南方科技大学
SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Microwave Engineering (Lab)

Lab 4: Rectangular Waveguide

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- 微波工程
  - 微波技术基础（理论，32学时）
  - 电磁仿真设计（实验，32学时）
    - Lab1-->实验目标：1、通过T型波导了解HFSS，3周，有Step-By-Step文档-->重点：1、HFSS设计流程介绍，2、HFSS优化设计
    - Lab2-->实验目标：1、通过阻抗变换器了解ADS软件，2、史密斯圆图，2周，有Step-By-Step文档，-->重点：LineCalc和Smith Chart工具
    - Lab3-->课堂任务：1、LC网络阻抗匹配，2、并联双枝节阻抗匹配，2周，-->重点：利用Smith Chart进行窄带/宽带阻抗匹配、VNA测试
    - Lab4-->实验目标：1、HFSS矩形波导仿真，1周，-->重点：建模，边界条件和激励，扫频设置，回波损耗，TE10模场结构
    - Lab5-->实验目标：1、3dB威尔金森功分器仿真，2周，重点-->威尔金森功分器建模、仿真和优化、ADS仿真和HFSS仿真比较
    - Lab6-->实验目标：1、3dB分支线耦合器仿真，1周，重点-->分支线耦合器建模、仿真和优化、ADS仿真和HFSS仿真比较
    - Lab7-->实验目标：1、微带天线建模和仿真，1周，重点-->微带天线尺寸设计、微带天线HFSS和ADS仿真比较
    - Project1-->命题-->11个题目中，选择一个完成，1周，布置这些题目，有答案，助教已经提前完成。VNA动手测试实验。
    - Project2-->分组完成-->需要Presentation，3周，分组设计制作一个无线通信系统（至少包含微带功分器、微带耦合器、微带天线）
  - 微波仿真软件

Waveguide

- 1、波导：用来引导电磁波进行定向传输的装置或系统称为导波系统，简称**波导（Waveguide）**。

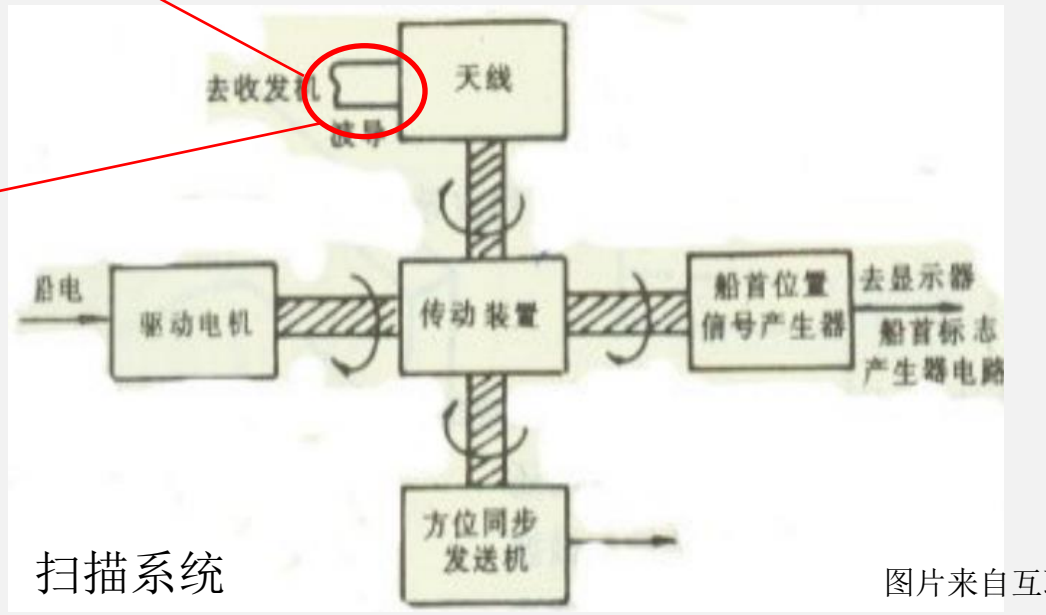
- 2、广义的波导有：平行双线、同轴线、带状线、微带线、**矩形波导（Rectangular Waveguide）**、圆形波导、介质波导等。

- 3、**规则波导（Regular waveguide）**：轴向均匀的无限长直波导，即截面形状，填充介质不随轴向距离变化。

同轴电缆（10cm雷达）

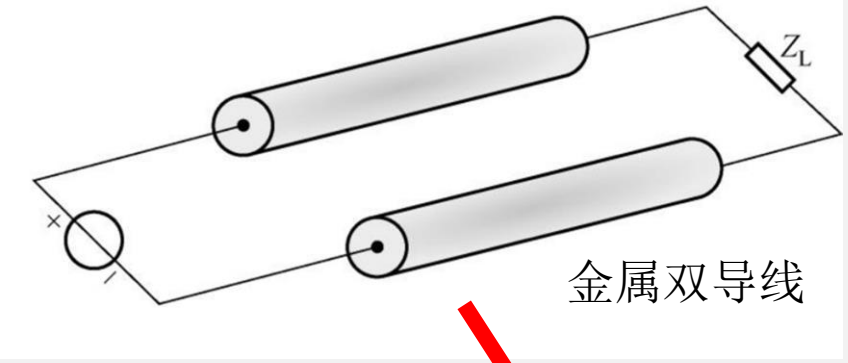
船用雷达设备

矩形波导（3cm雷达）



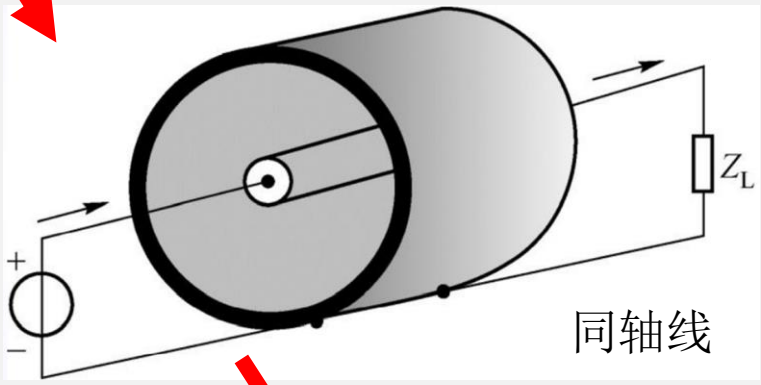
扫描系统

图片来自互联网



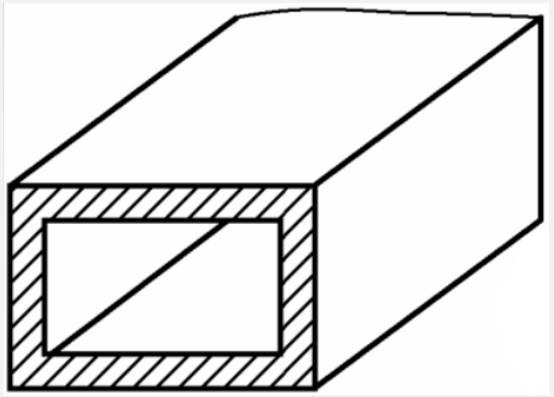
金属双导线

最早采用金属双导线，随着频率提高，距离增大，双导线损耗增大。

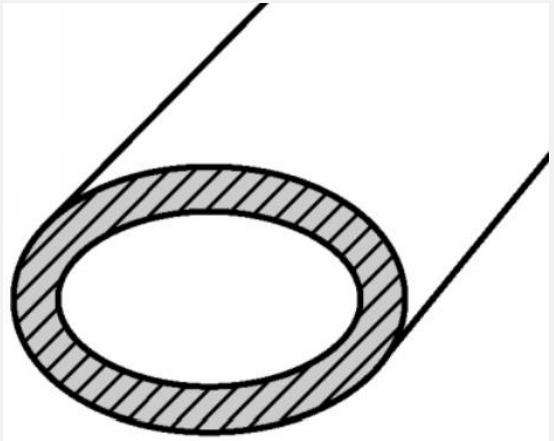


同轴线

同轴线或者金属波导可以解决双导线存在的问题。

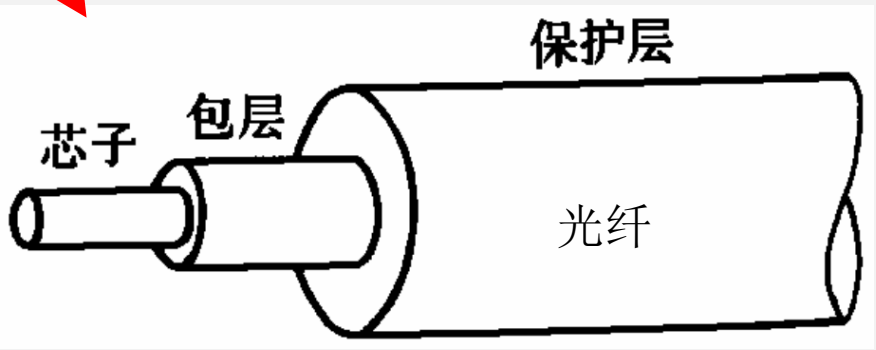


矩形波导



圆形波导

当前已经发展到光纤通信

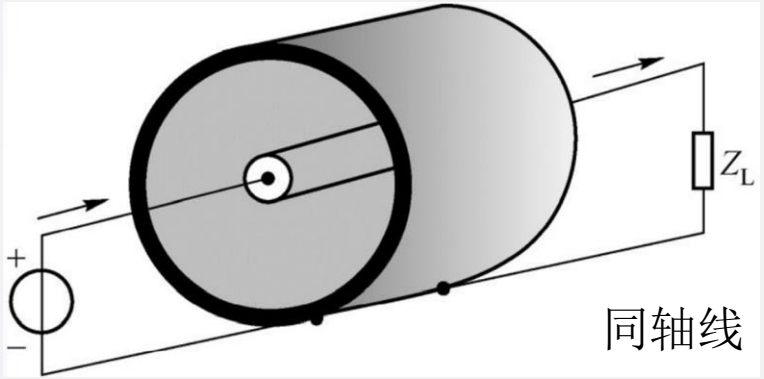


同轴线：

金属圆筒对电磁能的屏蔽、约束作用，在很大程度上解决了辐射损耗的问题。

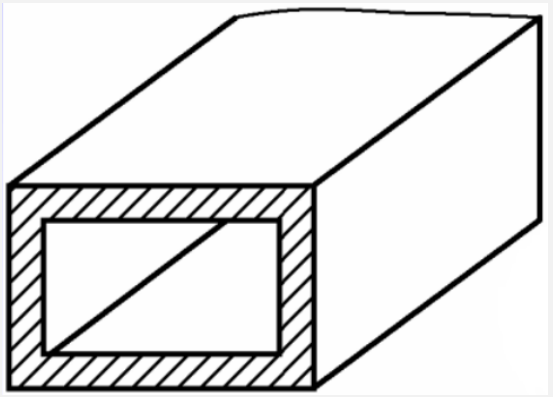
“趋肤效应”引起的导线热损耗增大；

横截面尺寸必须相应减少，以保证只传输TEM 波而不产生高次模式，会降低功率容量。



同轴线

V.S.


