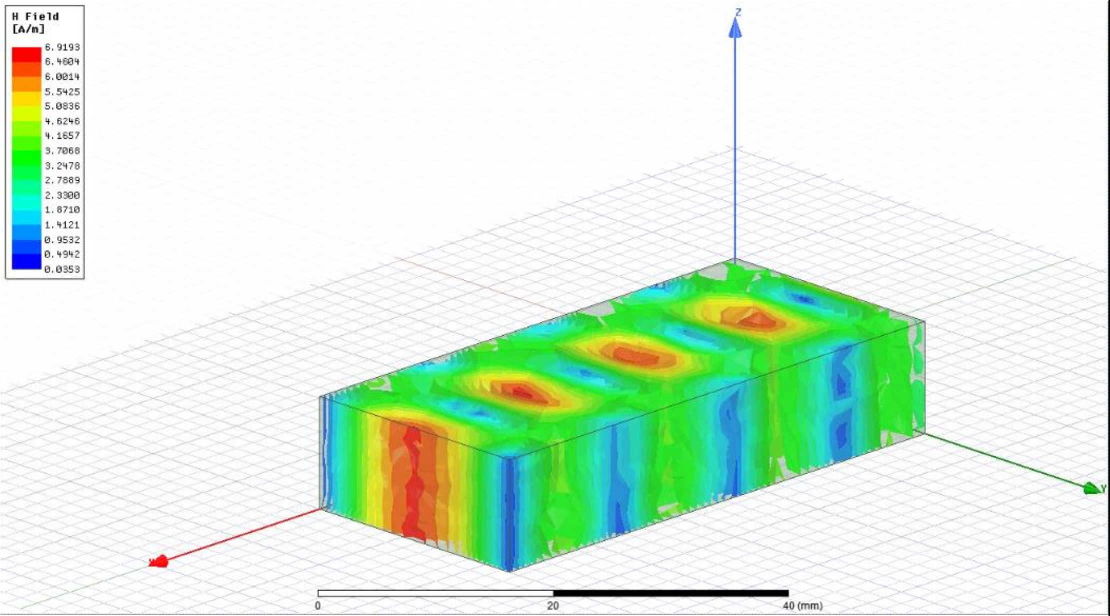
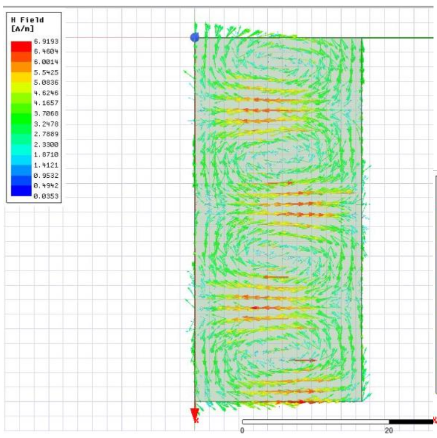
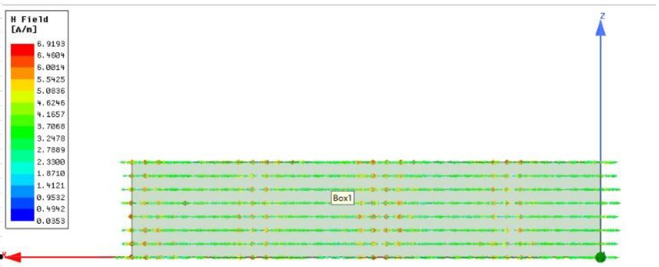
2643.8181
2454.9739
2266.1299
2077.2856
1888.4414
1699.5973
1510.7532
1321.9091
1133.0649
944.2207
755.3766
566.5325
377.6883
188.8441
0.0000
Z
Y
X
0
20
40 (mm)
E Field [V/m]
2832.6621
2643.8181
2454.9739
2266.1299
2077.2856
1888.4414
1699.5973
1510.7532
1321.9091
1133.0649
944.2207
755.3766
566.5325
377.6883
188.8441
0.0000
Z
Y
0
10
20 (mm)



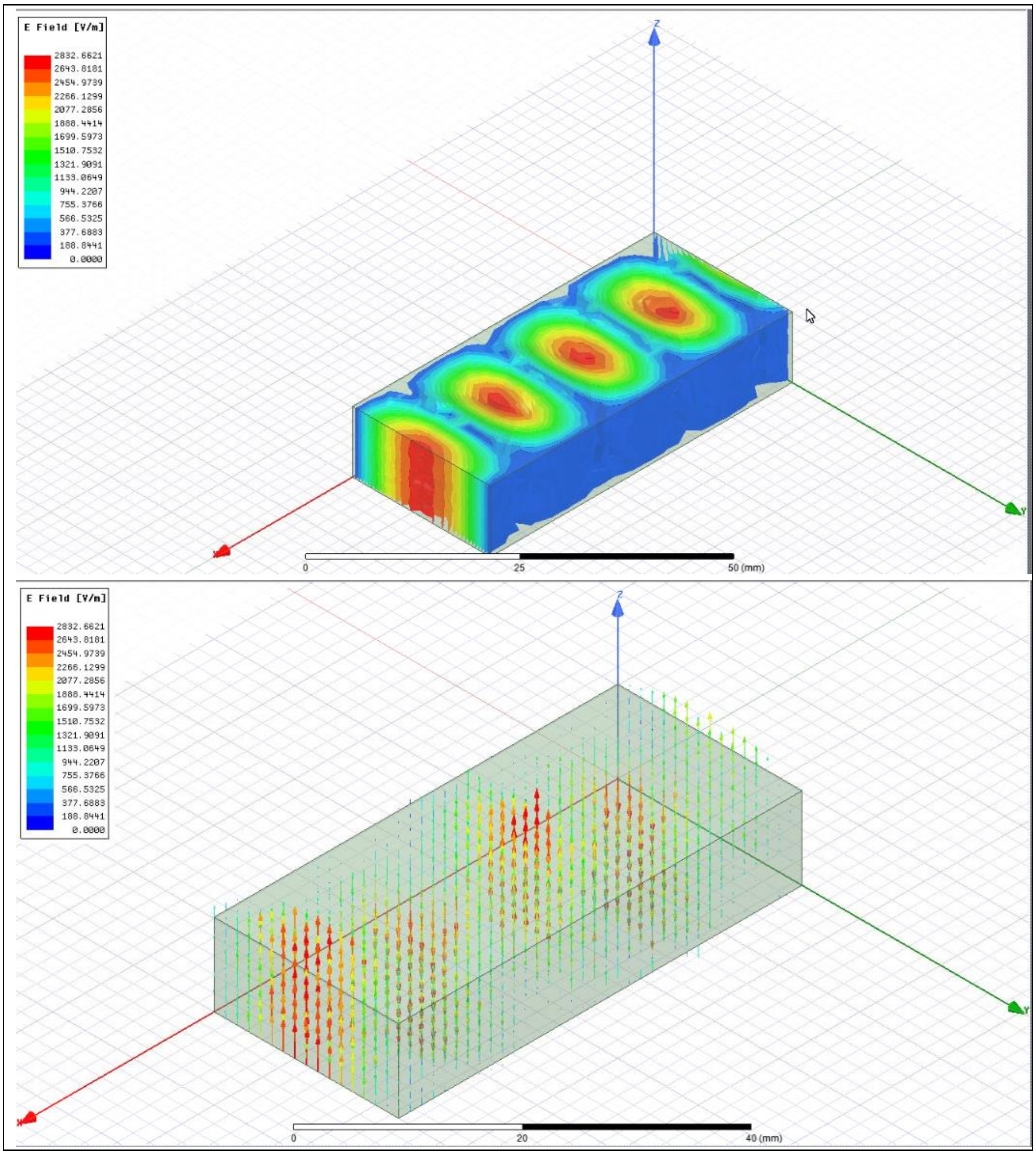

H field:




Center frequency: 15GHZ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1510.7532
1321.9091
1133.0649
944.2207
755.3766
566.5325
377.6883
188.8441
0.0000
Z
Y
X
0
25
50 (mm)
E Field [V/m]
2832.6621
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1133.0649
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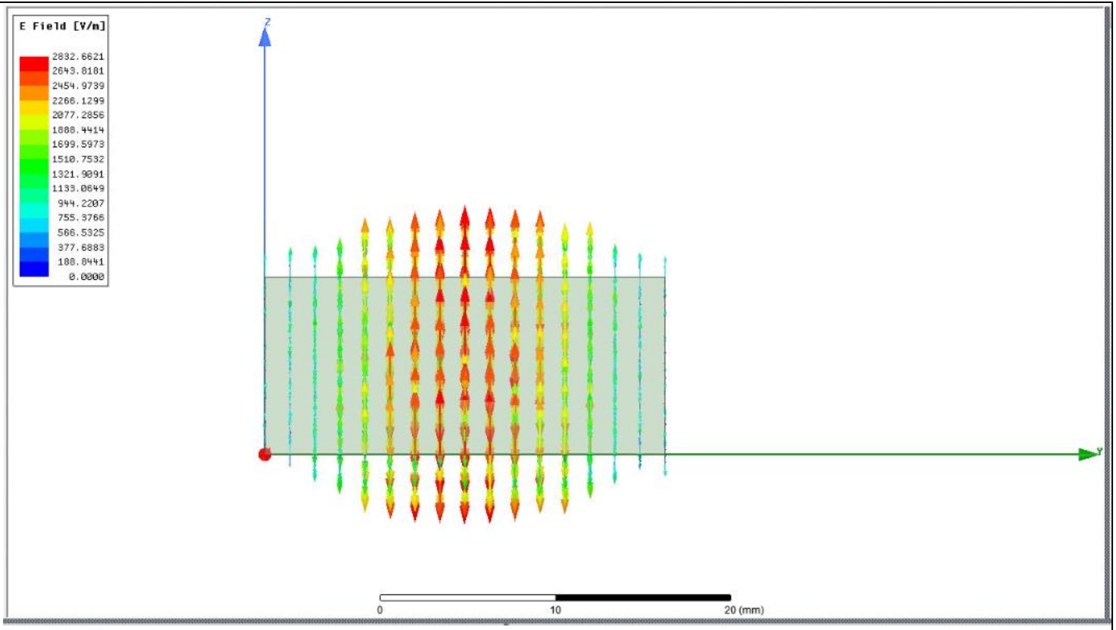
188.8441
0.0000
Z
Y
X
0
20
40 (mm)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755.3766
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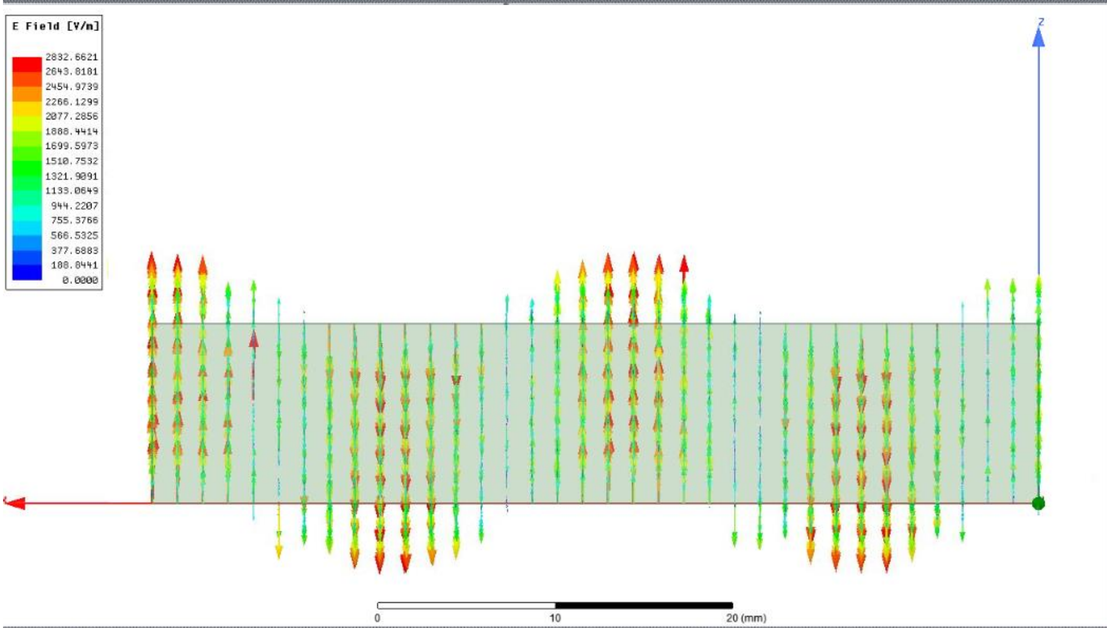
377.6883
188.8441
0.0000
z
y
0
10
20 (mm)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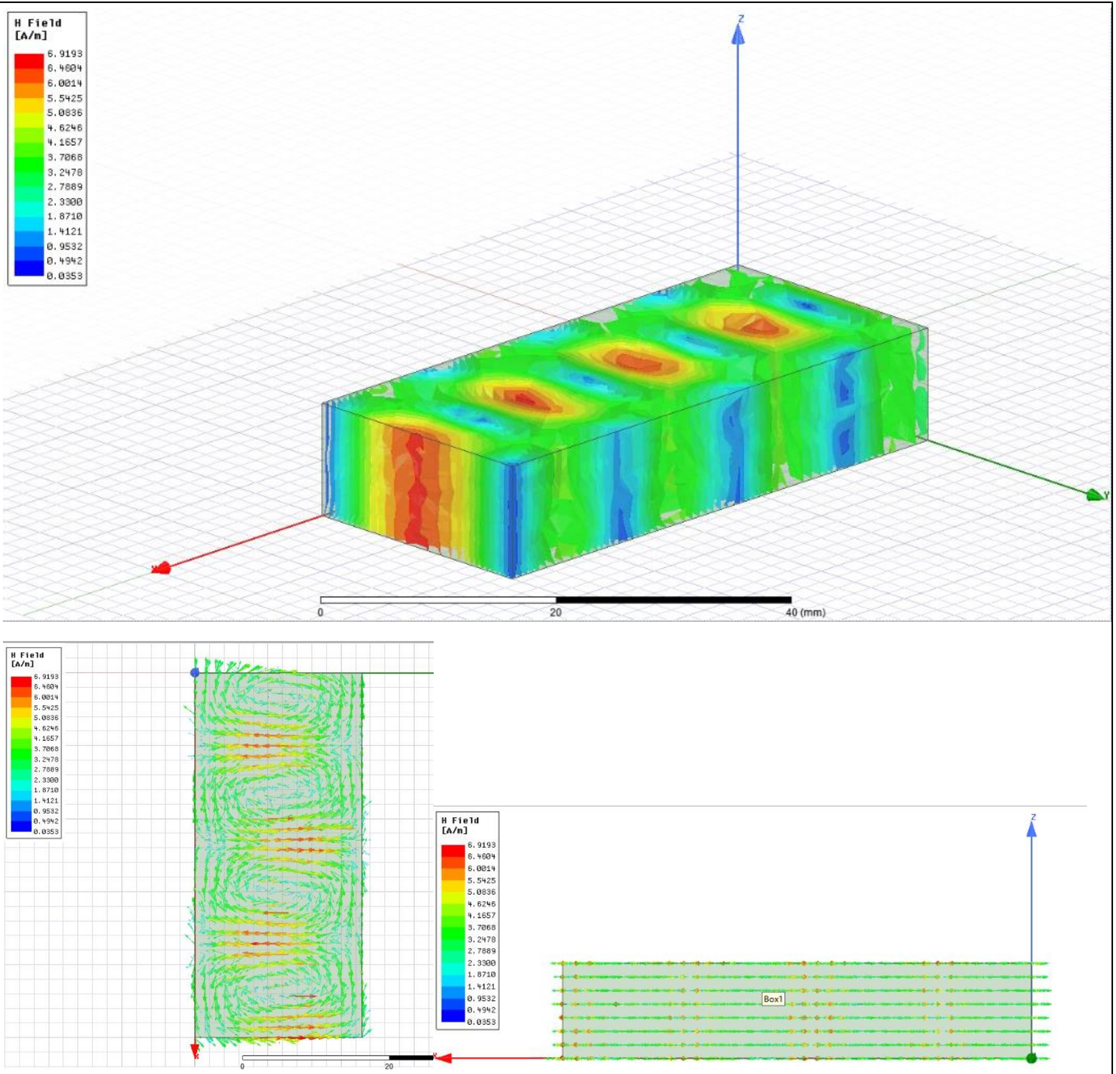
1699.5973
1510.7532
1321.9091
1133.0649
944.2207
755.3766
566.5325
377.6883
188.8441
0.0000
z
0
10
20 (mm)