矩形波导

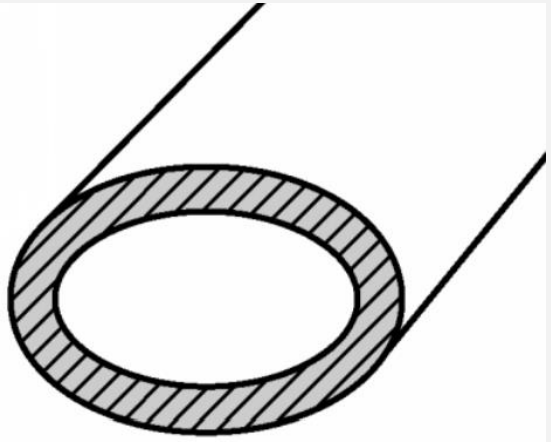
$U, I \rightarrow \vec{E}, \vec{H}$

波导：

只要金属管横截面尺寸与波长比足够大，就可以在管内导引轴向电磁波。

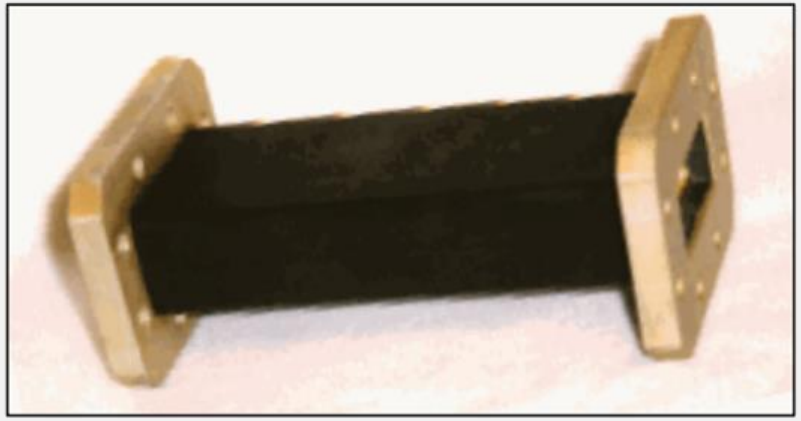
波导可有各种截面形状，常用的是矩形波导和圆形波导。

波导可传输从厘米波段到毫米波段的电磁波，具有功耗小、容量大等特点。

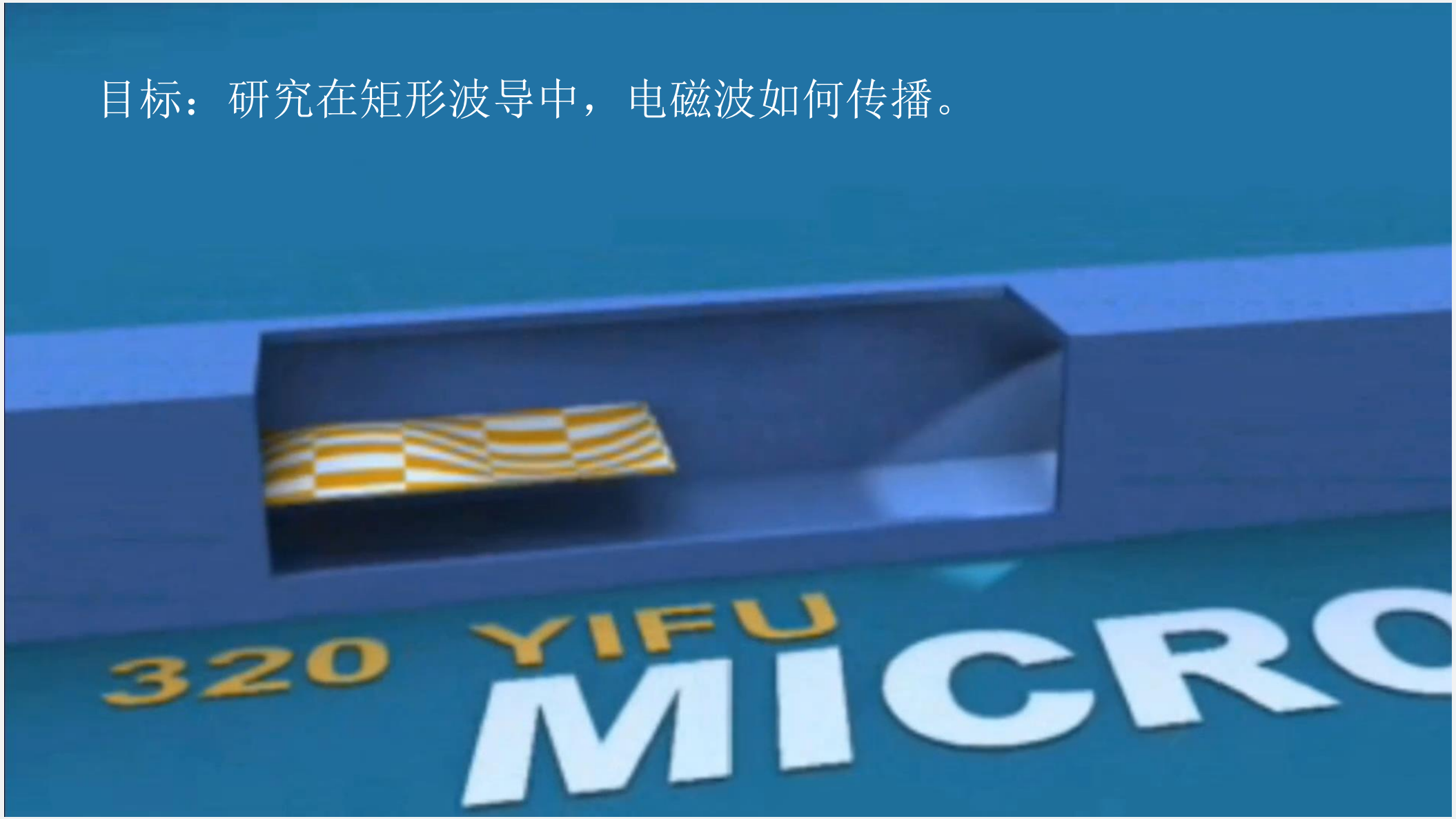

圆形波导

Rectangular Waveguide

- Existence of lower and upper cut-off frequencies.
- Cut-off frequencies are defined by the dimension and shape of the cross-section.
- Rectangular- and circular-shaped waveguide are common types.
- Extremely low loss
- Can handle high power
- Large size, heavy weight
- Difficult to manufacture



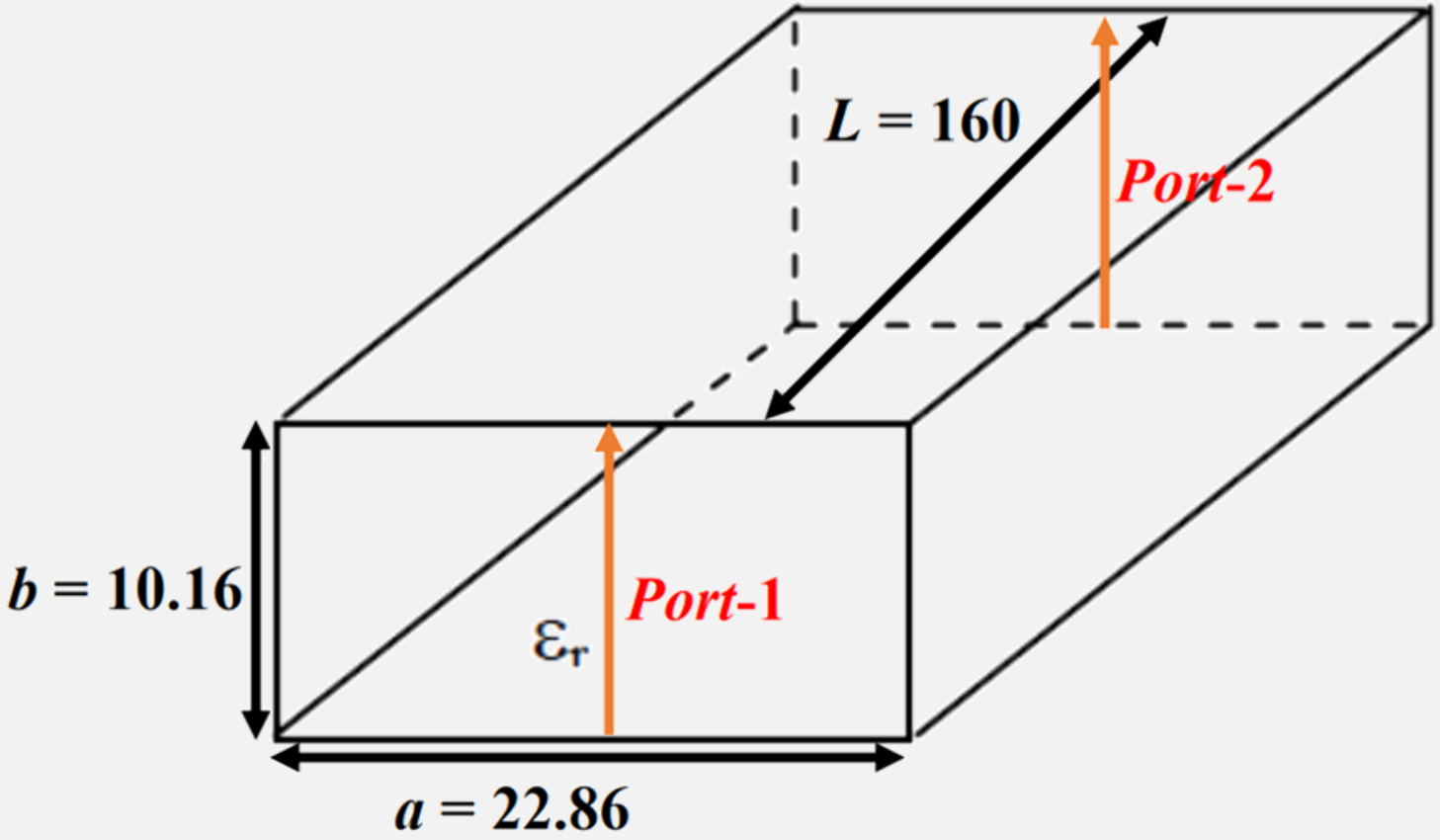
目标：研究在矩形波导中，电磁波如何传播。

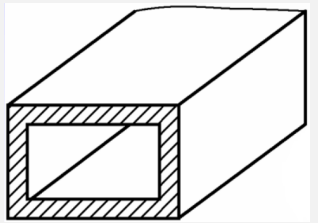


Characterization of Rectangular Waveguide

Objective

- Using HFSS, simulate an air-filled WR-90 waveguide shown in Fig. 1.
- To obtain the Field patterns, propagation constant for the first 4 modes (TE_{10}, TE_{20}, TE_{01}, TE_{11} modes).





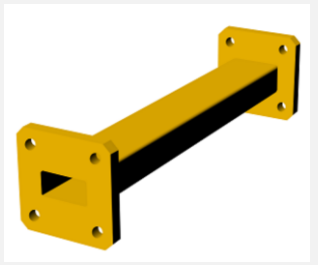
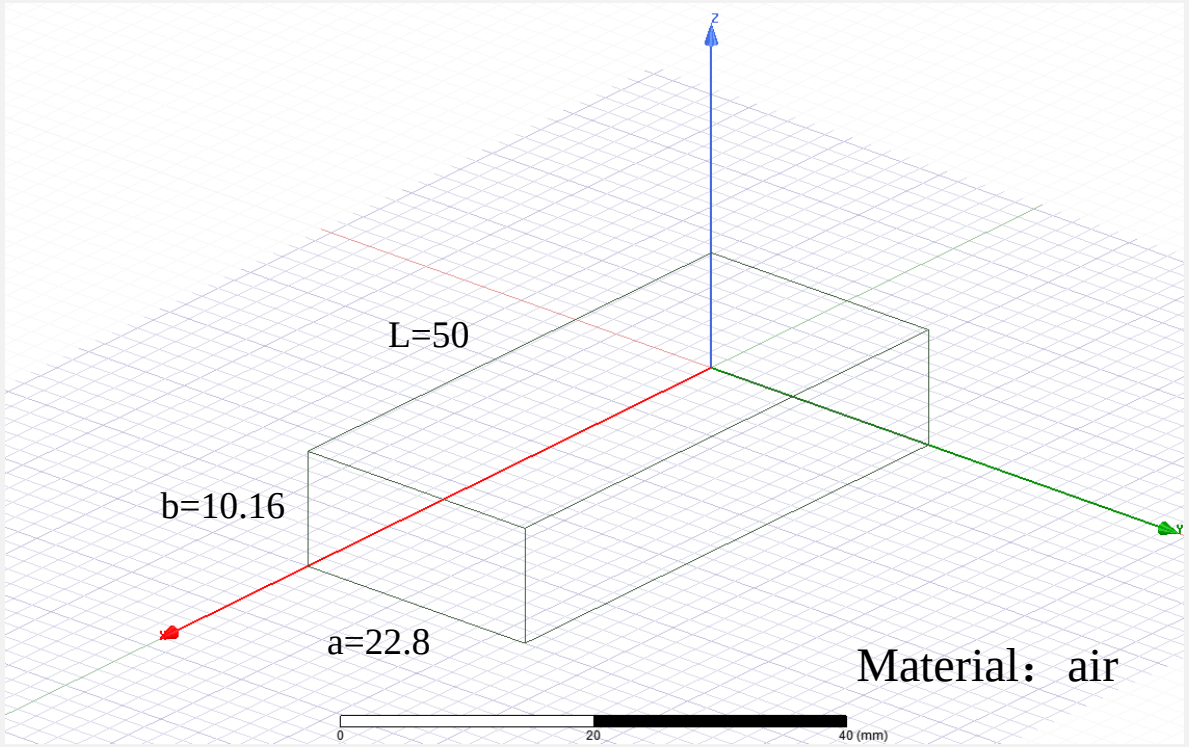
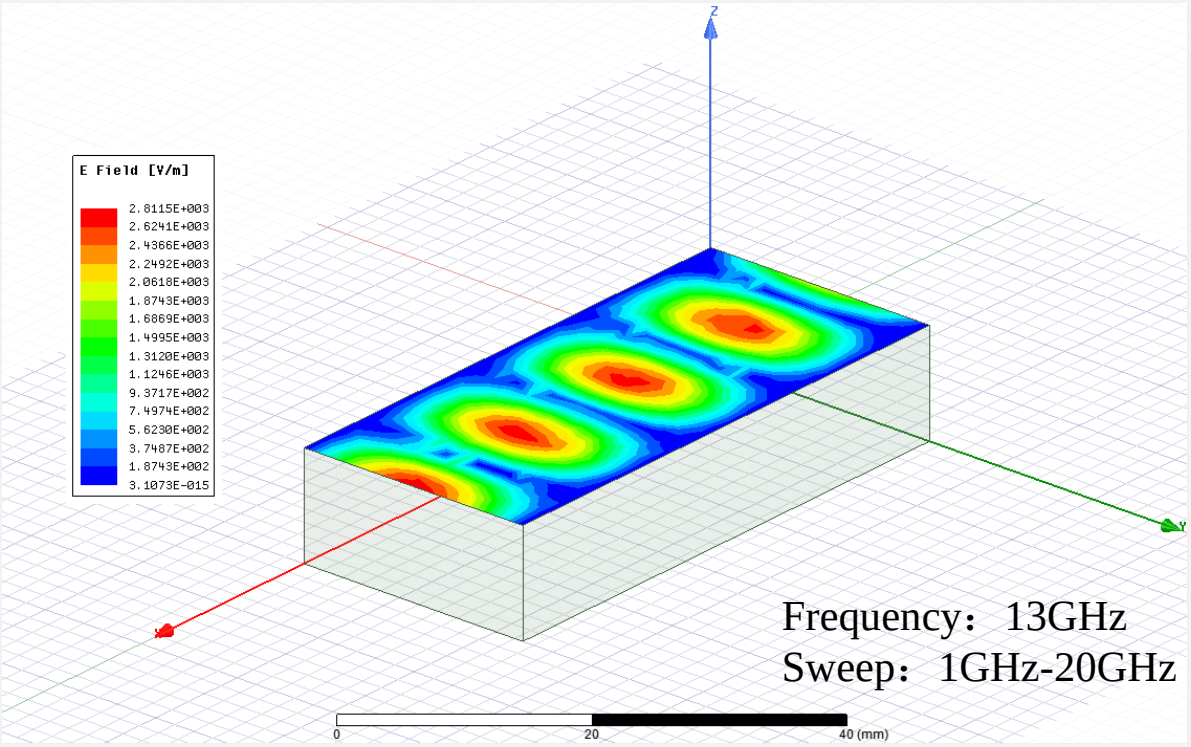
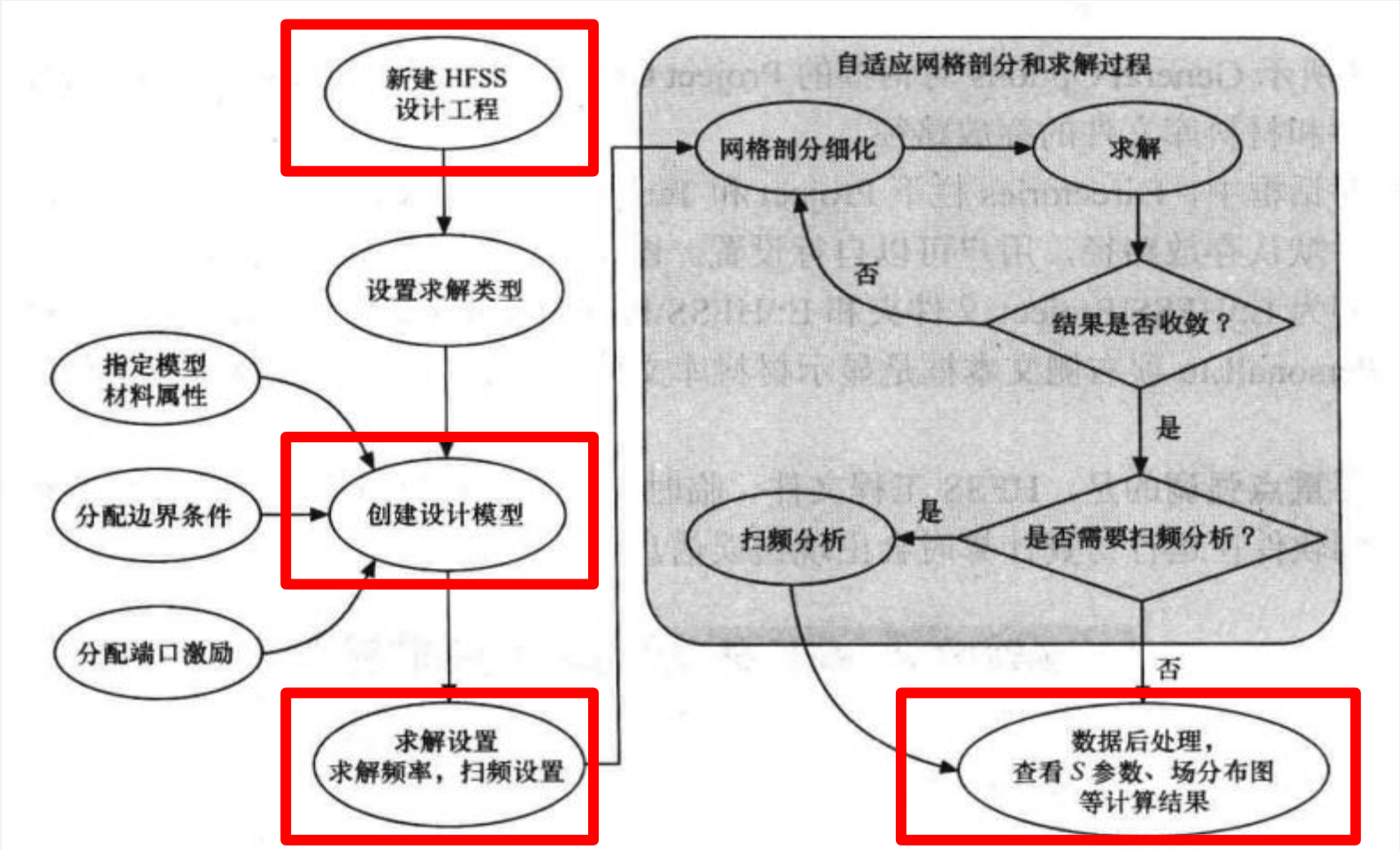


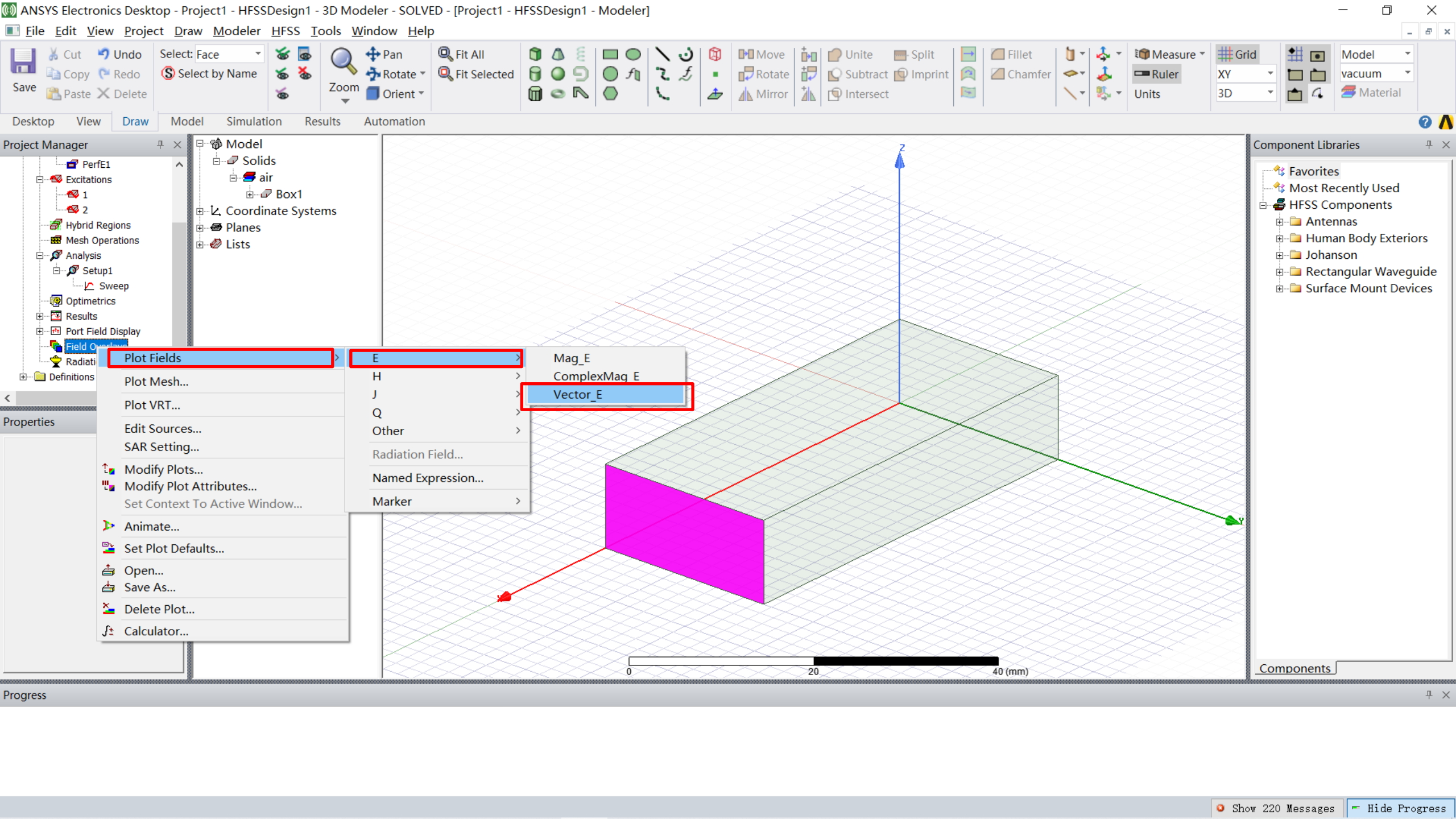
Figure 1 Rectangular waveguide. Units are in mm.