H field:

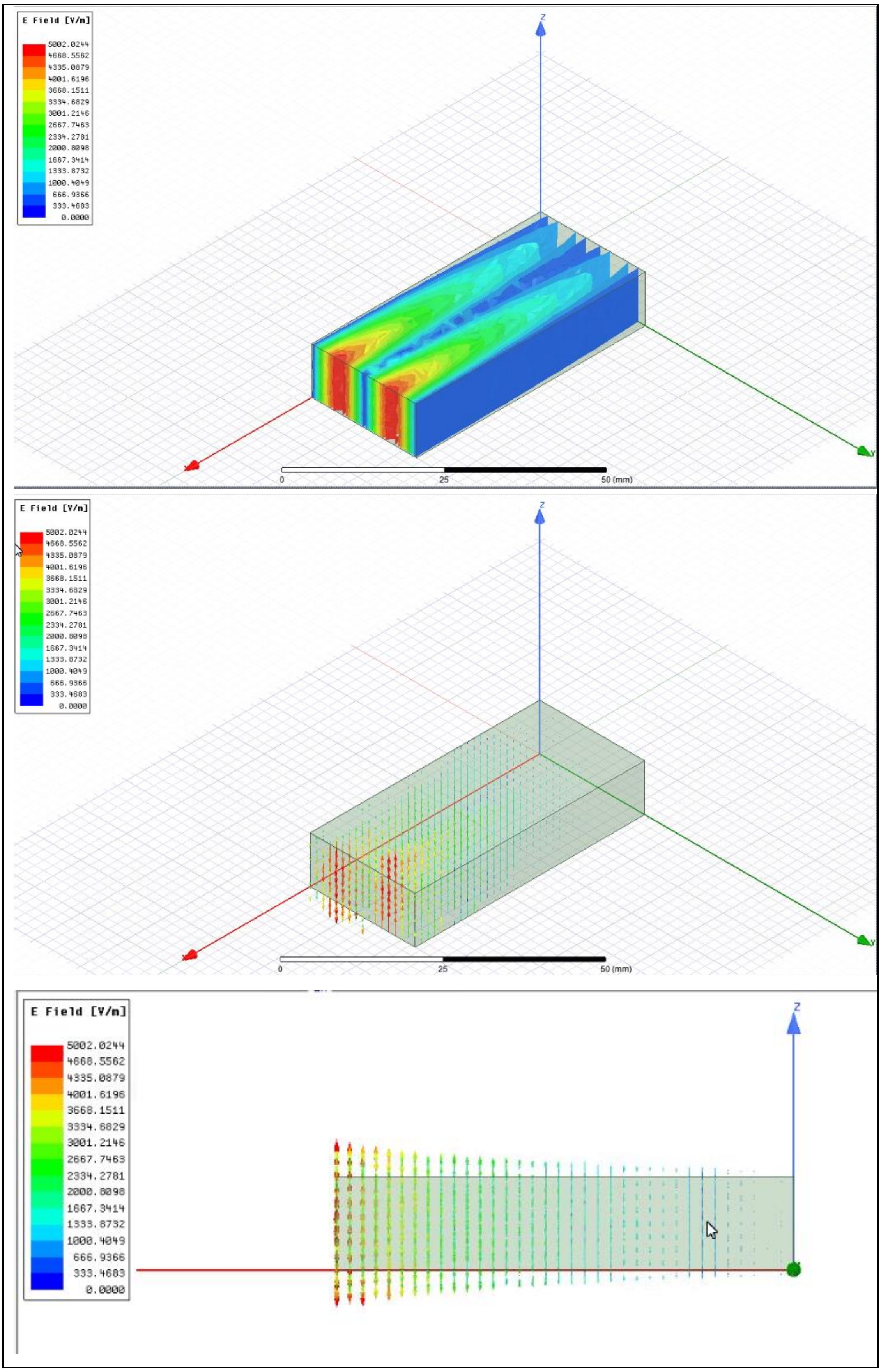



**Analysis:**

The figure above illustrates the electric and magnetic field distribution of the TE10 mode, which aligns with the theoretical formulas introduced in the introduction. Specifically, the agreement is achieved by substituting m=1 and n=0 into the equations. Additionally, it can be observed that the distribution patterns at the center frequencies of 13 GHz and 15 GHz are identical. This is because the cutoff frequency of the TE10 mode is 6.557 GHz, and both 13 GHz and 15 GHz center frequencies are above the cutoff frequency, indicating that they are not affected by the cutoff.

**TE20:**

Center frequency: 13GHZ


E Field [V/m]
5002.0244
4668.5562
4335.0879
4001.6196
3668.1511
3334.6829
3001.2146
2667.7463
2334.2781
2000.8098
1667.3414
1333.8732
1000.4049
666.9366
333.4683
0.0000
Z
0
25
50 (mm)
E Field [V/m]
5002.0244
4668.5562
4335.0879
4001.6196
3668.1511
3334.6829
3001.2146
2667.7463
2334.2781
2000.8098
1667.3414
1333.8732
1000.4049
666.9366
333.4683
0.0000
Z
0
25
50 (mm)
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3001.2146
2667.7463
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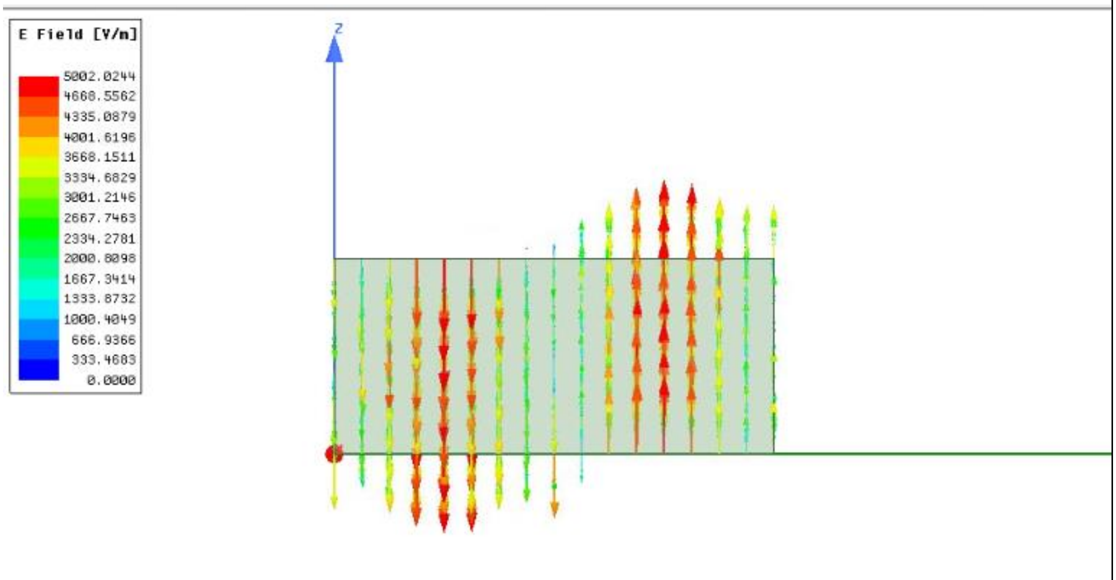
1333.8732
1000.4049
666.9366
333.4683
0.0000
Z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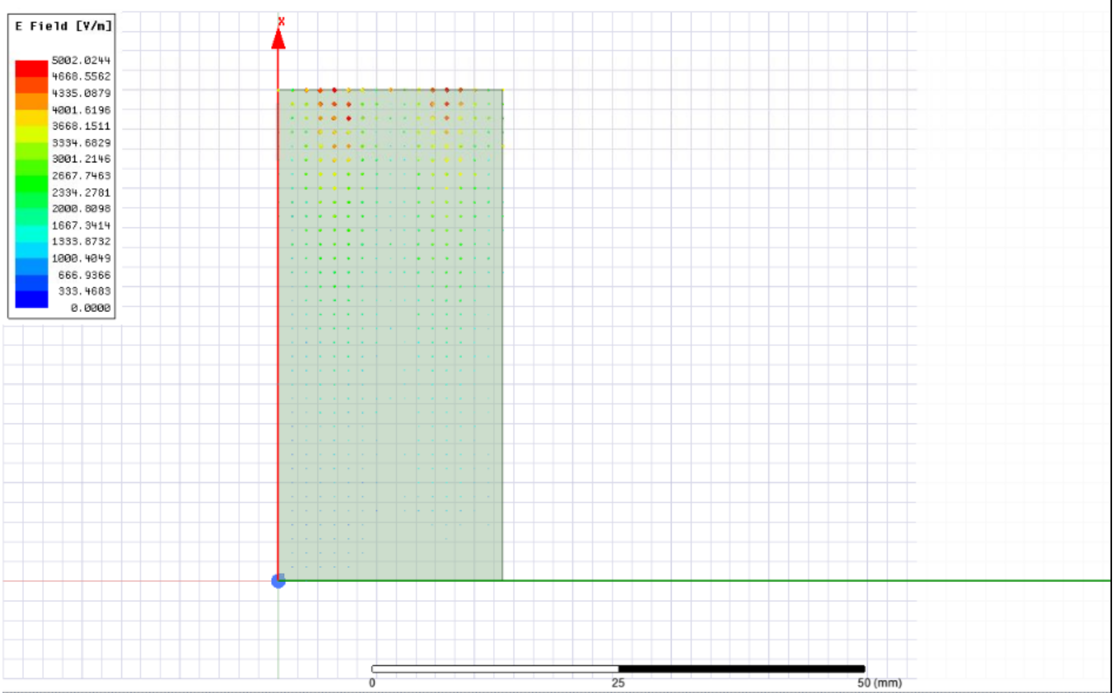
4335.0879
4001.6196
3668.1511
3334.6829
3001.2146
2667.7463
2334.2781
2000.8098
1667.3414
1333.8732
1000.4049
666.9366
333.4683
0.0000
Z