Exercise 1


L=50
b=10.16
a=22.8
Material：air
0
20
40 (mm)


E Field [V/m]
2.8115E+003
2.6241E+003
2.4366E+003
2.2492E+003
2.0618E+003
1.8743E+003
1.6869E+003
1.4995E+003
1.3120E+003
1.1246E+003
9.3717E+002
7.4974E+002
5.6230E+002
3.7487E+002
1.8743E+002
3.1073E-015
Frequency：13GHz
Sweep：1GHz-20GHz
0
20
40 (mm)


新建 HFSS
设计工程
设置求解类型
指定模型
材料属性
分配边界条件
创建设计模型
分配端口激励
求解设置
求解频率，扫频设置
自适应网格剖分和求解过程
网格剖分细化
求解
否
结果是否收敛？
是
是
扫频分析
是否需要扫频分析？
否
数据后处理，
查看 S 参数、场分布图
等计算结果


ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]
File Edit View Project Draw Modeler HFSS Tools Window Help
Save Cut Copy Paste Undo Redo Delete
Select: Face
Select by Name
Zoom Pan Rotate Orient
Fit All Fit Selected
Move Rotate Mirror
Unite Subtract Intersect
Split Imprint
Fillet Chamfer
Measure Ruler Units
Grid XY 3D
Model vacuum Material
Desktop View Draw Model Simulation Results Automation
Project Manager
PerfE1
Excitations
1
2
Hybrid Regions
Mesh Operations
Analysis
Setup1
Sweep
Optimetrics
Results
Port Field Display
Field Overlays
Radiation
Definitions
Model
Solids
air
Box1
Coordinate Systems
Planes
Lists
Plot Fields
Plot Mesh...
Plot VRT...
Edit Sources...
SAR Setting...
Modify Plots...
Modify Plot Attributes...
Set Context To Active Window...
Animate...
Set Plot Defaults...
Open...
Save As...
Delete Plot...
Calculator...
E
H
J
Q
Other
Radiation Field...
Named Expression...
Marker
Mag_E
ComplexMag_E
Vector_E
Z
Y
0
20
40 (mm)
Component Libraries
Favorites
Most Recently Used
HFSS Components
Antennas
Human Body Exteriors
Johanson
Rectangular Waveguide
Surface Mount Devices
Components
Properties
Progress
Show 220 Messages
Hide Progress

ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]

File Edit View Project Draw Modeler HFSS Tools Window Help

Save Cut Copy Paste Undo Redo Delete Select: Face Select by Name Zoom Pan Rotate Orient Fit All Fit Selected Move Rotate Mirror Unite Subtract Intersect Split Imprint Fillet Chamfer Measure Ruler Units Grid XY 3D Model vacuum Material

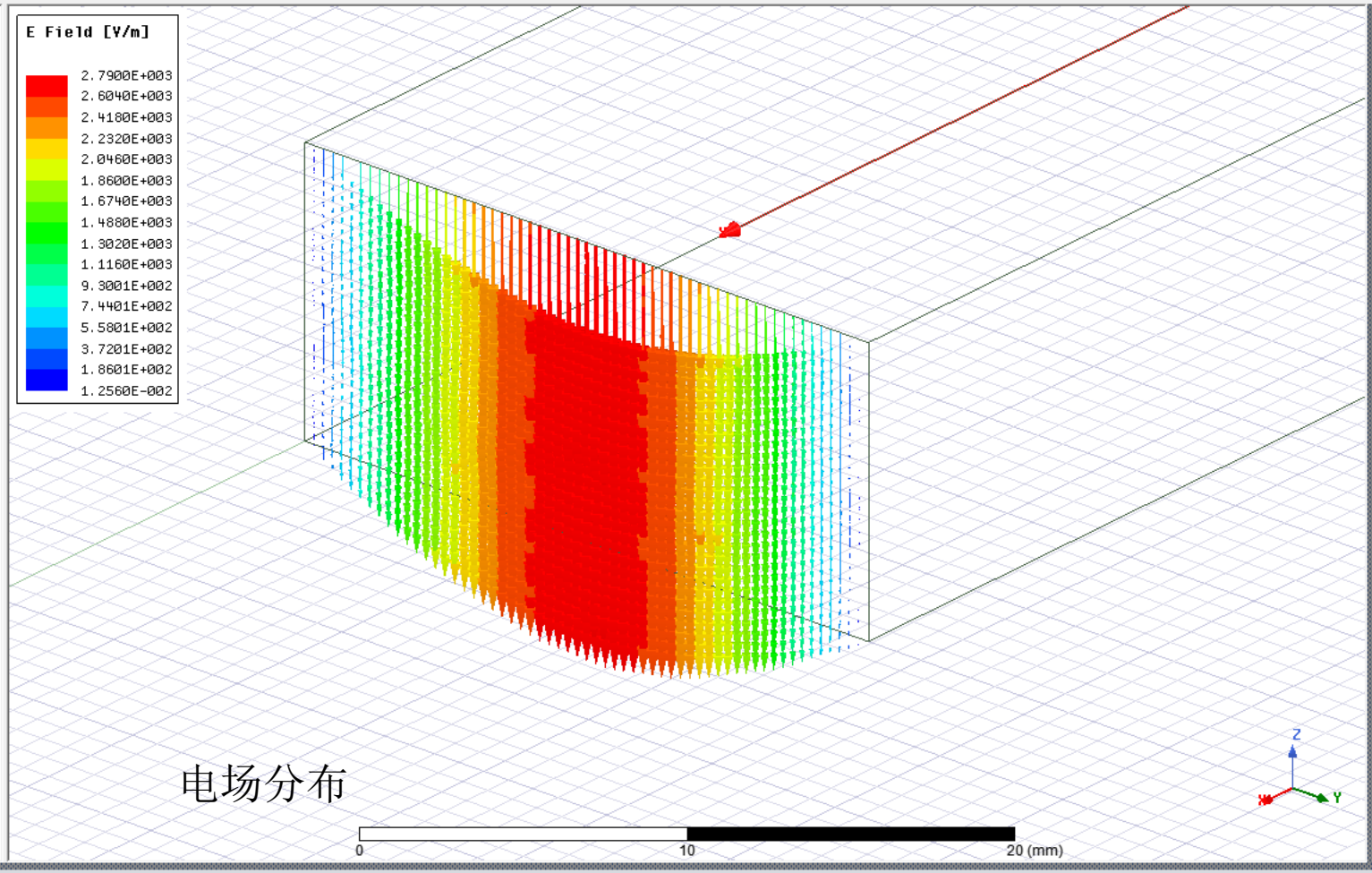
Desktop View Draw Model Simulation Results Automation

Project Manager

- PerfE1
- Excitations
  - 1
  - 2
- Hybrid Regions
- Mesh Operations
- Analysis
  - Setup1
    - Sweep
- Optimetrics
- Results
- Port Field Display
- Field Overlays
  - E Field
- Radiation

Properties

Model
- Solids
  - air
    - Box1
- Coordinate Systems
- Planes
- Lists



Component Libraries

- Favorites
- Most Recently Used
- HFSS Components
  - Antennas
  - Human Body Exteriors
  - Johanson
  - Rectangular Waveguide
  - Surface Mount Devices

Components

Progress

Nothing is selected

Show 220 Messages Hide Progress

ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]

File Edit View Project Draw Modeler HFSS Tools Window Help

Save Cut Copy Paste Undo Redo Delete Select: Face Select by Name Zoom Pan Rotate Orient Fit All Fit Selected Move Rotate Mirror Unite Subtract Intersect Split Imprint Fillet Chamfer Measure Ruler Units Grid XY 3D Model vacuum Material

Desktop View Draw Model Simulation Results Automation

Project Manager

- 1
- 2
- Hybrid Regions
- Mesh Operations
- Analysis
  - Setup1
    - Sweep
- Optimetrics
- Results
- Port Field Display
- Field Overlays
  - E Field
    - Vector_E1
    - Vector_E2
  - H Field

Properties

Name	Va...	Unit	Evaluated...
Name	V...		
Soluti...	Se...		
Phase	0	deg	
Freq	13	GHz	

Definition

- Model
  - Solids
    - air
      - Box1
  - Coordinate Systems
  - Planes
  - Lists

H Field [A/m]
6.7259E+000
6.2783E+000
5.8307E+000
5.3830E+000
4.9354E+000
4.4877E+000
4.0401E+000
3.5925E+000
3.1448E+000
2.6972E+000
2.2496E+000
1.8019E+000
1.3543E+000
9.0664E-001
4.5900E-001
1.1364E-002

磁场分布

0 5 10 (mm)

Component Libraries

- Favorites
- Most Recently Used
- HFSS Components
  - Antennas
  - Human Body Exteriors
  - Johanson
  - Rectangular Waveguide
  - Surface Mount Devices

Components

Progress

Nothing is selected

Show 220 Messages Hide Progress

ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]

File Edit View Project Draw Modeler HFSS Tools Window Help

Save Cut Copy Paste Undo Redo Delete Select: Face Select by Name Zoom Pan Rotate Orient Fit All Fit Selected Move Rotate Mirror Unite Subtract Intersect Split Imprint Fillet Chamfer Measure Ruler Units Grid XY 3D Model vacuum Material

Desktop View Draw Model Simulation Results Automation

Project Manager

- 1
- 2
- Hybrid Regions
- Mesh Operations
- Analysis
  - Setup1
    - Sweep
- Optimetrics
- Results
- Port Field Display
- Field Overlays
  - E Field
    - Vector_E1
    - Vector_E2
  - H Field

Properties

Model
- Solids
  - air
    - Box1
- Coordinate Systems
- Planes
- Lists

H Field [A/m]
6.7259E+000
6.2783E+000
5.8307E+000
5.3830E+000
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4.4877E+000
4.0401E+000
3.5925E+000
3.1448E+000
2.6972E+000
2.2496E+000
1.8019E+000
1.3543E+000
9.0664E-001
4.5900E-001
1.1364E-002

电磁场分布

Z
Y
0 10 20 (mm)

Component Libraries
- Favorites
- Most Recently Used
- HFSS Components
  - Antennas
  - Human Body Exteriors
  - Johanson
  - Rectangular Waveguide
  - Surface Mount Devices