E Field [V/m]
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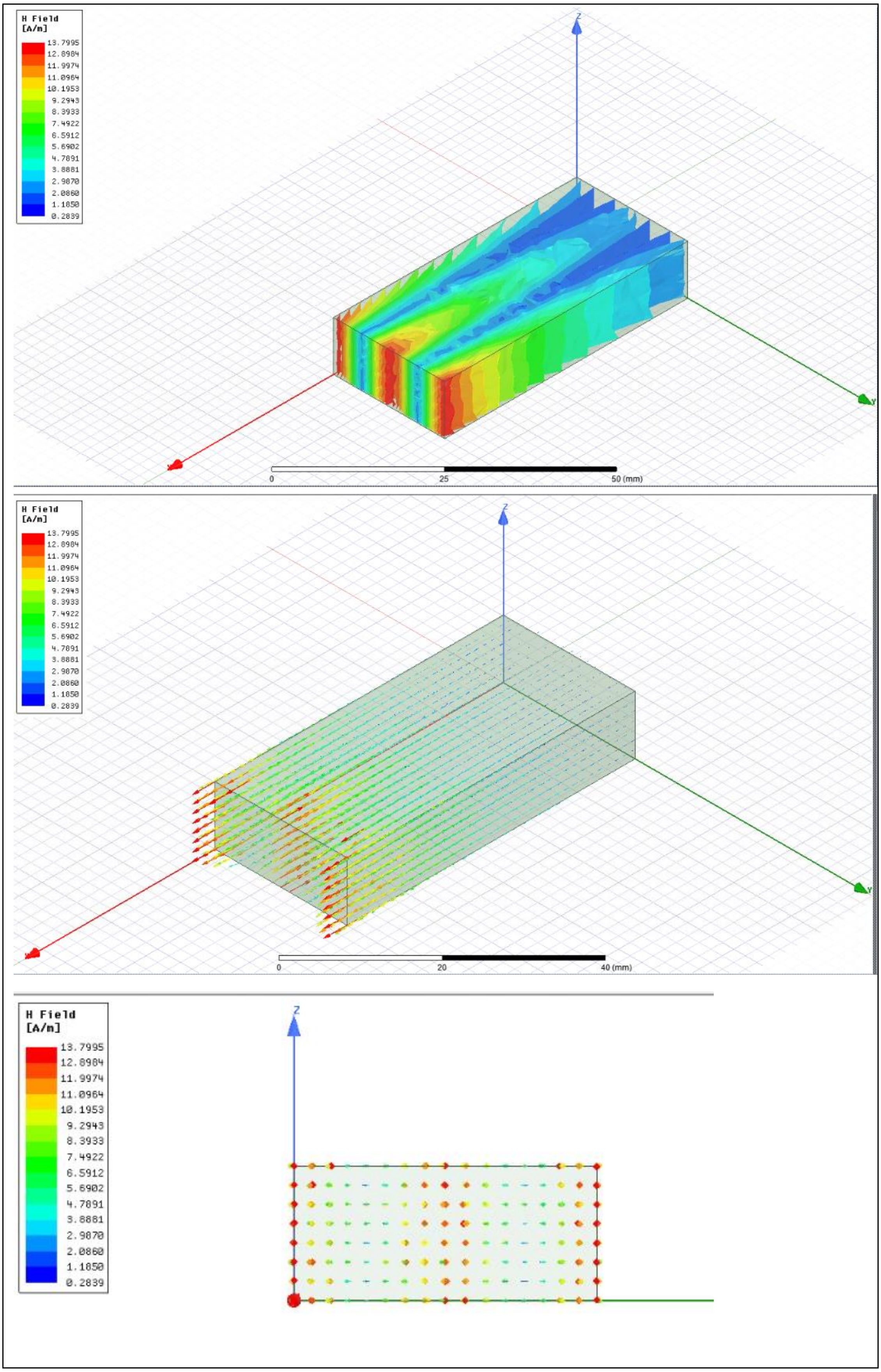
4668.5562
4335.0879
4001.6196
3668.1511
3334.6829
3001.2146
2667.7463
2334.2781
2000.8098
1667.3414
1333.8732
1000.4049
666.9366
333.4683
0.0000
X
0
25
50 (mm)

H field:


H Field
[A/m]
13.7995
12.8984
11.9974
11.0964
10.1953
9.2943
8.3933
7.4922
6.5912
5.6902
4.7891
3.8881
2.9870
2.0860
1.1850
0.2839
z
y
x
0
25
50 (mm)
H Field
[A/m]
13.7995
12.8984
11.9974
11.0964
10.1953
9.2943
8.3933
7.4922
6.5912
5.6902
4.7891
3.8881
2.9870
2.0860
1.1850
0.2839
z
y
0
20
40 (mm)
H Field
[A/m]
13.7995
12.8984
11.9974
11.0964
10.1953
9.2943
8.3933
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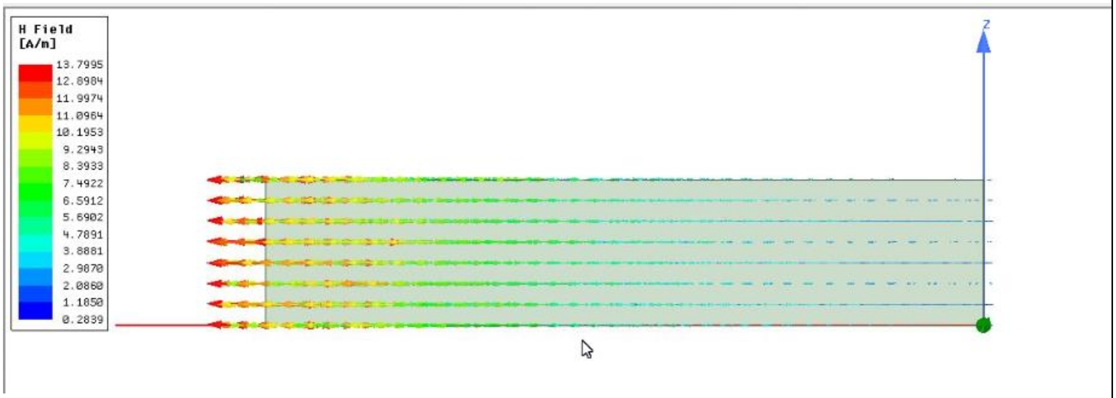
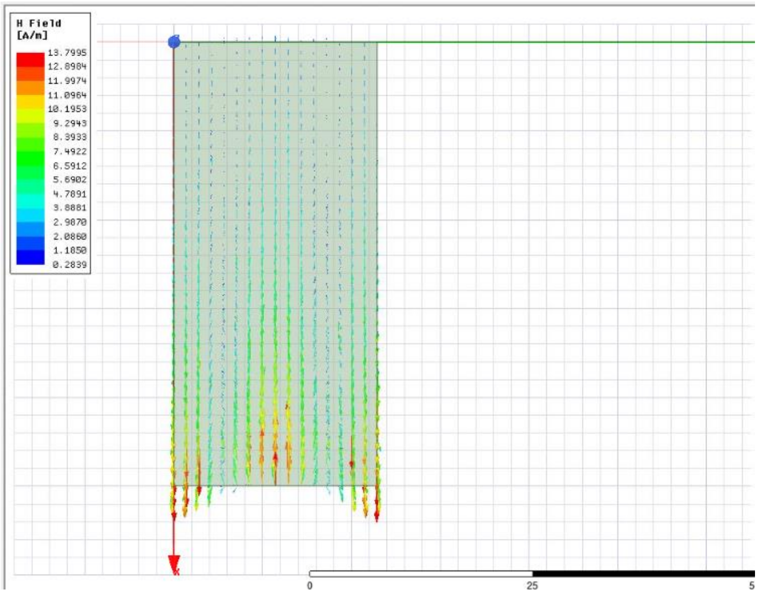
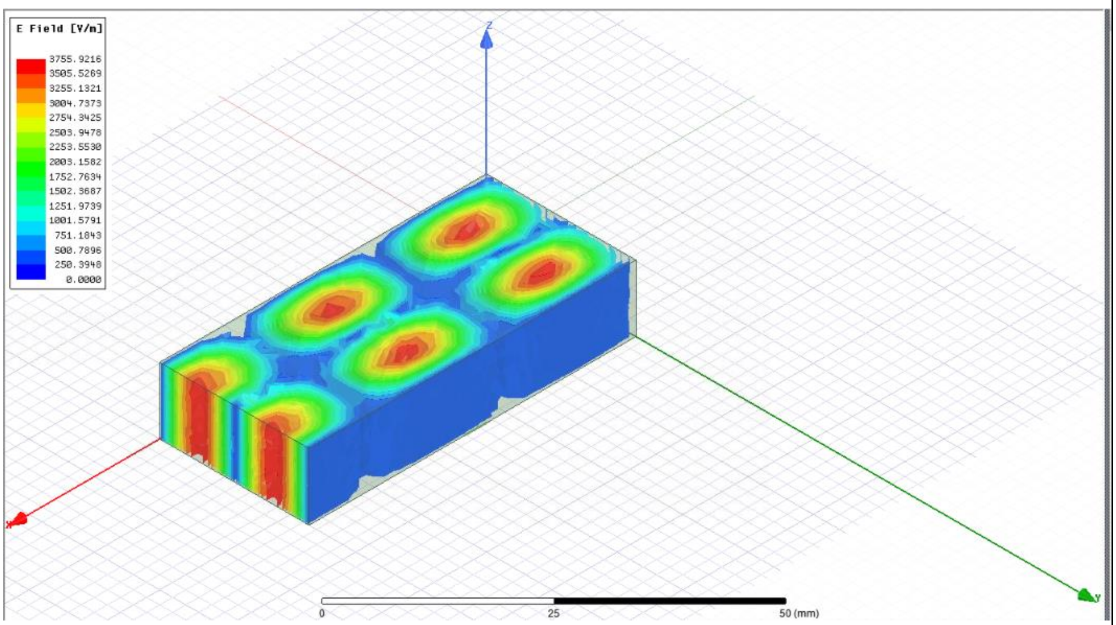
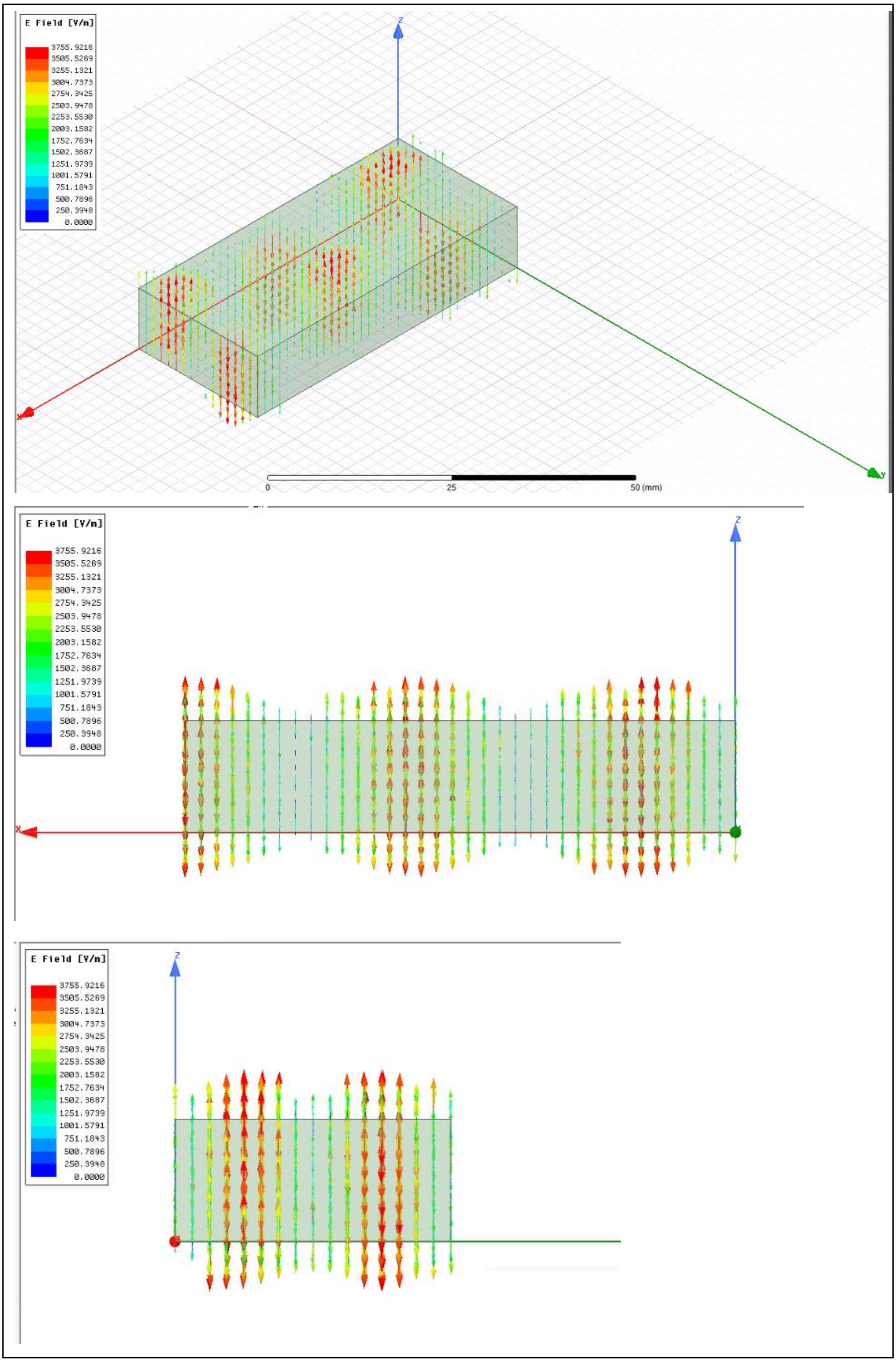
z