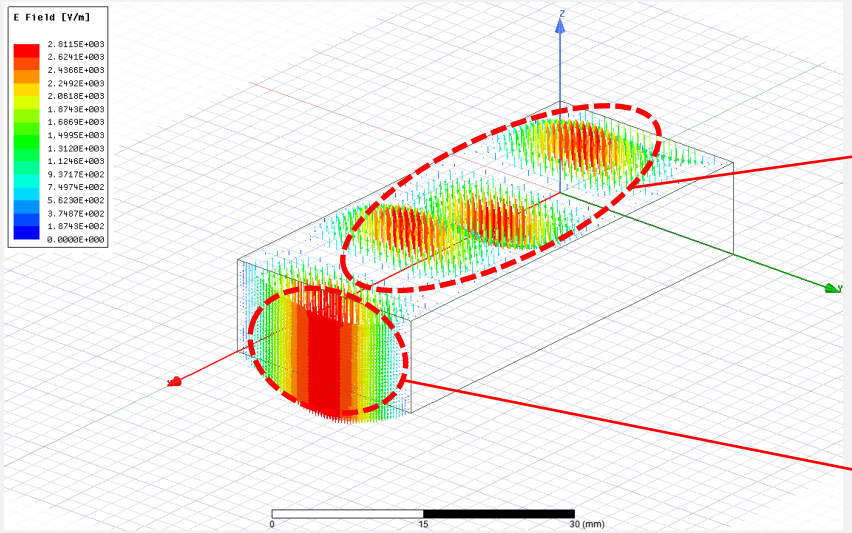
Components

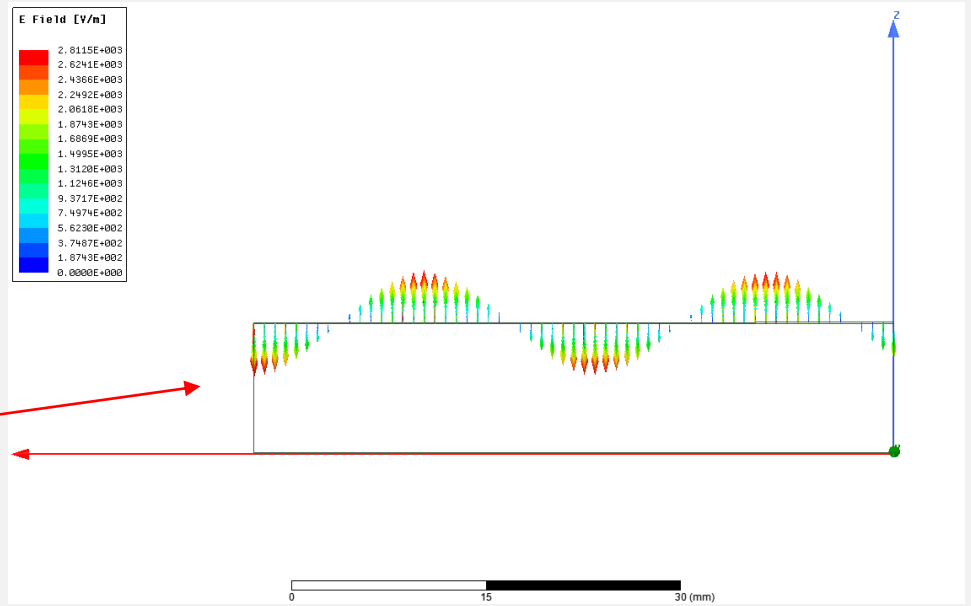
Progress

Nothing is selected

Show 220 Messages Hide Progress

电场分布


E Field [V/m]
2.8115E+003
2.6241E+003
2.4366E+003
2.2492E+003
2.0618E+003
1.8743E+003
1.6869E+003
1.4995E+003
1.3120E+003
1.1246E+003
9.3717E+002
7.4974E+002
5.6230E+002
3.7487E+002
1.8743E+002
0.0000E+000
Z
Y
0
15
30 (mm)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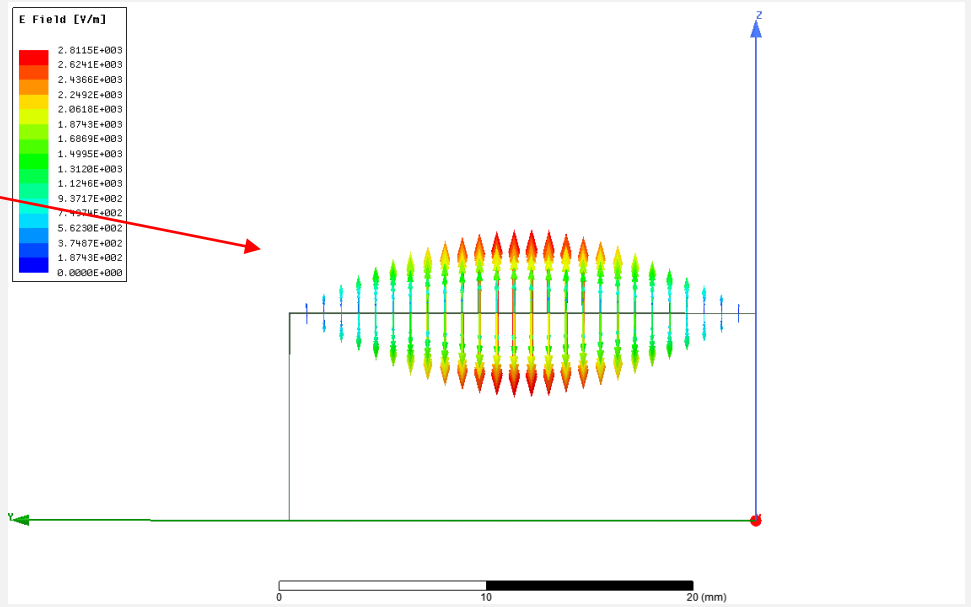
1.4995E+003
1.3120E+003
1.1246E+003
9.3717E+002
7.4974E+002
5.6230E+002
3.7487E+002
1.8743E+002
0.0000E+000
Z
0
15
30 (mm)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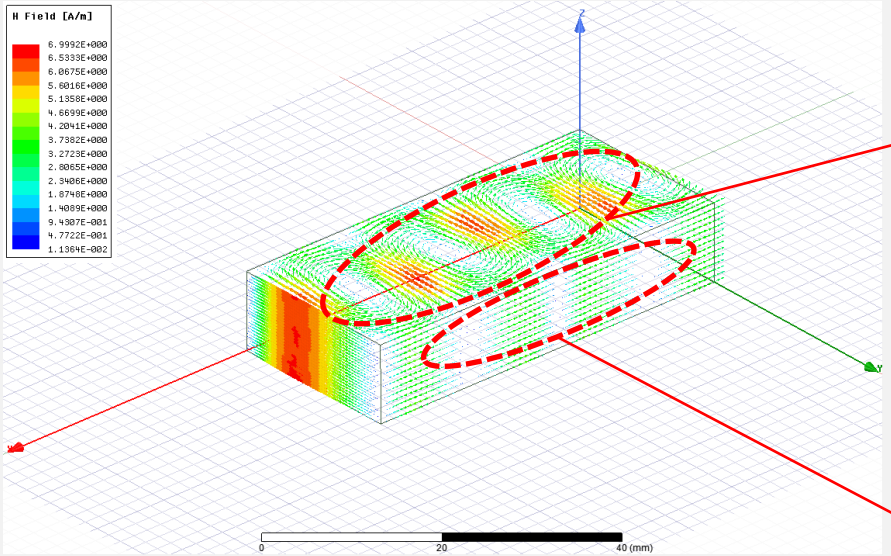
2.4366E+003
2.2492E+003
2.0618E+003
1.8743E+003
1.6869E+003
1.4995E+003
1.3120E+003
1.1246E+003
9.3717E+002
5.6230E+002
3.7487E+002
1.8743E+002
0.0000E+000
Z
Y
0
10
20 (mm)

磁场分布


H Field [A/m]
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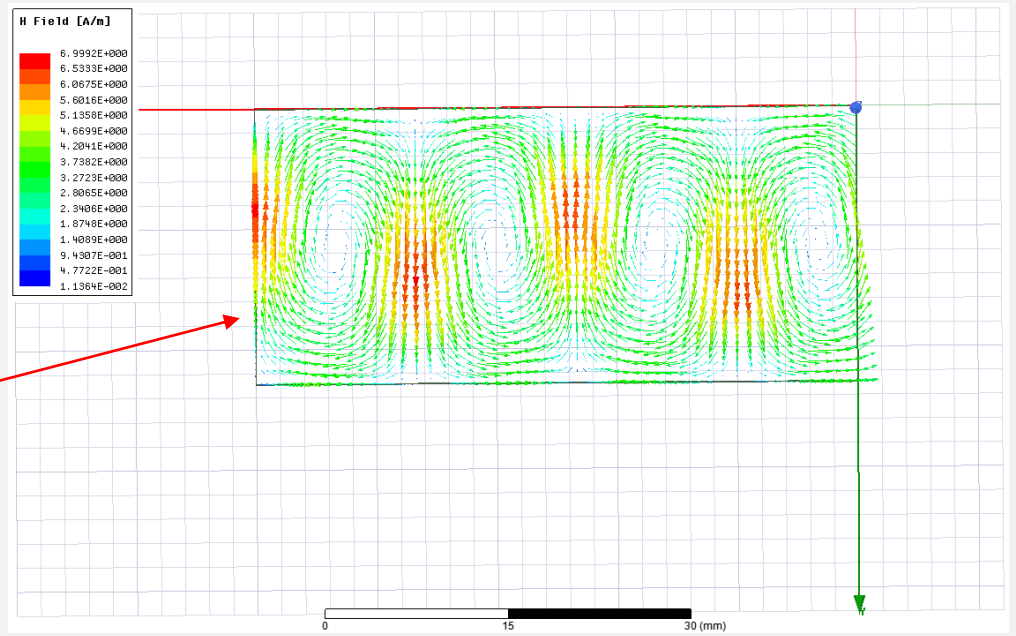
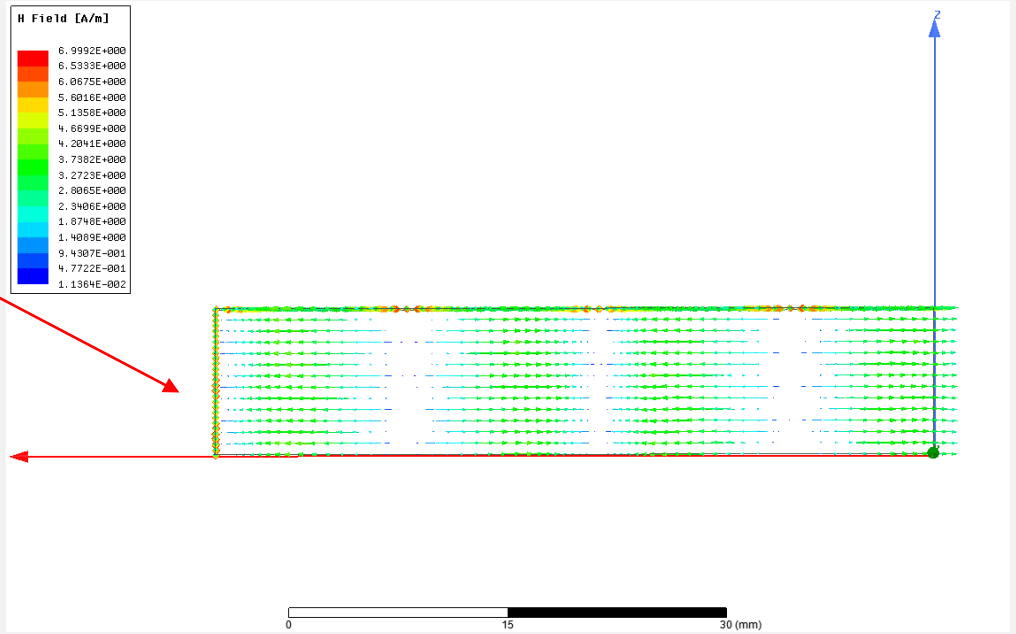
6.5333E+000
6.0675E+000
5.6016E+000
5.1358E+000
4.6699E+000
4.2041E+000
3.7382E+000
3.2723E+000
2.8065E+000
2.3406E+000
1.8748E+000
1.4089E+000
9.4307E-001
4.7722E-001
1.1364E-002
Z
Y
0
20
40 (mm)

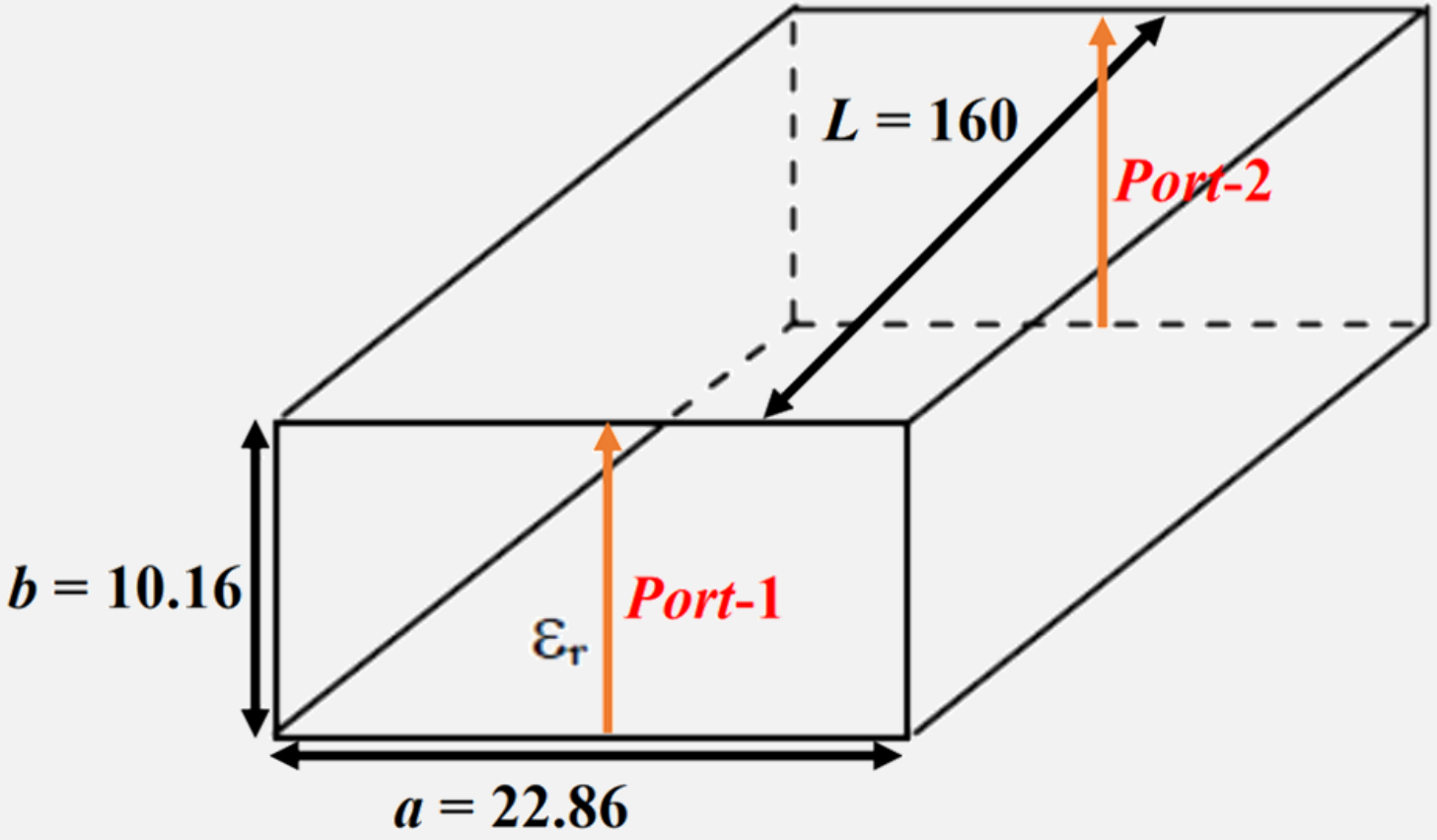

H Field [A/m]
6.9992E+000
6.5333E+000
6.0675E+000
5.6016E+000
5.1358E+000
4.6699E+000
4.2041E+000
3.7382E+000
3.2723E+000
2.8065E+000
2.3406E+000
1.8748E+000
1.4089E+000
9.4307E-001
4.7722E-001
1.1364E-002
0
15
30 (mm)

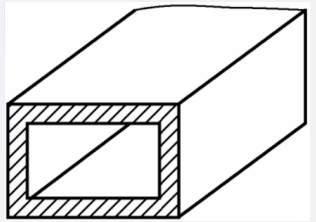

H Field [A/m]
6.9992E+000
6.5333E+000
6.0675E+000
5.6016E+000
5.1358E+000
4.6699E+000
4.2041E+000
3.7382E+000
3.2723E+000
2.8065E+000
2.3406E+000
1.8748E+000
1.4089E+000
9.4307E-001
4.7722E-001
1.1364E-002
Z
0
15
30 (mm)

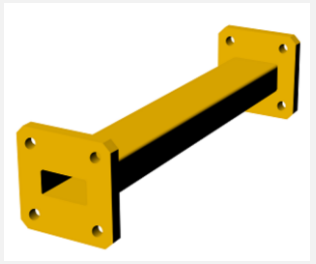
Characterization of Rectangular Waveguide

Objective

- Using HFSS, simulate an air-filled WR-90 waveguide shown in Fig. 1.
- To obtain the Field patterns, propagation constant for the first 4 modes (TE_{10}, TE_{20}, TE_{01}, TE_{11} modes).







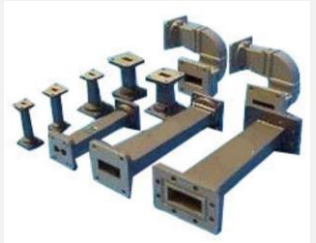
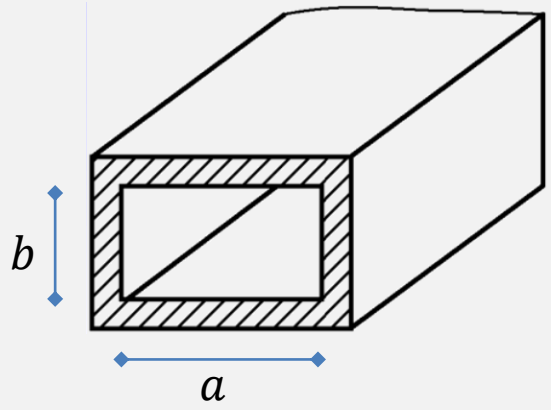


Figure 1 Rectangular waveguide. Units are in mm.

$\mathrm{TE}_{10}, \mathrm{TE}_{20}, \mathrm{TE}_{01}, \mathrm{TE}_{11}$



模式（Mode）：对于给定横截面的波导或者传输线，特定频率下有一系列的解满足相应的边界条件和麦克斯韦方程组。每个解都称为一种模式。

通常，模式是根据电场和磁场沿导波系统传输方向上有无分量这一情况来命名的。

假设导波系统沿着z轴放置，上述分量是指z向的电场分量E_z和磁场分量H_z。

TEM模：对于$E_z = 0, H_z = 0$一类的模，称为横电磁波。

TE模：对于 $E_z = 0, H_z \neq 0$ 一类的模，称为横电模，即TE模。

TM模：对于$E_z \neq 0, H_z = 0$一类的模，称为横磁模，即TM模。

$$H_z = H_{10} \cos\left(\frac{\pi}{a}x\right) e^{-j\beta z}$$

$$H_x = \frac{j\beta}{K_c^2}\left(\frac{\pi}{a}\right) H_{10} \sin\left(\frac{\pi}{a}x\right) e^{-j\beta z}$$

$$E_x = E_z = H_y = 0$$

$$E_y = -\frac{j\omega\mu}{K_c^2}\left(\frac{\pi}{a}\right) H_{10} \sin\left(\frac{\pi}{a}x\right) e^{-j\beta z}$$

$TE_{10}, TE_{20}, TE_{01}, TE_{11}$

TE波的纵向电场强度为0，即$E_z = 0$。

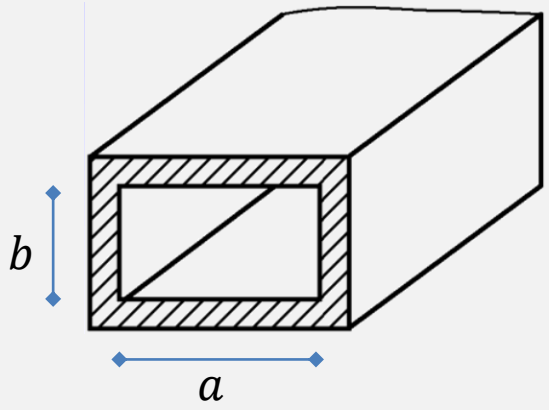
$$H_z = H_0 \cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)e^{-j\beta z}$$

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

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

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

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



$m = 1, n = 0$

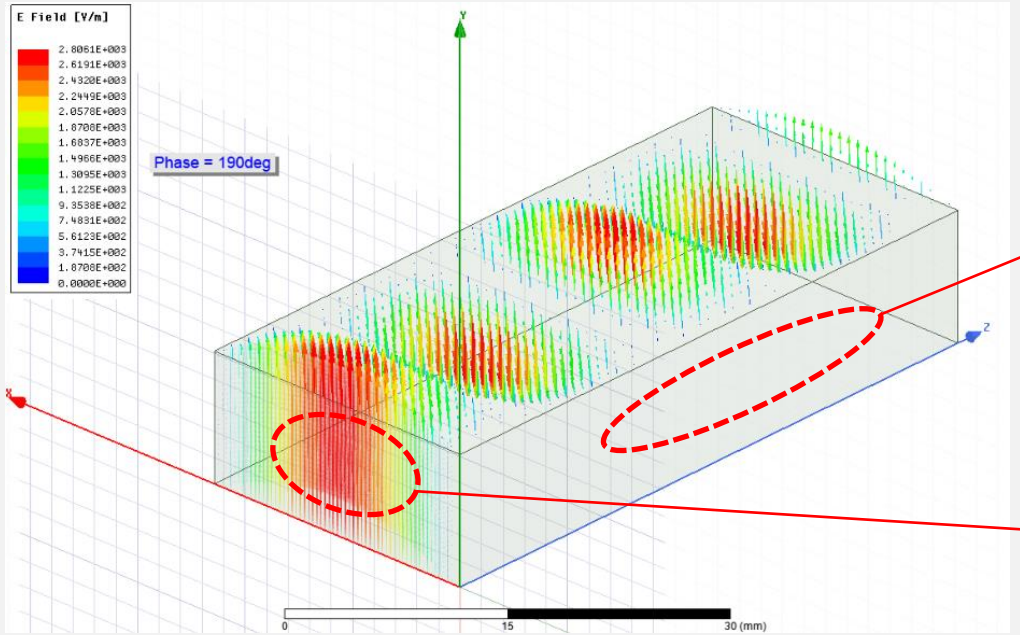
$$H_z = H_{10} \cos\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

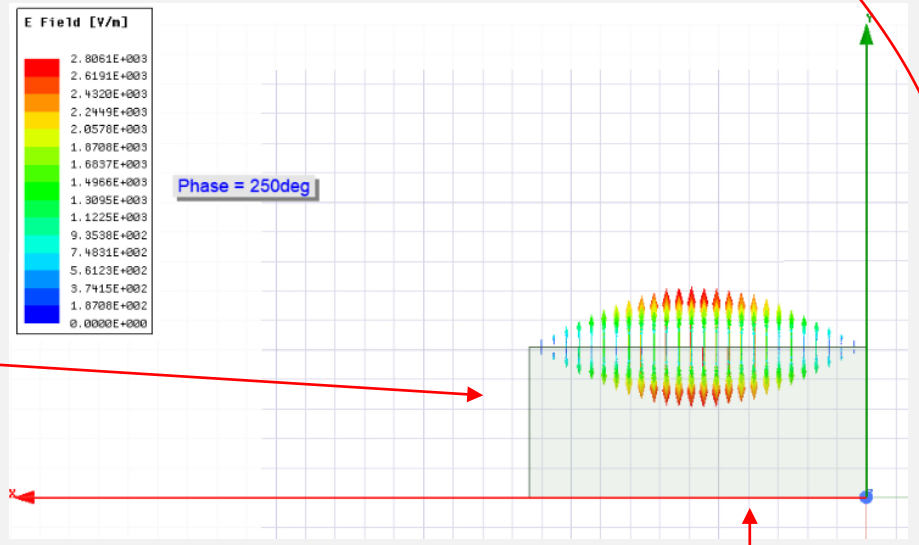
$$H_x = \frac{j\beta}{K_c^2}\left(\frac{\pi}{a}\right)H_{10} \sin\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

$$E_x = E_z = H_y = 0$$

$$E_y = -\frac{j\omega\mu}{K_c^2}\left(\frac{\pi}{a}\right)H_{10} \sin\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