Center frequency: 15GHZ

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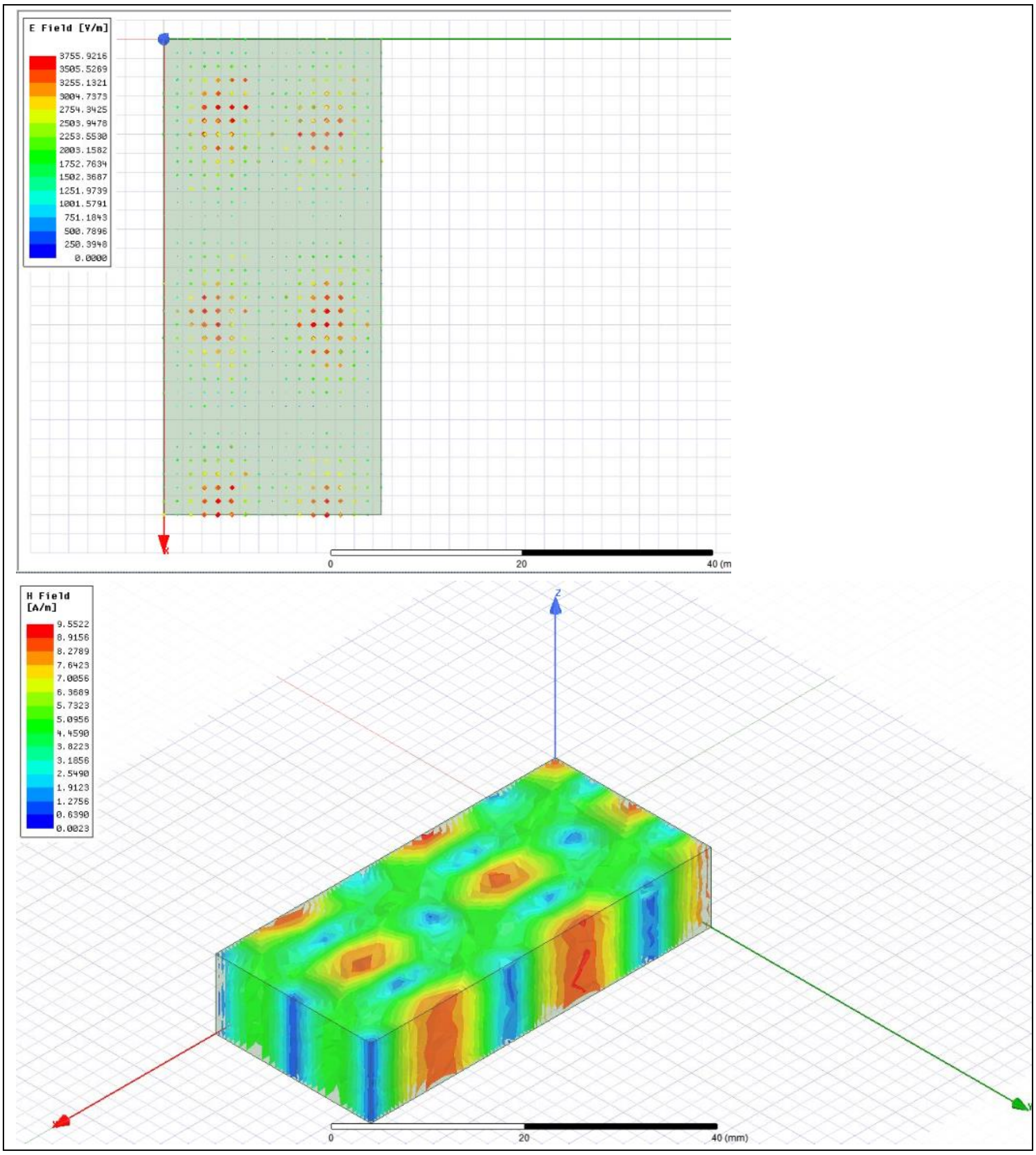
3505.5269
3255.1321
3004.7373
2754.3425
2503.9478
2253.5530
2003.1582
1752.7634
1502.3687
1251.9739
1001.5791
751.1843
500.7896
250.3948
0.0000
z
x
y
0
25
50 (mm)


E Field [V/m]
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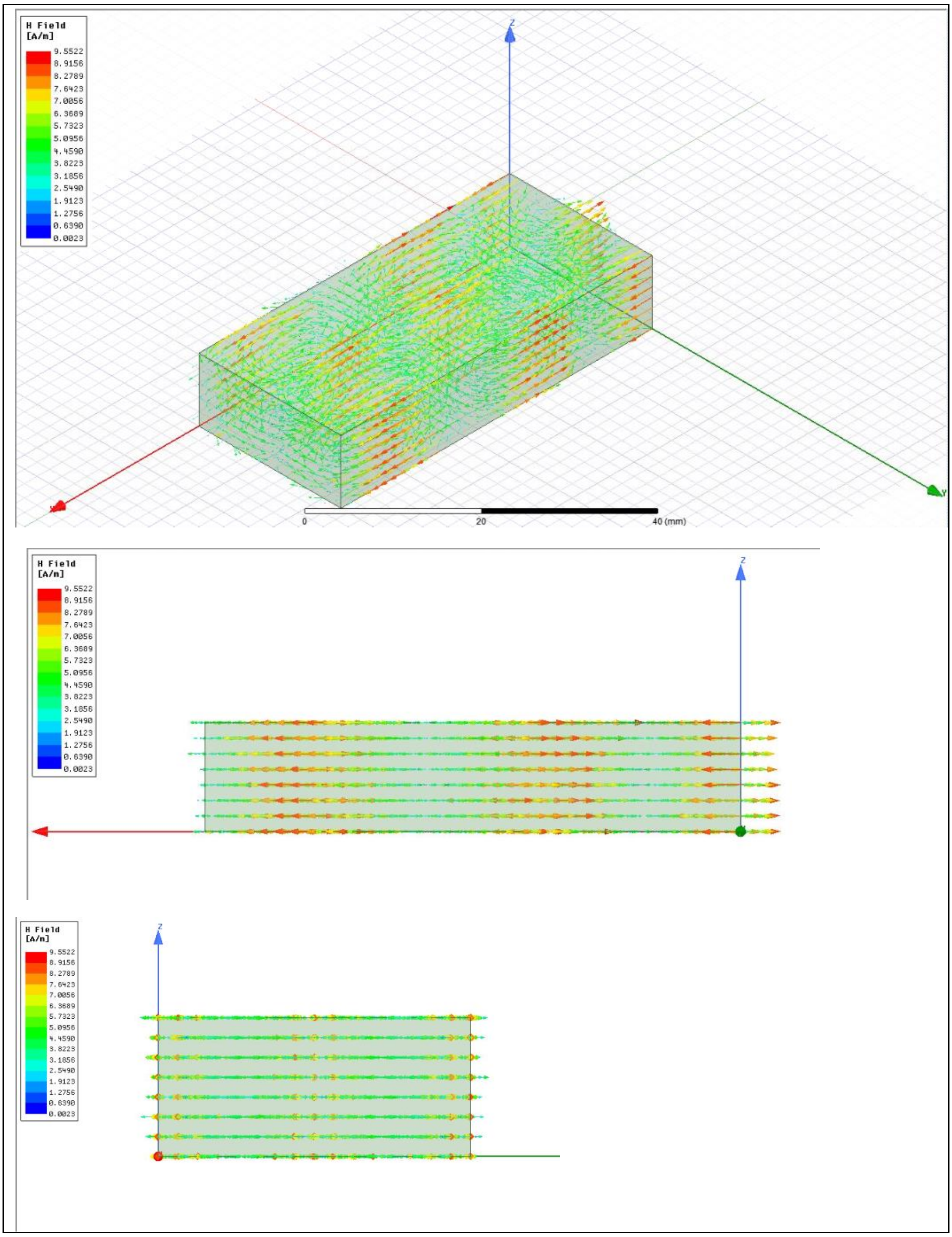
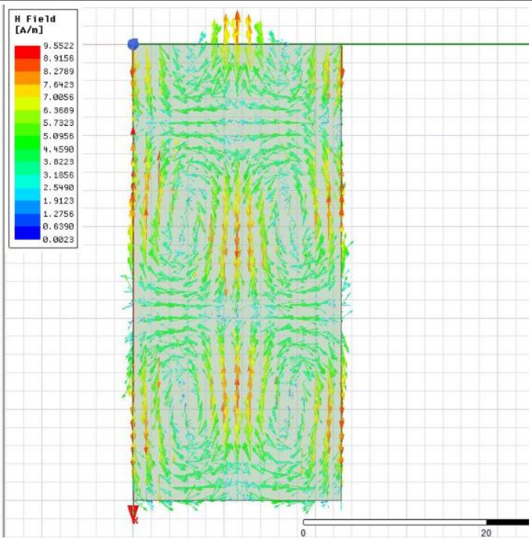
3505.5269
3255.1321
3004.7373
2754.3425
2503.9478
2253.5530
2003.1582
1752.7634
1502.3687
1251.9739
1001.5791
751.1843
500.7896
250.3948
0.0000
0
20
40 (m
H Field [A/m]
9.5522
8.9156
8.2789
7.6423
7.0056
6.3689
5.7323
5.0956
4.4590
3.8223
3.1856
2.5490
1.9123
1.2756
0.6390
0.0023
0
20
40 (mm)


H Field
[A/m]
9.5522
8.9156
8.2789
7.6423
7.0056
6.3689
5.7323
5.0956
4.4590
3.8223
3.1856
2.5490
1.9123
1.2756
0.6390
0.0023
Z
Y
0
20
40 (mm)