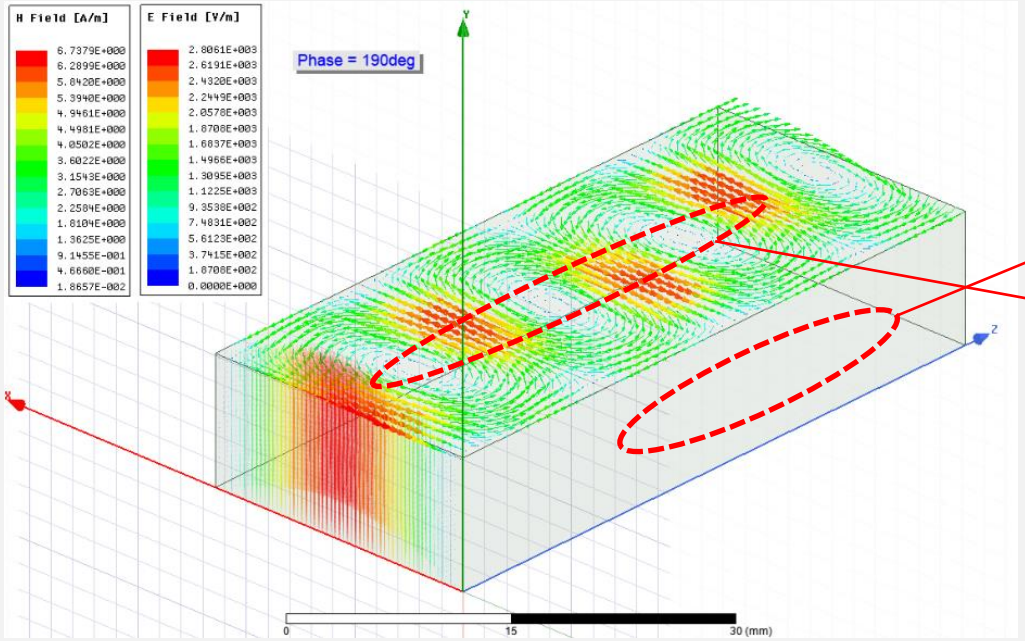
TE_{10}

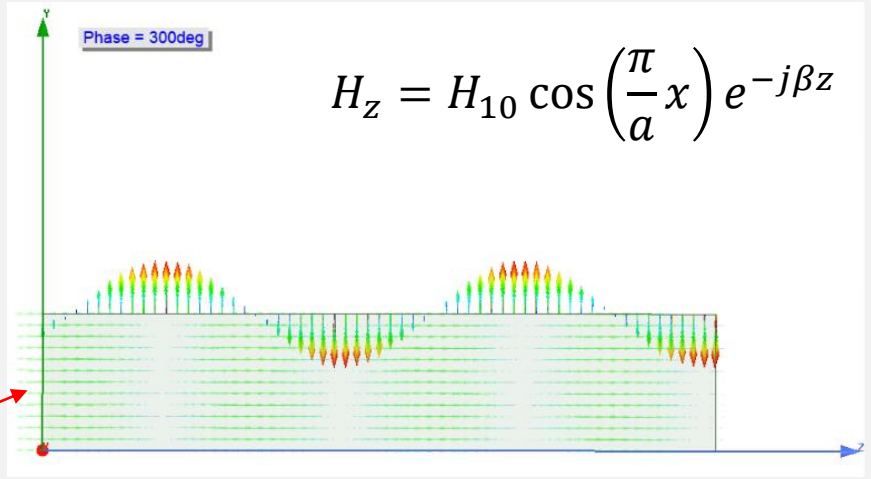




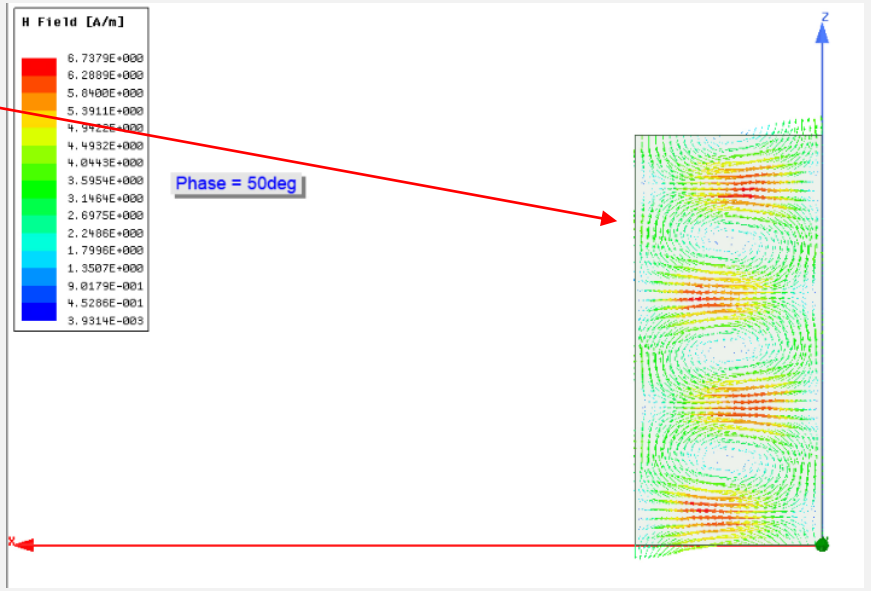
$$E_y = -\frac{j\omega\mu}{K_c^2}\left(\frac{\pi}{a}\right)H_{10}\sin\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

TE_{10}





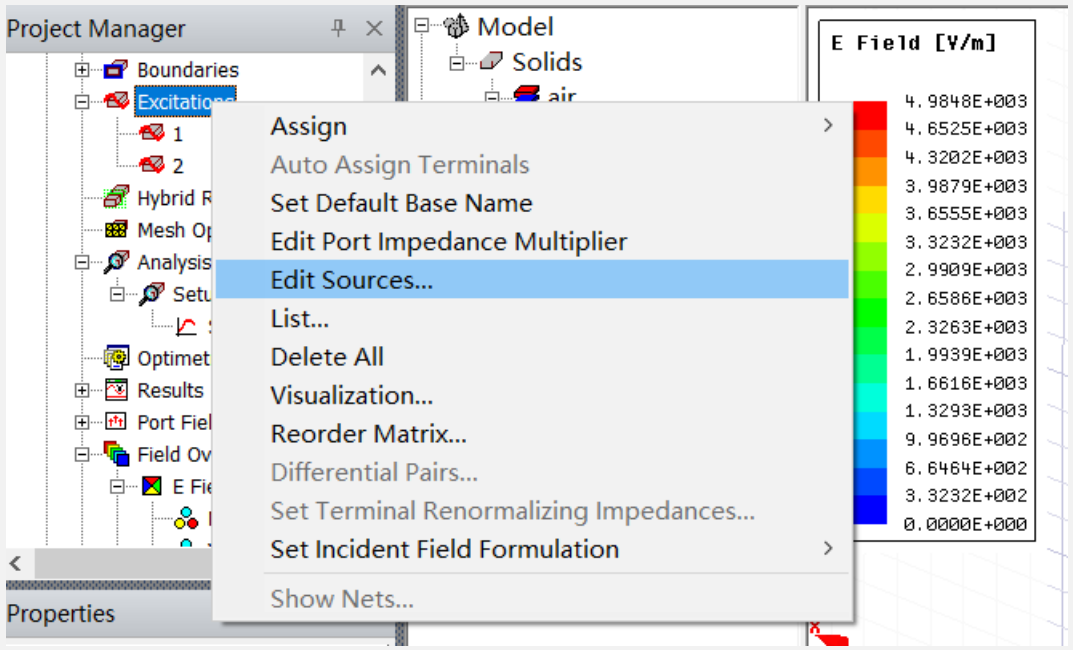
$$H_z = H_{10}\cos\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

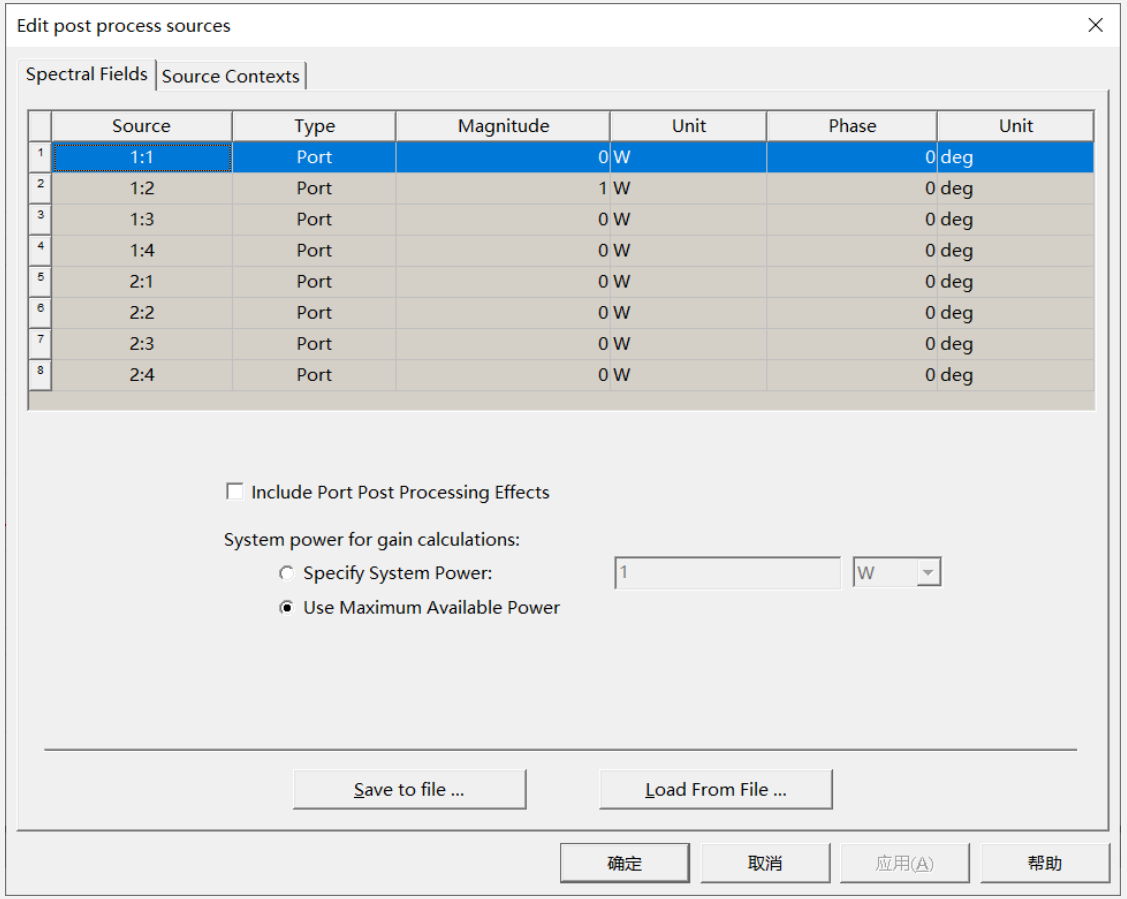


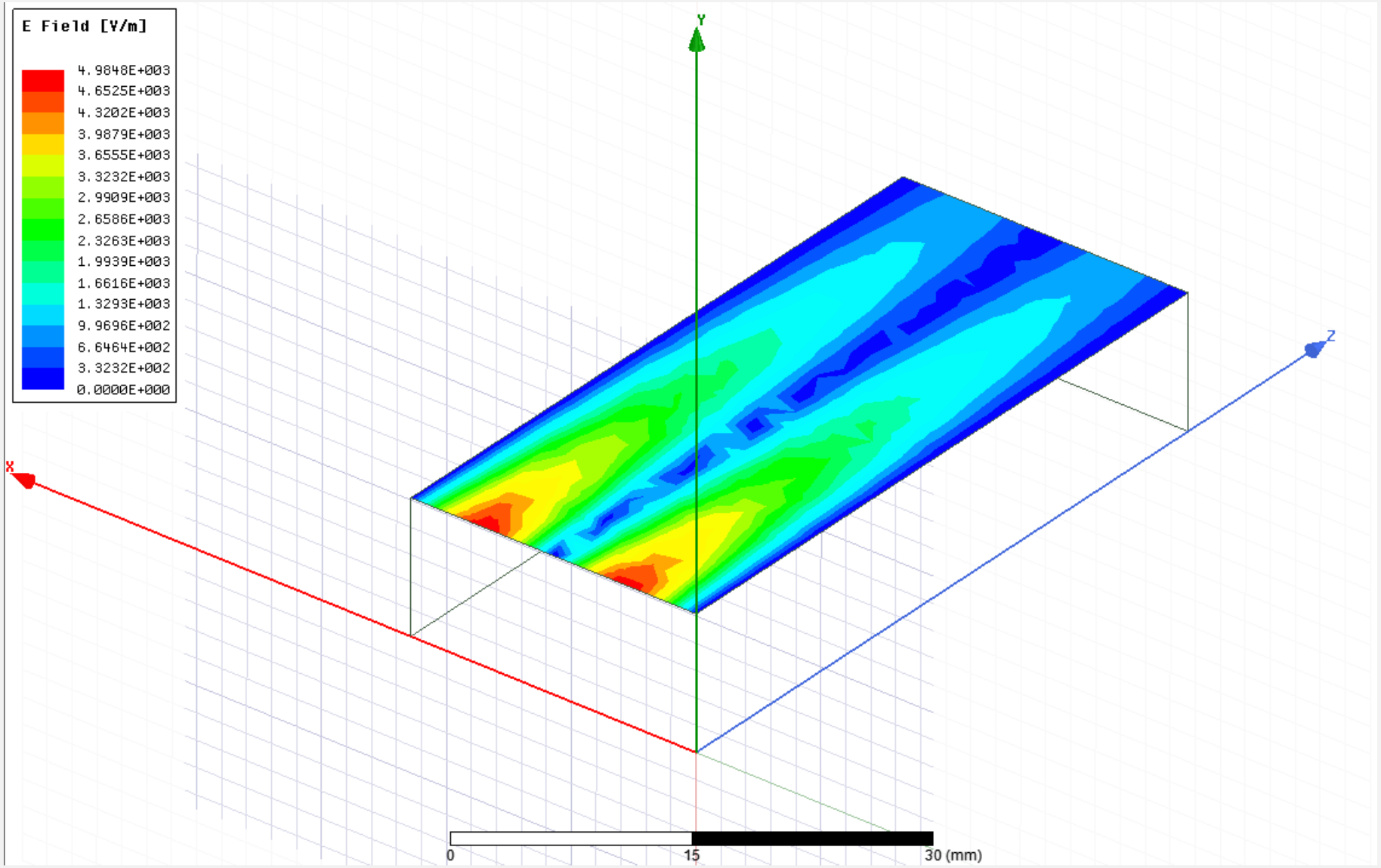
$$H_x = \frac{j\beta}{K_c^2}\left(\frac{\pi}{a}\right)H_{10}\sin\left(\frac{\pi}{a}x\right)e^{-j\beta z}$$

在默认的情况下，HFSS只计算主模，即模式1，但是在某些情况下，计算中考虑高阶模的影响是必须的。

例如，在一个端口模式1经过某个结构传输到另一个端口变为模式2时，这时有必要计算模式2下的参数。



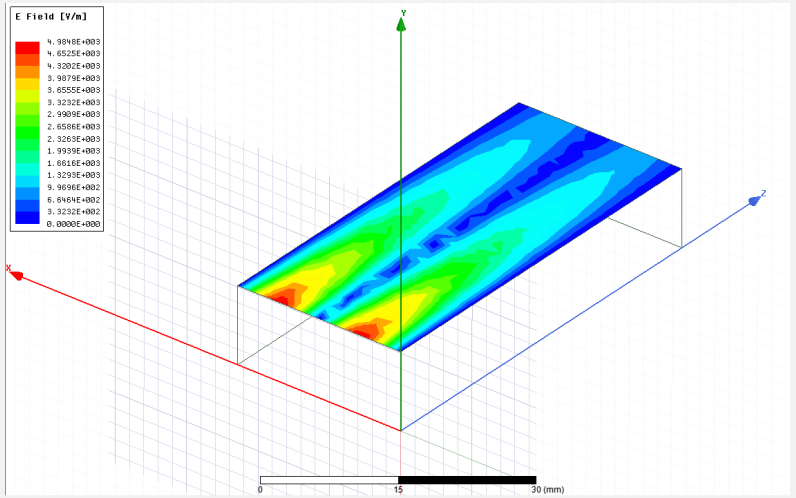



E Field [V/m]
4.9848E+003
4.6525E+003
4.3202E+003
3.9879E+003
3.6555E+003
3.3232E+003
2.9909E+003
2.6586E+003
2.3263E+003
1.9939E+003
1.6616E+003
1.3293E+003
9.9696E+002
6.6464E+002
3.3232E+002
0.0000E+000
Y
X
Z
0
15
30 (mm)

对于给定的工作频率或者波长，只有满足传播条件，

$$f > f_c \text{ 或者 } \lambda < \lambda_c$$

该模式才能在波导中传播。由公式可以看出矩形波导的f_c，λ_c不仅与波导的尺寸a, b有关，还和模数m, n有关。



当a, b一定时，随着f的改变，矩形波导可以多模传播，也可以单模传播，甚至可以处于截止。

例如，$a = 22.86mm, b = 10.16mm$的空心矩形波导，由

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

可得：$f_{cTE10} = 6.56GHz, f_{cTE20} = 13.12GHz, f_{cTE01} = 14.76GHz$，所以波导单模的频率范围为：$6.56 - 13.12GHz$。

ANSYS Electronics Desktop - Project2 - HFSSDesign1 - S Parameter Plot 1 - SOLVED - [Project2 - HFSSDesign1 - S Parameter Plot 1]

File Edit View Project Report2D HFSS Tools Window Help

Save | Cut Copy Paste Delete | Undo Redo | Docking Windows Layouts | Zoom | Zoom In Zoom Out | Pan | Fit All Fit Selected

Desktop View Simulation Results Automation

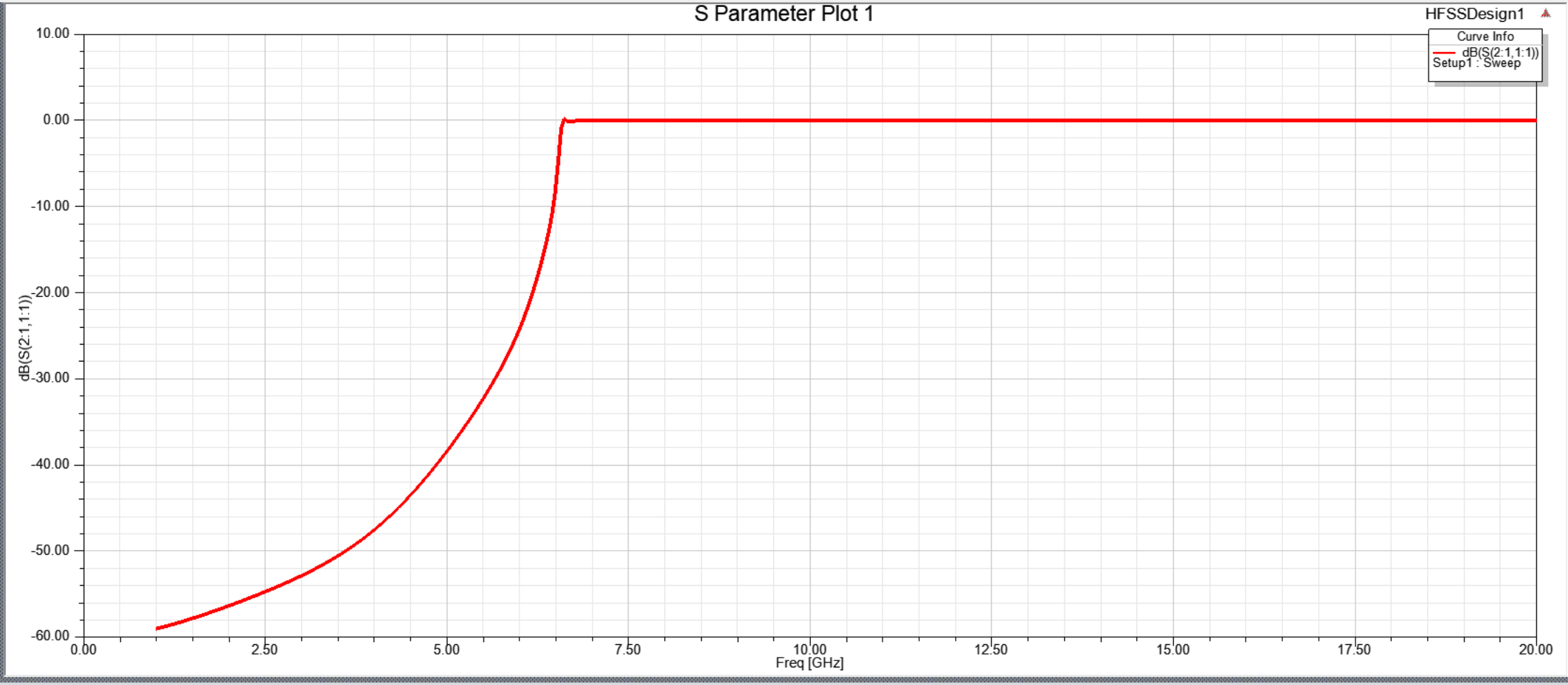
Project Manager

- Model
- Boundaries
- Excitations
  - 1
  - 2
- Hybrid Regions
- Mesh Operations
- Analysis
  - Setup1
    - Sweep
- Optimetrics
- Results
  - S Parameter Plot 1
    - dB(S(2:1,1:1))
- Port Field Display

Properties

Name	Value
Specif...	
Name	dB(S(2:1,1:1))
Y Axis	Y1
Primar...	Freq
Components	
Y Com...	dB(S(2:1,1:1))
X Com...	Freq
Context	
Soluti...	Setup1 : Sweep

Trace



Progress

Nothing is selected

Show 1 Messages | Hide Progress | X 4.1731 Y1 8.8006

ANSYS Electronics Desktop - Project2 - HFSSDesign1 - Gamma Plot 1 - SOLVED - [Project2 - HFSSDesign1 - Gamma Plot 1]

File Edit View Project Report2D HFSS Tools Window Help

Save | Cut Copy Paste Delete | Undo Redo | Docking Windows Layouts | Zoom Zoom In Zoom Out | Pan | Fit All Fit Selected

Desktop View Simulation Results Automation

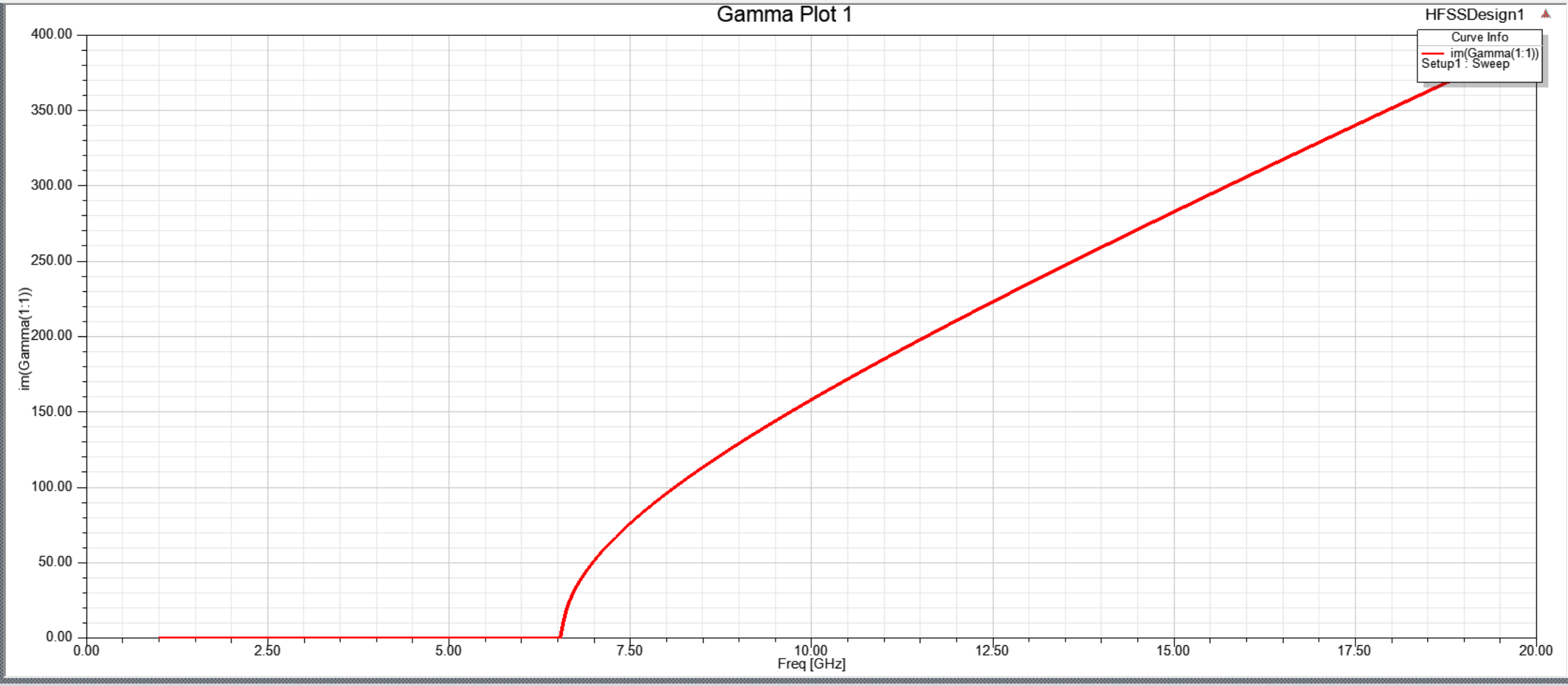
Project Manager

- Boundaries
- Excitations
  - 1
  - 2
- Hybrid Regions
- Mesh Operations
- Analysis
  - Setup1
    - Sweep
- Optimetrics
- Results
  - S Parameter Plot 1
    - dB(S(2:1,1:1))
  - **Gamma Plot 1**
    - im(Gamma(1:1))

Properties

Name	Value
Specif...	
Name	im(Gamma(1:1))
Y Axis	Y1
Primar...	Freq
Components	
Y Com...	im(Gamma(1:1))
X Com...	Freq
Context	
Soluti...	Setup1 : Sweep

Trace



Progress

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Show 1 Messages | Hide Progress | X 11.7152 Y1 397.5078

Reference

- https://zhuanlan.zhihu.com/p/81556773
- https://www.docin.com/p-1429660812.html
- http://www.doc88.com/p-9942895078347.html
- http://www.doc88.com/p-097107766668.html

Homework

Design rectangular waveguide based on HFSS and get the electric field distribution of its first three modes at

(1) 13 GHz and
(2) 15 GHz.

Waveguide size 22.86*10.16*100 (Unit: mm)。

Report：

1. Format should include title, objective, analysis/discussion, results, and conclusion
2. Include all relevant graphs and outputs from HFSS
3. Compare results for β with those obtained using corresponding theoretical expressions