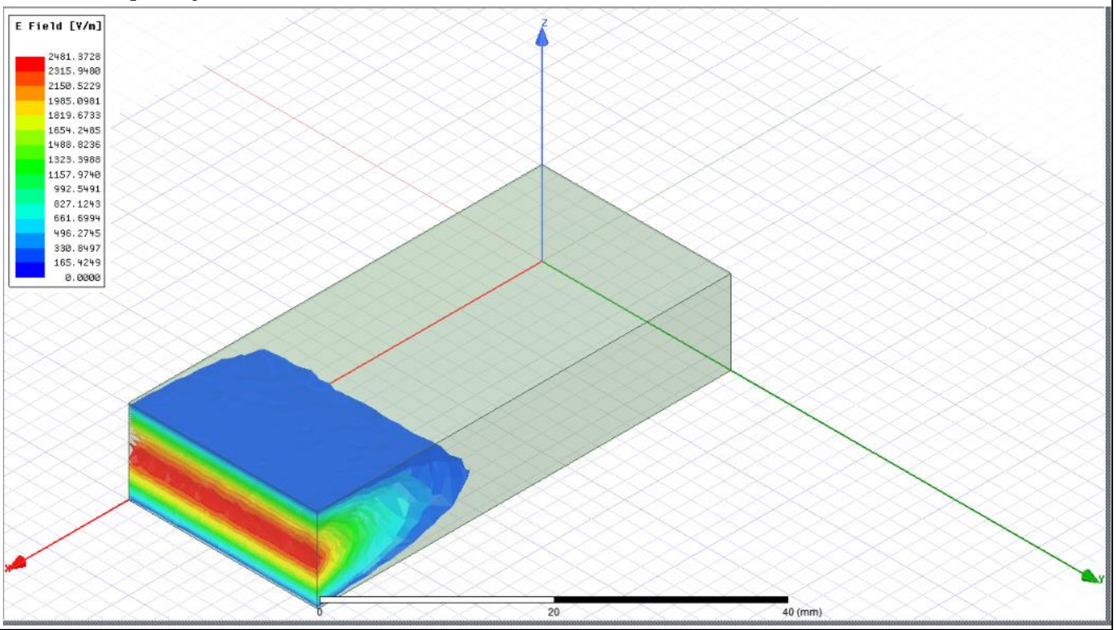


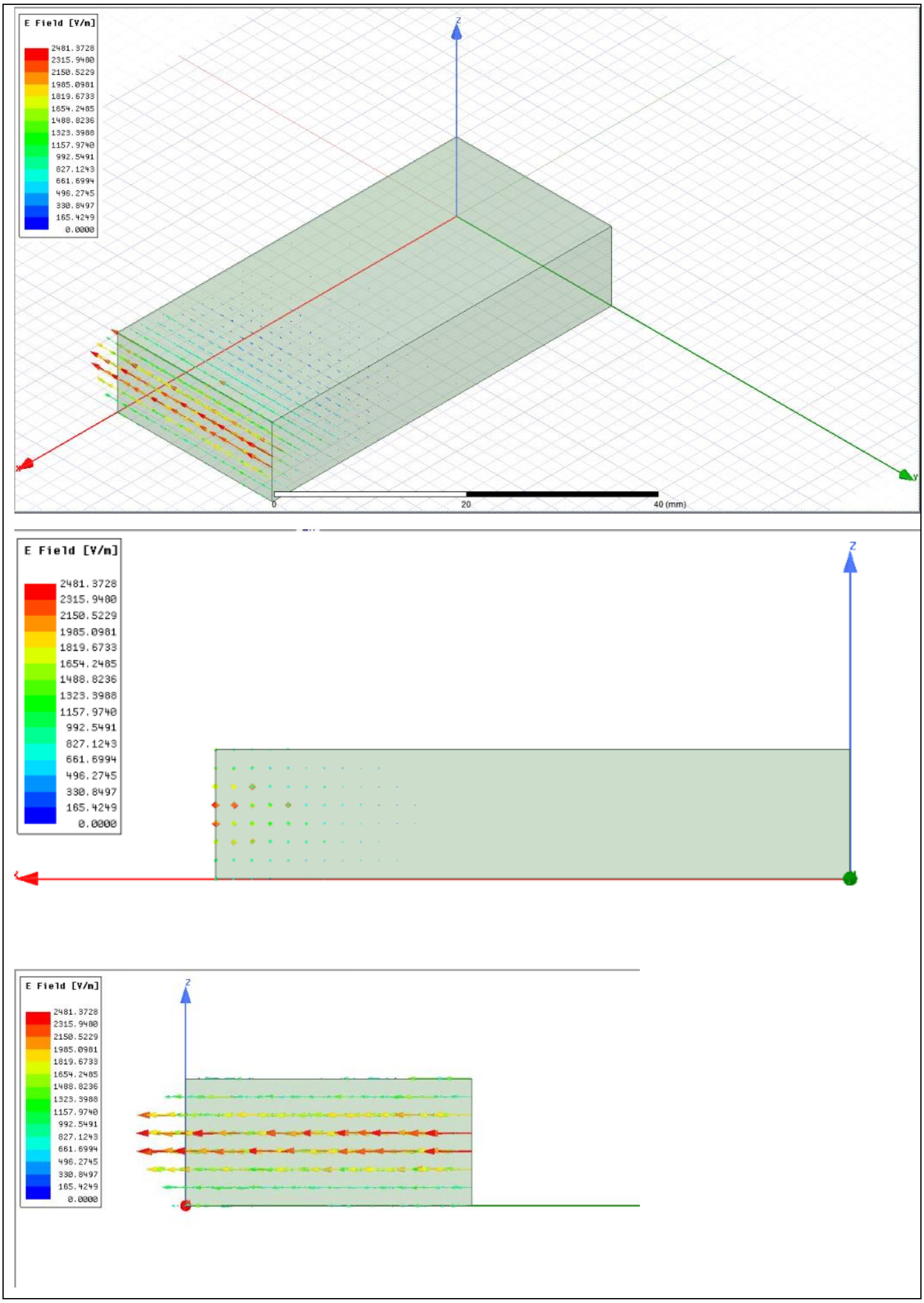

**Analysis:**

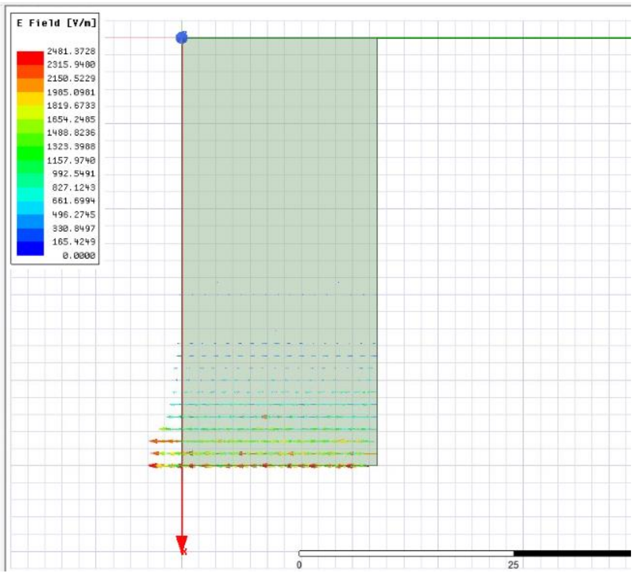
The figure above illustrates the electric and magnetic field distribution of the TE20 mode, which aligns with the theoretical formulas introduced in the introduction. Specifically, the agreement is achieved by substituting m=2 and n=0 into the equations. It can be observed that the distribution patterns at the center frequencies of 13 GHz and 15 GHz are not the same. The distribution pattern at 15 GHz appears normal, while at 13 GHz, it is not. This is because the cutoff frequency of the TE20 mode is 13.114 GHz. The center frequency of 13 GHz is below the cutoff frequency, preventing the normal formation of the TE20 mode's electromagnetic field distribution. Only at 15 GHz can the TE20 mode be displayed correctly.

**TE01:**

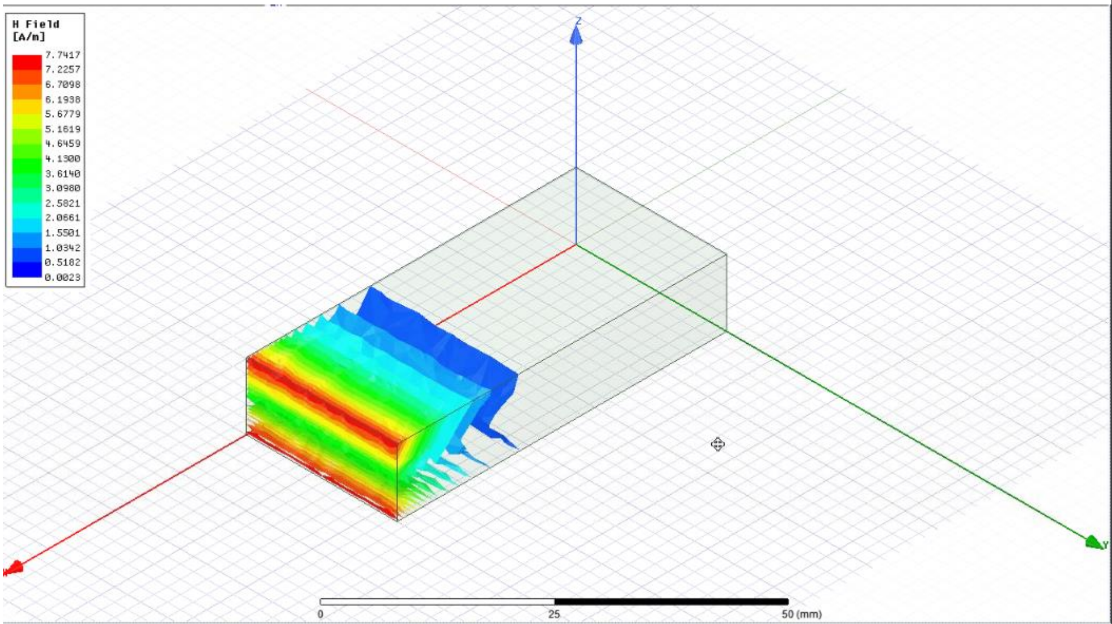
Center frequency: 13GHZ

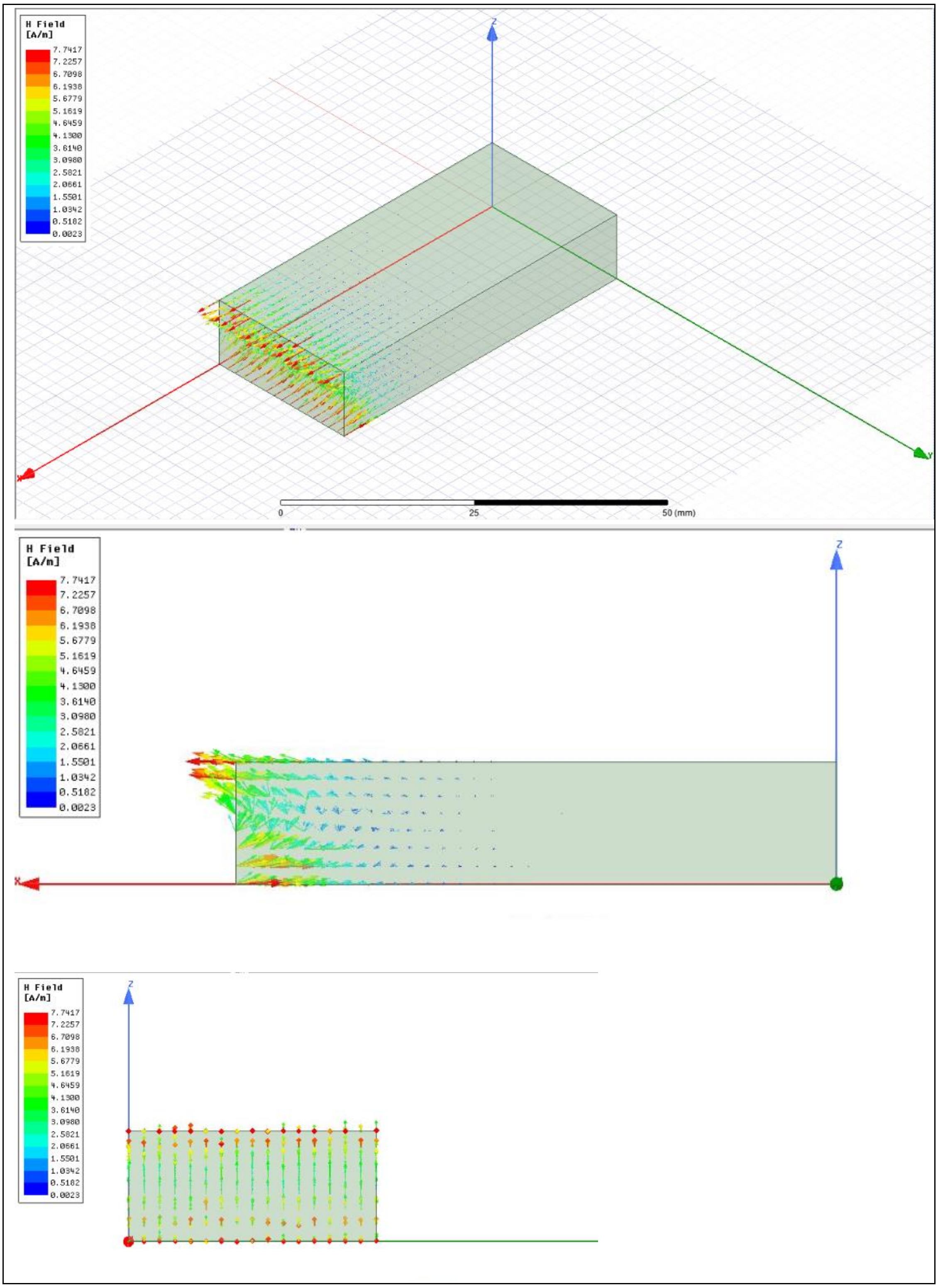



E Field [V/m]
2481.3728
2315.9480
2150.5229
1985.0981
1819.6733
1654.2485
1488.8236
1323.3988
1157.9740
992.5491
827.1243
661.6994
496.2745
330.8497
165.4249
0.0000
Z
X
Y
0
20
40 (mm)
E Field [V/m]
2481.3728
2315.9480
2150.5229
1985.0981
1819.6733
1654.2485
1488.8236
1323.3988
1157.9740
992.5491
827.1243
661.6994
496.2745
330.8497
165.4249
0.0000
Z
E Field [V/m]
2481.3728
2315.9480
2150.5229
1985.0981
1819.6733
1654.2485
1488.8236
1323.3988
1157.9740
992.5491
827.1243
661.6994
496.2745
330.8497
165.4249
0.0000
Z

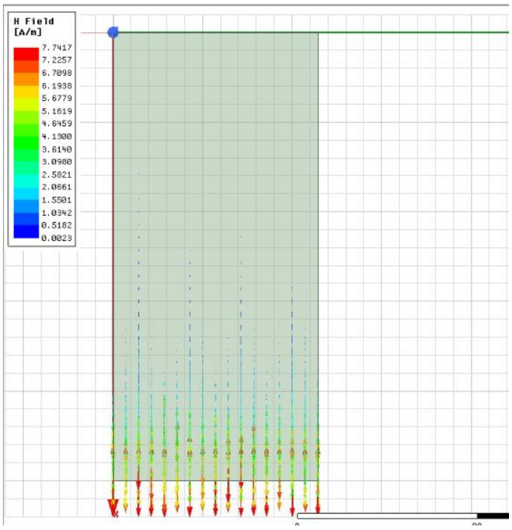

E Field [V/m]
2481.3728
2315.9480
2150.5229
1985.0981
1819.6733
1654.2485
1488.8236
1323.3988
1157.9740
992.5491
827.1243
661.6994
496.2745
330.8497
165.4249
0.0000
0
25

H field:

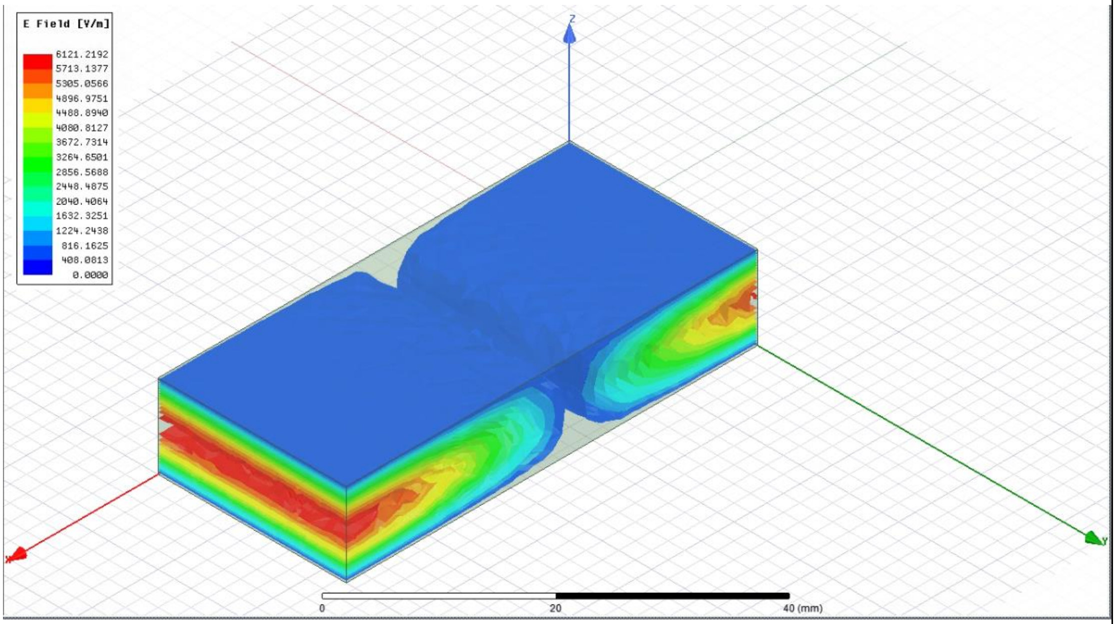

H Field [A/m]
7.7417
7.2257
6.7098
6.1938
5.6779
5.1619
4.6459
4.1300
3.6140
3.0980
2.5821
2.0661
1.5501
1.0342
0.5182
0.0023
Z
Y
0
25
50 (mm)

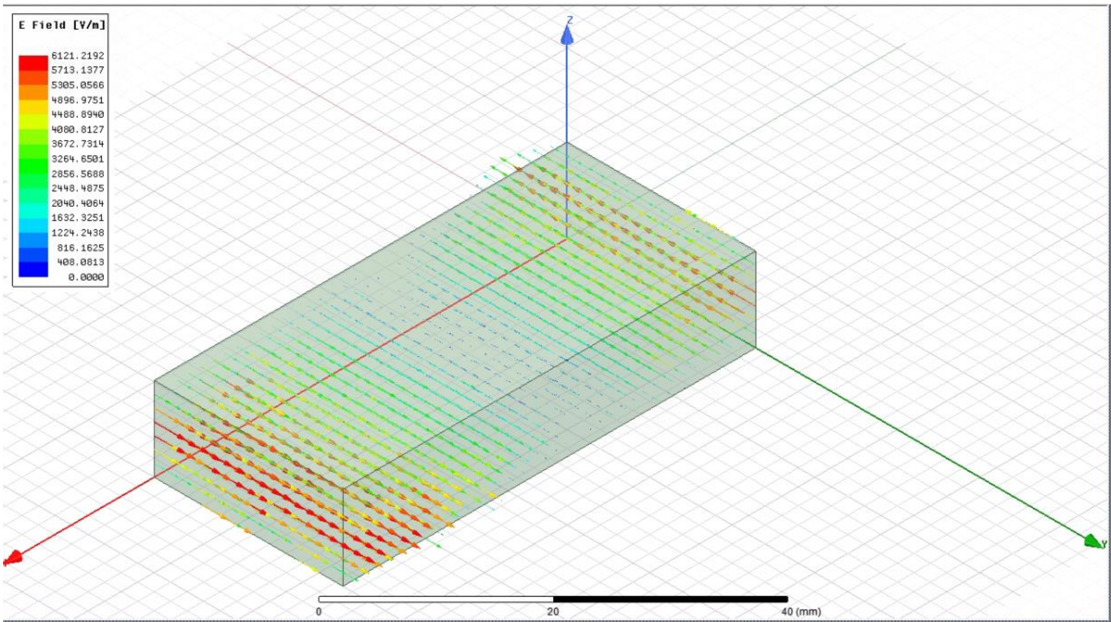


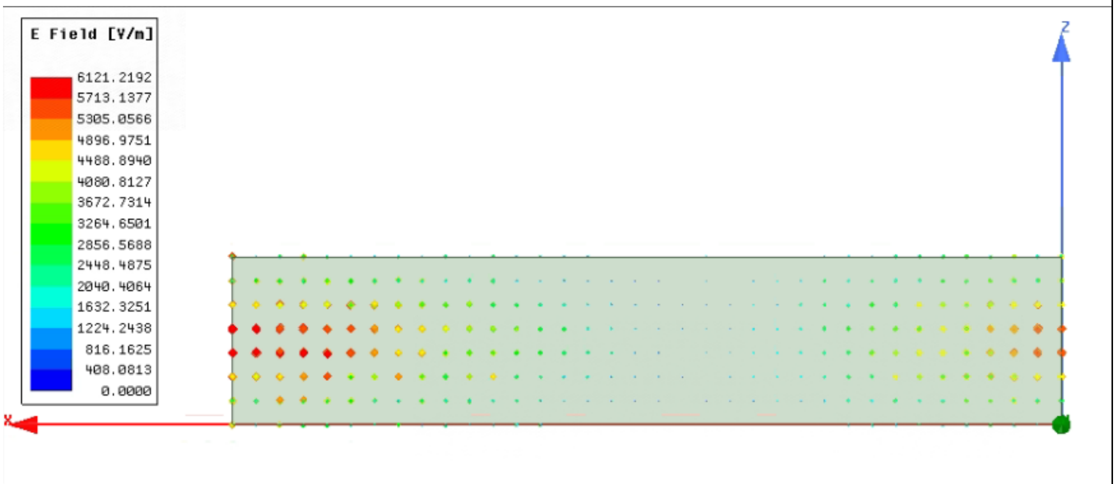
H Field [A/m]
7.7417
7.2257
6.7098
6.1938
5.6779
5.1619
4.6459
4.1300
3.6140
3.0980
2.5821
2.0661
1.5501
1.0342
0.5182
0.0023
0
25
50 (mm)

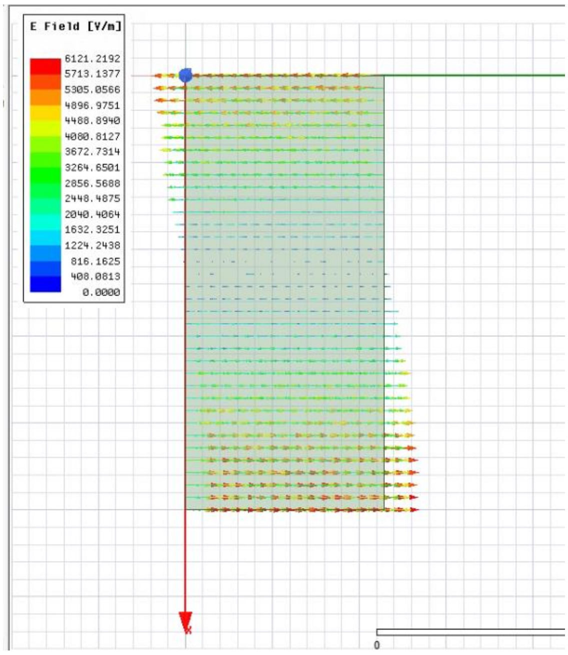


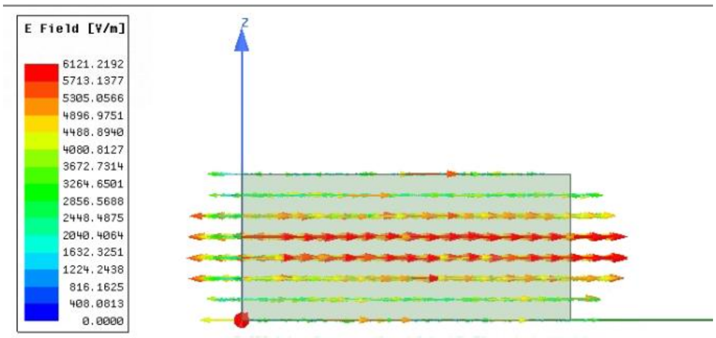

Center frequency: 15GHZ



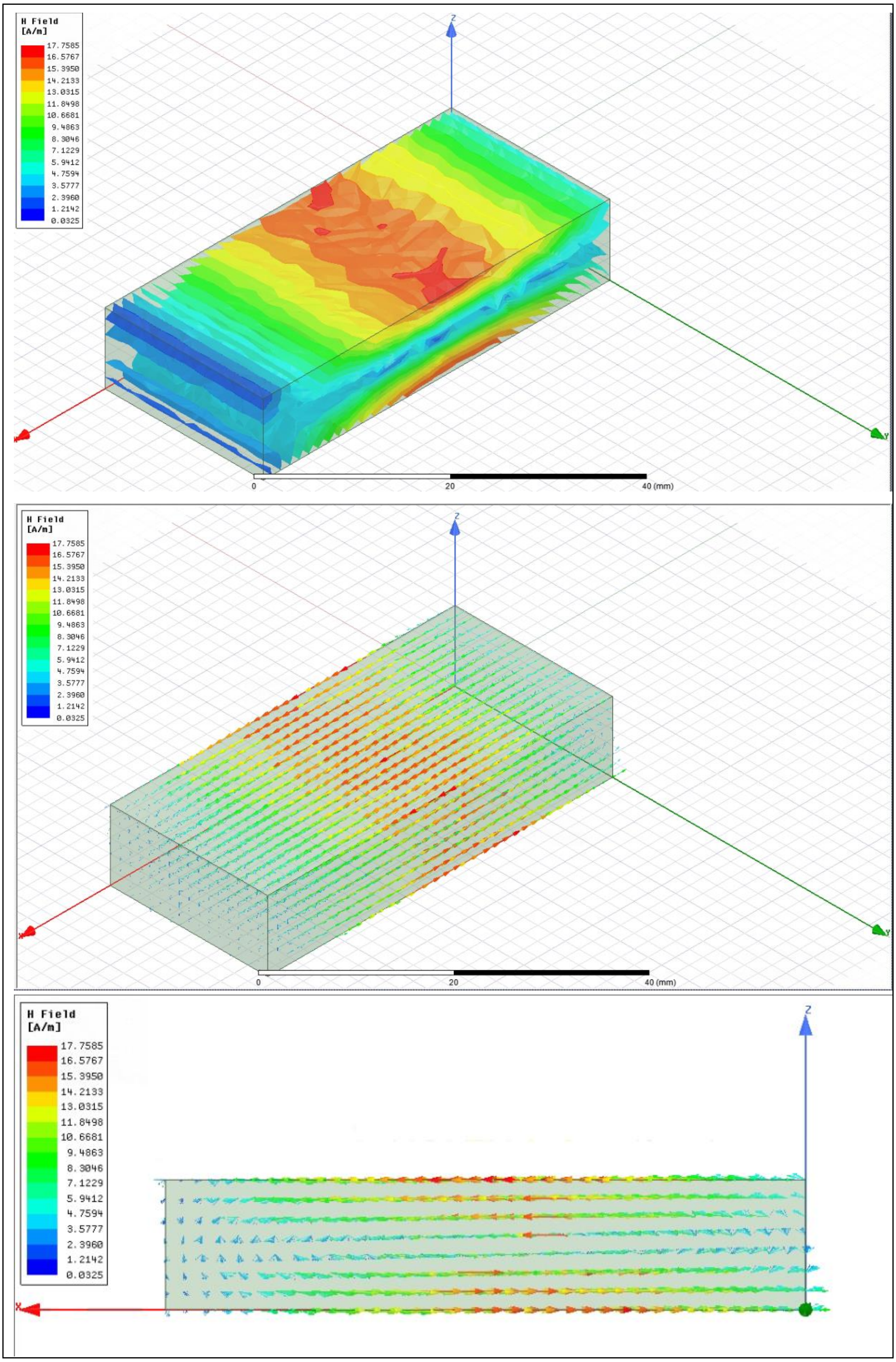



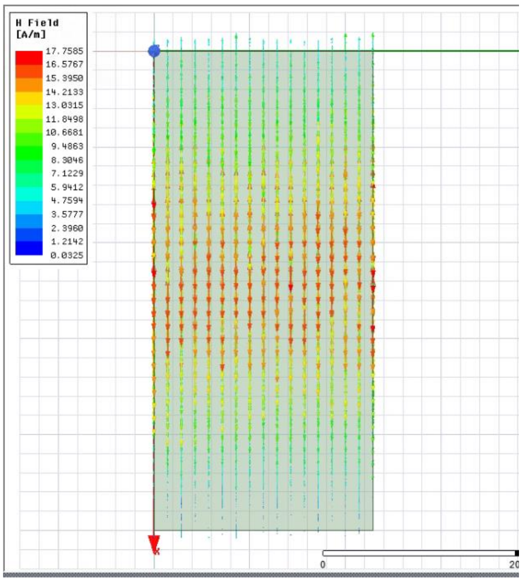

E Field [V/m]
6121.2192
5713.1377
5305.0566
4896.9751
4488.8940
4080.8127
3672.7314
3264.6501
2856.5688
2448.4875
2040.4064
1632.3251
1224.2438
816.1625
408.0813
0.0000
Z
X

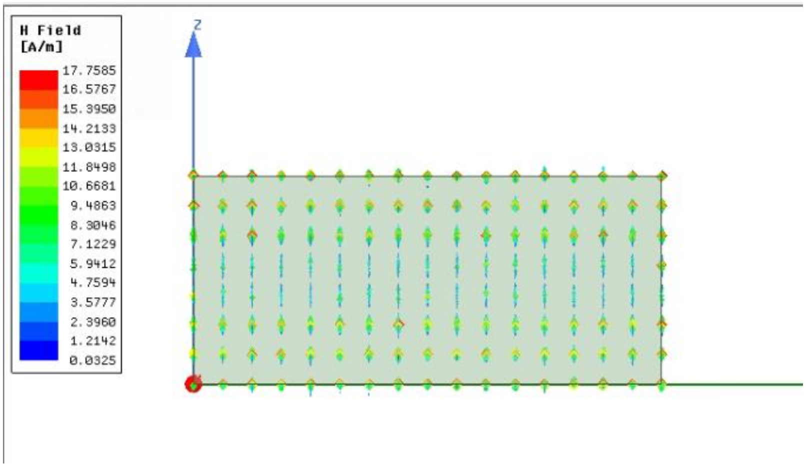

E Field [V/m]
6121.2192
5713.1377
5305.0566
4896.9751
4488.8940
4080.8127
3672.7314
3264.6501
2856.5688
2448.4875
2040.4064
1632.3251
1224.2438
816.1625
408.0813
0.0000
X
0


E Field [V/m]
6121.2192
5713.1377
5305.0566
4896.9751
4488.8940
4080.8127
3672.7314
3264.6501
2856.5688
2448.4875
2040.4064
1632.3251
1224.2438
816.1625
408.0813
0.0000
Z

H field:


H Field
[A/m]
17.7585
16.5767
15.3950
14.2133
13.0315
11.8498
10.6681
9.4863
8.3046
7.1229
5.9412
4.7594
3.5777
2.3960
1.2142
0.0325
Z
X
Y
0
20
40 (mm)
H Field
[A/m]
17.7585
16.5767
15.3950
14.2133
13.0315
11.8498
10.6681
9.4863
8.3046
7.1229
5.9412
4.7594
3.5777
2.3960
1.2142
0.0325
Z
X
Y
0
20
40 (mm)
H Field
[A/m]
17.7585
16.5767
15.3950
14.2133
13.0315
11.8498
10.6681
9.4863
8.3046
7.1229
5.9412
4.7594
3.5777
2.3960
1.2142
0.0325
Z
X



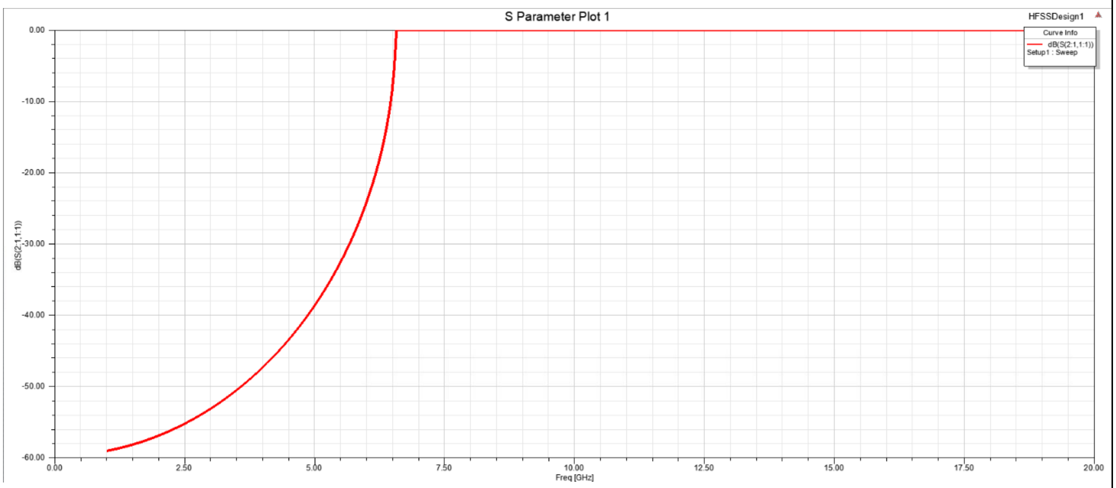

**Analysis:**

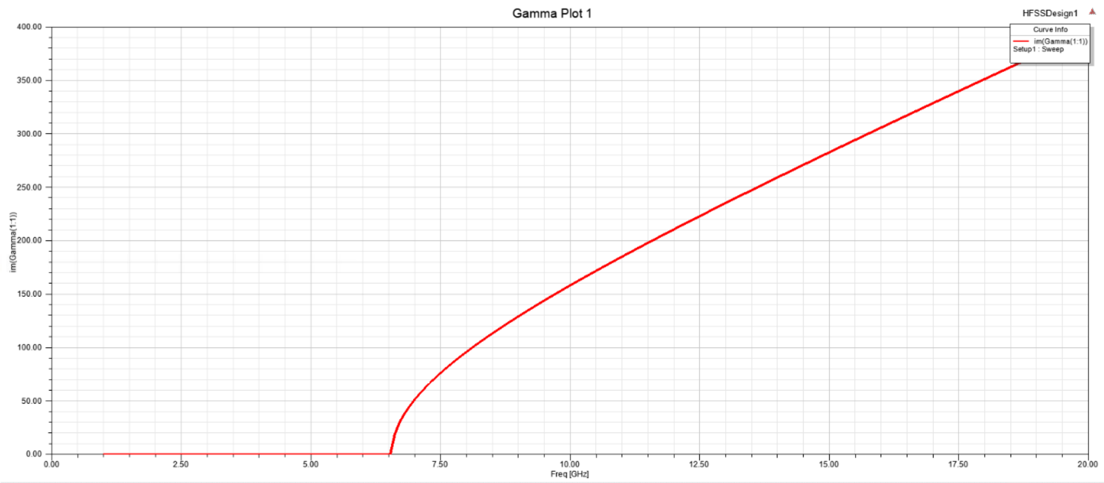
The figure above illustrates the electric and magnetic field distribution of the TE01 mode, which aligns with the theoretical formulas introduced in the introduction. Specifically, the agreement is achieved by substituting m=0 and n=1 into the equations. It can be observed that the distribution patterns at the center frequencies of 13 GHz and 15 GHz are not the same. The distribution pattern at 15 GHz appears normal, while at 13 GHz, it is not. This is because the cutoff frequency of the TE20 mode is 14.754 GHz. The center frequency of 13 GHz is below the cutoff frequency, preventing the normal formation of the TE01 mode's electromagnetic field distribution. Only at 15 GHz can the TE01 mode be displayed correctly.

**S-parameter & Gamma-parameter Analysis**

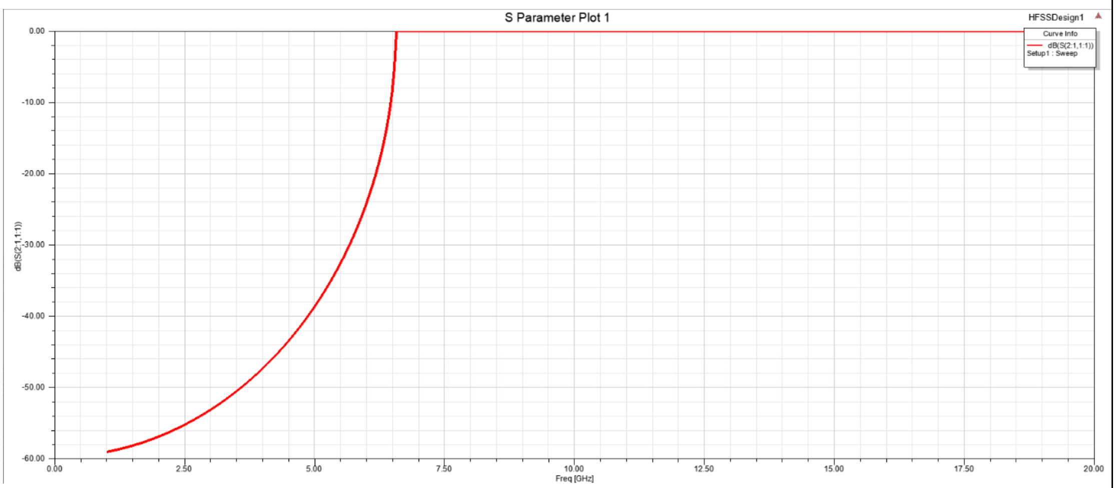
**TE10:**

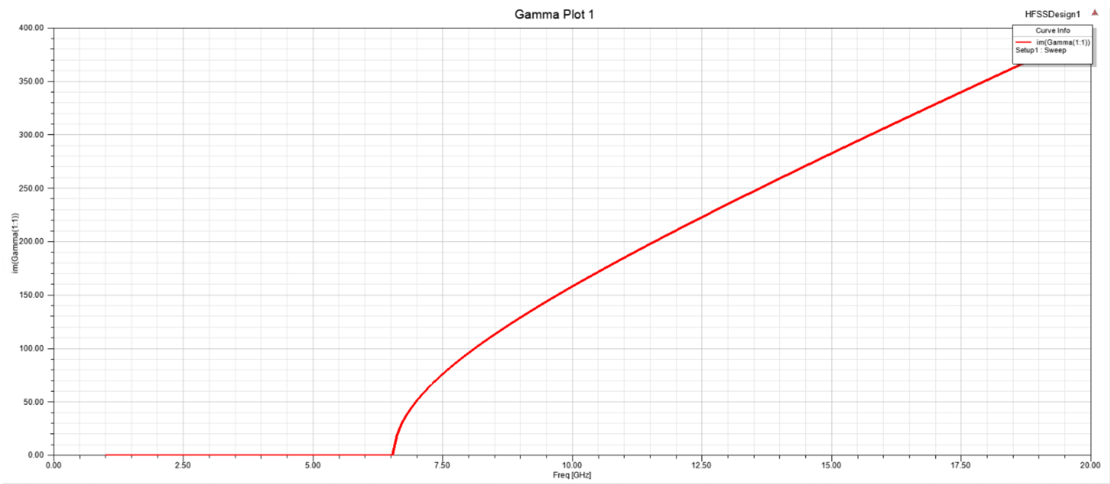
Center frequency: 13GHZ




Center frequency: 15GHZ



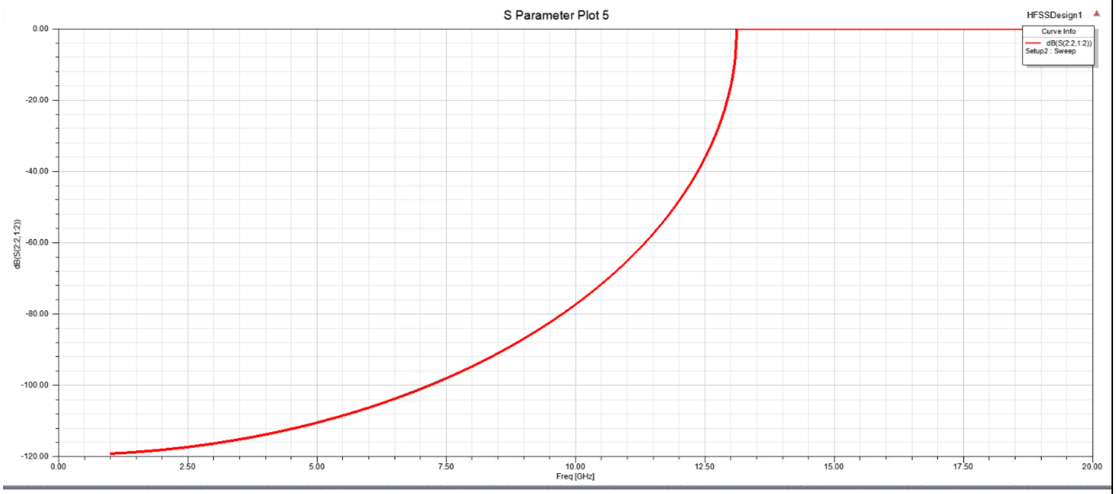


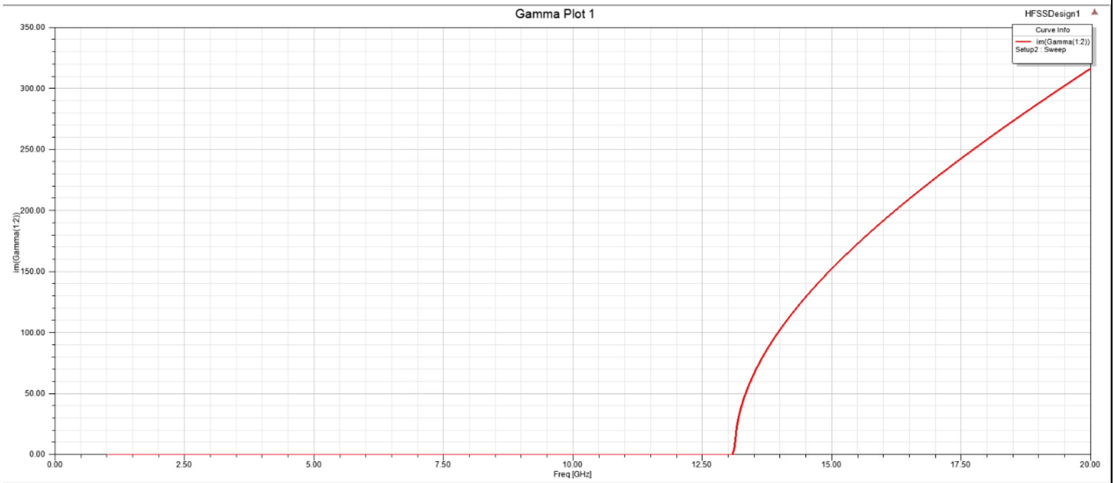

**Analysis:**

From the graph, it can be observed that the cutoff frequency aligns with the theoretically calculated cutoff frequency of 6.557 GHz for the TE10 mode mentioned earlier, indicating that both the theory and simulation are consistent. Additionally, there is no distinction between the center frequencies of 13 GHz and 15 GHz in the parameter graph. This is because these parameter graphs represent overall patterns and are not influenced by specific center frequencies.

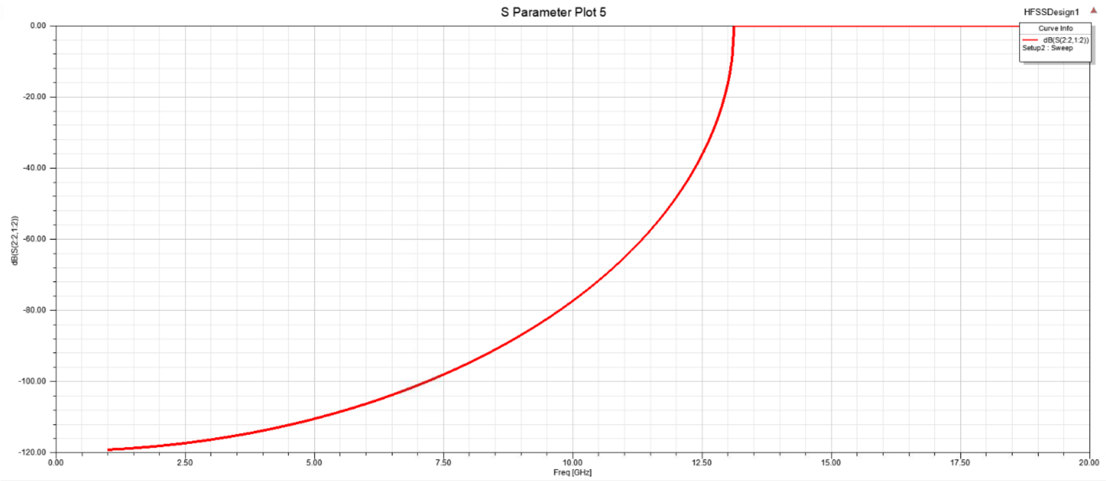
**TE20:**

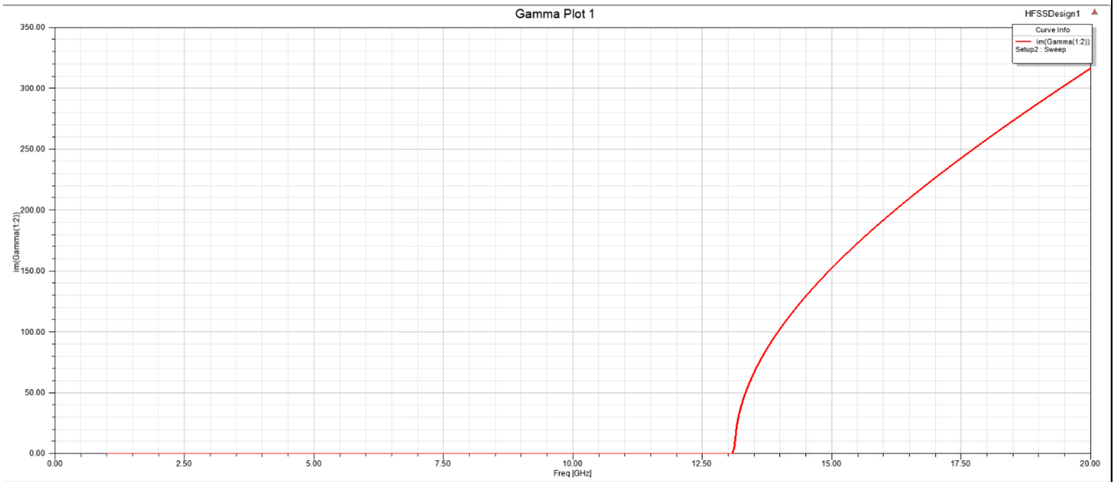
Center frequency: 13GHZ






Center frequency: 15GHZ



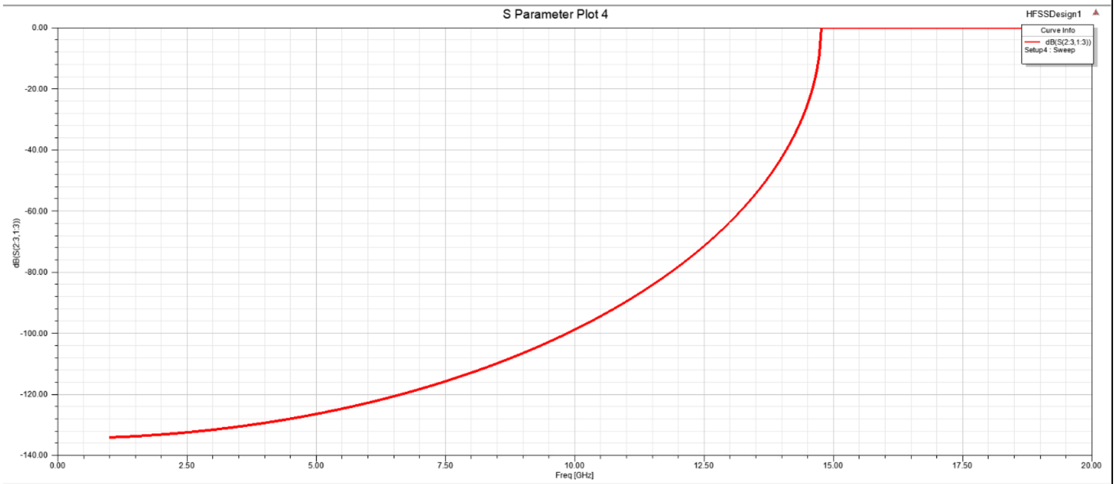



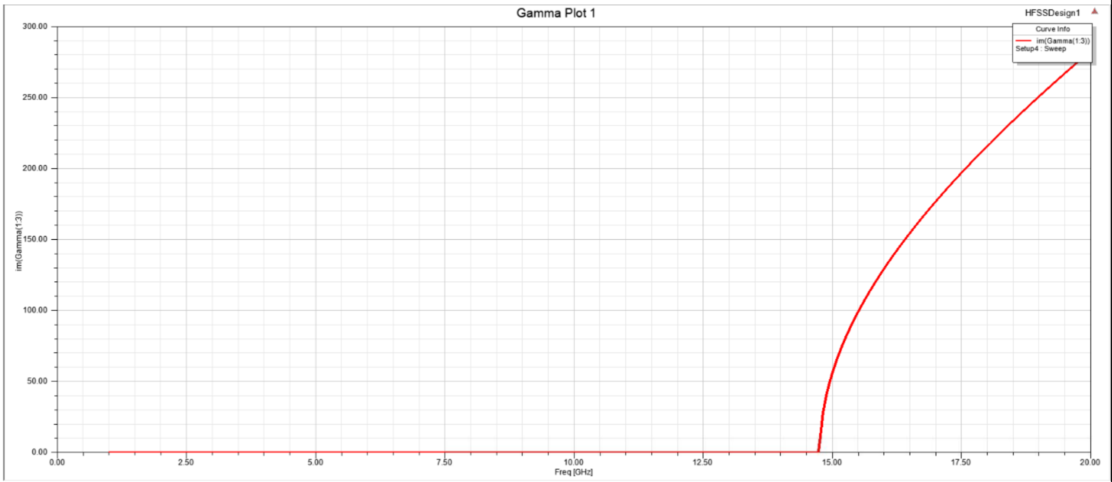

**Analysis:**

From the graph, it can be observed that the cutoff frequency aligns with the theoretically calculated cutoff frequency of 13.114GHz for the TE20 mode mentioned earlier, indicating that both the theory and simulation are consistent. Additionally, there is no distinction between the center frequencies of 13 GHz and 15 GHz in the parameter graph. This is because these parameter graphs represent overall patterns and are not influenced by specific center frequencies.

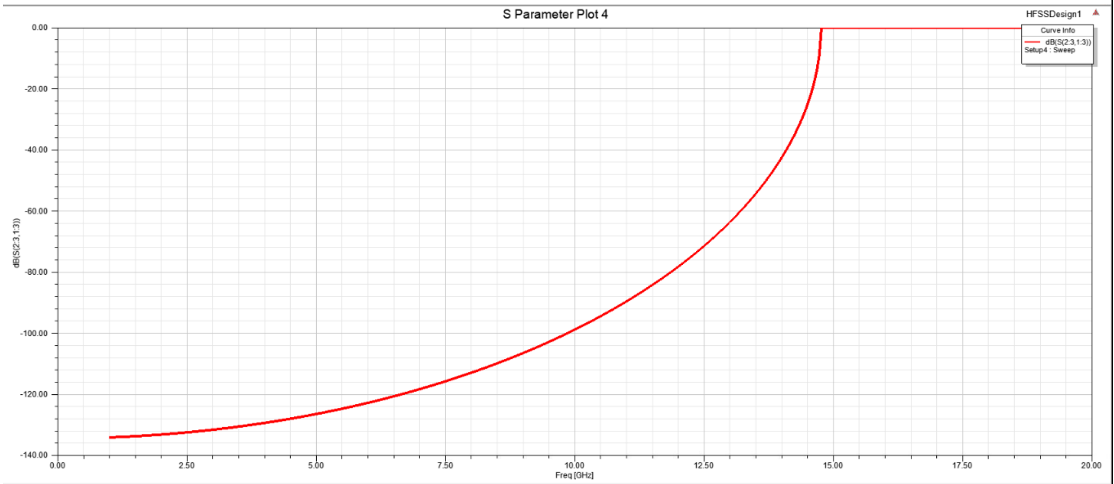
**TE01:**

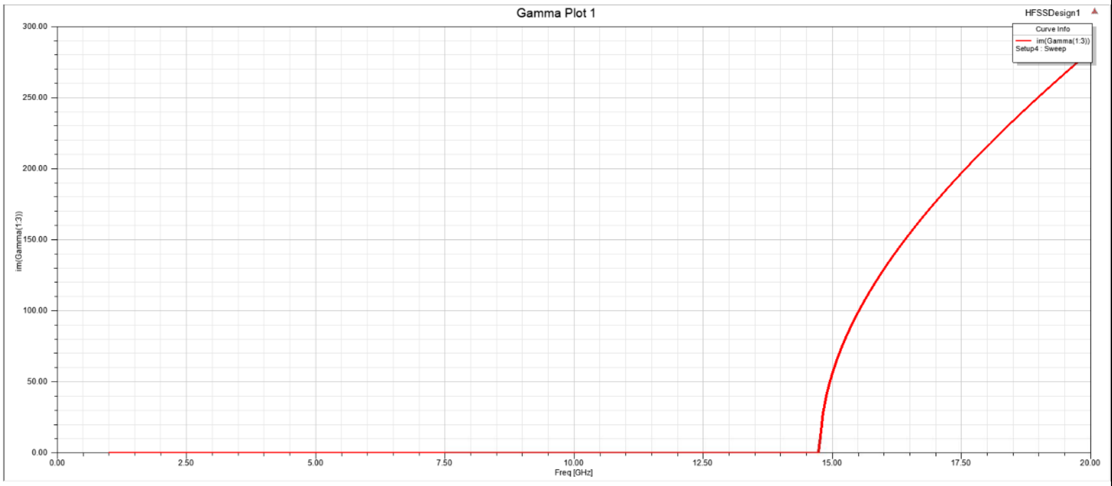
Center frequency: 13GHZ




Center frequency: 15GHZ



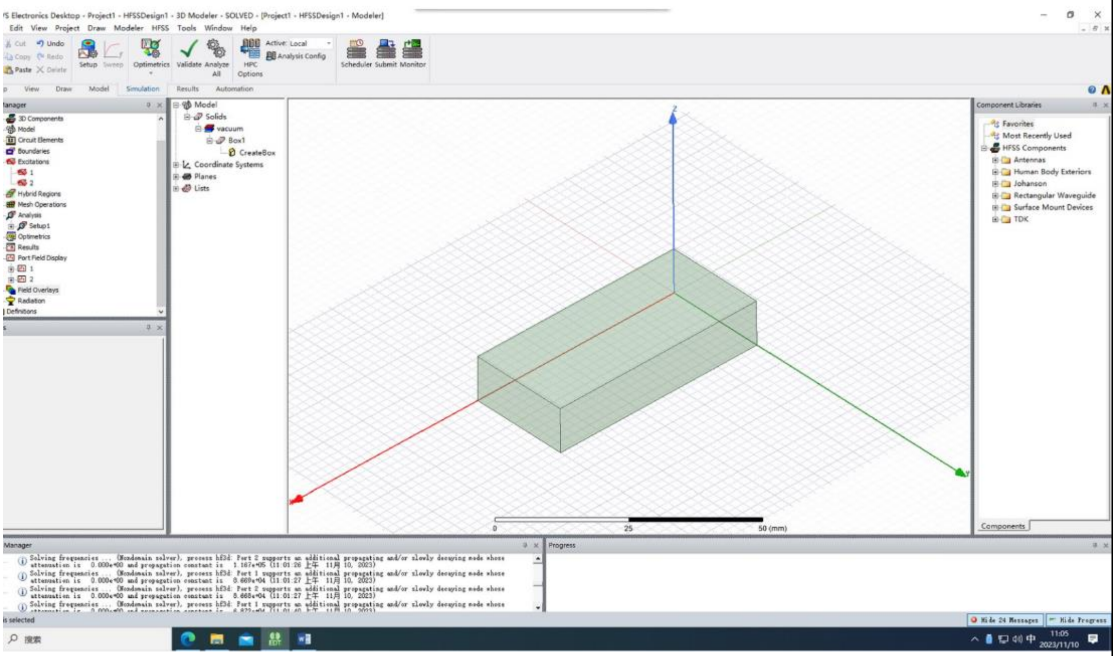


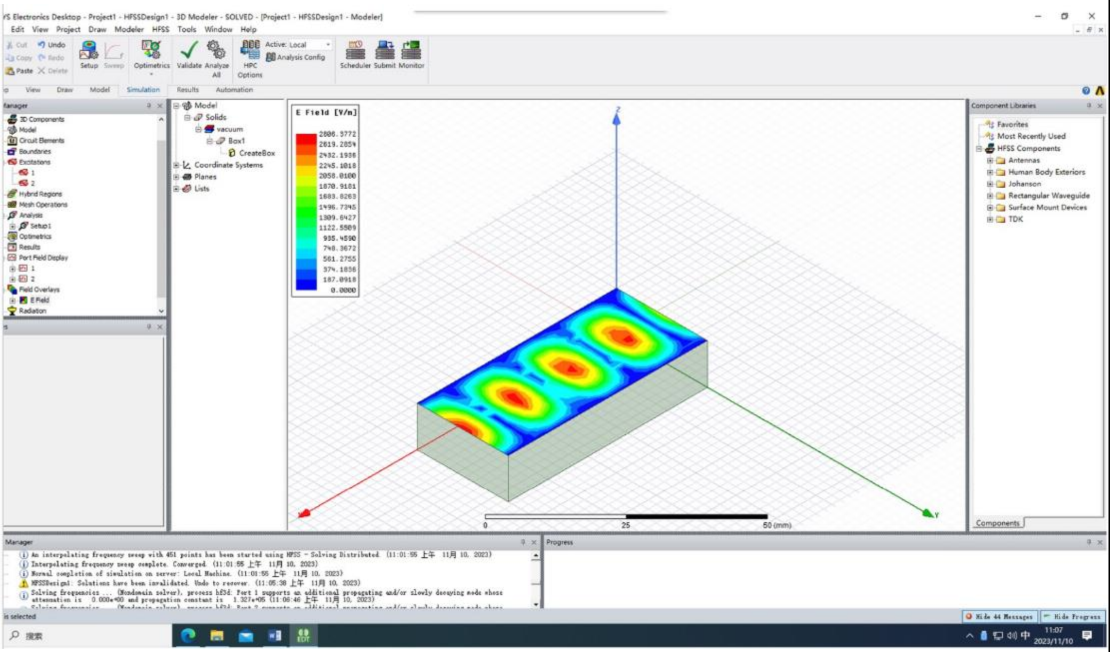

**Analysis:**

From the graph, it can be observed that the cutoff frequency aligns with the theoretically calculated cutoff frequency of 14.754 GHz for the TE01 mode mentioned earlier, indicating that both the theory and simulation are consistent. Additionally, there is no distinction between the center frequencies of 13 GHz and 15 GHz in the parameter graph. This is because these parameter graphs represent overall patterns and are not influenced by specific center frequencies.

# Experience

## In-class lab screenshot





**Experience and problem we meet**

In this lab, I have learned how to exchange different modes of the waveguide and simulate their corresponding electric field distribution.

The most important is, after completion of this report, I had a better understanding of rectangular waveguide modelling and simulation, as well as its field structures.

One noteworthy aspect is the importance of setting the units correctly to obtain accurate results. Additionally, it is crucial to ensure that the frequency sweep range encompasses both the center frequency and the cutoff frequency to generate accurate graphical representations.

| | |
|---|---|
| **Score** | 98 |