



INSTITUTE OF AERONAUTICAL ENGINEERING

(Autonomous)

Dundigal - 500 043, Hyderabad, Telangana

COURSE CONTENT

ANTENNAS AND MICROWAVE ENGINEERING LABORATORY								
VI Semester: ECE								
Course Code	Category	Hours / Week			Credits	Maximum Marks		
AECC41	Core	L	T	P	C	CIA	SEE	Total
		-	-	4	2	30	70	100
Contact Classes: Nil	Tutorial Classes: Nil	Practical Classes: 45			Total Classes: 45			
Prerequisite: Electromagnetic Waves and Transmission Lines								

I. COURSE OVERVIEW:

This course introduces a basic introduction to the extensive field of RF microwave engineering. It involves measurement of frequency, wave length, VSWR, impedance and scattering parameters of various micro wave devices like circulator, directional coupler, and magic-tee. Microwave devices support larger bandwidth and hence higher data rates are transmitted. There are a wide variety of applications for microwaves like outdoor broadcasting transmissions and long distance telephone calls.

II. COURSES OBJECTIVES:

The students will try to learn

- The experiments on microwave test equipment to make measurements of microwave parameters and devices.
- The measurement of S-Parameters of microwave components to gain the practical hands on experience on the microwave test bench.
- The simulation to plot the radiation pattern for an antenna using High Frequency Software Simulator

III. COURSE OUTCOMES:

At the end of the course students should be able to:

CO1	Summarize the waveguide components and their specifications using microwave test bench set-up.
CO2	Sketch the characteristics of reflex klystron to obtain the electronic tuning range using klystron bench set up.
CO3	Analyze the characteristics of directional coupler, circulator and magic tee using microwave test bench setup.
CO4	Distinguish the low and high voltage standing wave ratio of unknown load to find out the reflection coefficient using slotted line section.
CO5	Identify fundamental parameters of the antenna to measure far-field radiation pattern using High frequency Structure Simulator.
CO6	Design various antennas to find out the antenna parameters using test setup and High Frequency Structure Simulator

IV. COURSE CONTENT:

EXERCISES FOR ANTENNAS AND MICROWAVE ENGINEERING LABORATORY

1. Getting Started Exercises

Introduction to Microwave Bench Setup

The microwave bench setup is designed to provide students and researchers with a hands-on experience in the field of microwave engineering. This setup allows for the study of various microwave components, devices, and systems, enabling practical exploration of concepts crucial in communication, radar, and other microwave applications.

Equipment and Components:

1. Microwave Signal Generator:

- Produces microwave signals with adjustable frequency and power.
- Used to generate input signals for various experiments.

2. Microwave Power Meter:

- Measures the power of microwave signals.
- Essential for characterizing the output power of microwave sources and devices.

3. Microwave Components:

- Attenuators, circulators, isolators, couplers, and various waveguide components.
- These components allow the construction of different microwave circuits and systems.

4. Reflex Klystron:

- A microwave tube used for generating and amplifying microwave signals.
- Provides insights into velocity modulation and frequency stability.

5. Waveguide System:

- Rectangular or circular waveguides for guiding microwave signals.
- Waveguide components such as twists, bends, and shorts for experimentation.

6. Directional Couplers and Magic Tees:

- Used for coupling and splitting microwave signals.
- Enable the study of power division and coupling in microwave circuits.

7. Frequency Meters and Oscilloscope:

- Frequency meters for accurate frequency measurement.
- Oscilloscope for visualizing microwave signals and waveforms.

8. VSWR Meter:

- Measures the Voltage Standing Wave Ratio to assess impedance matching.
- Ensures optimal performance of microwave circuits.

9. Antennas:

- Various types of antennas for radiating and receiving microwave signals.

- Allows experimentation with different antenna configurations.

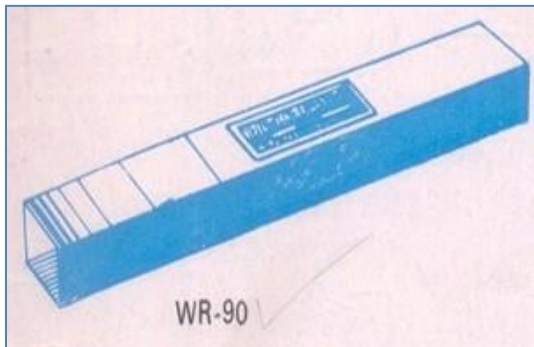


Figure: Rectangular waveguide

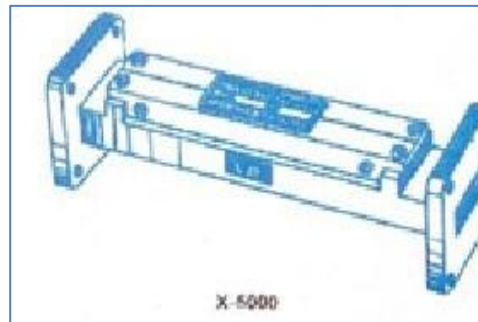


Figure: Fixed attenuator

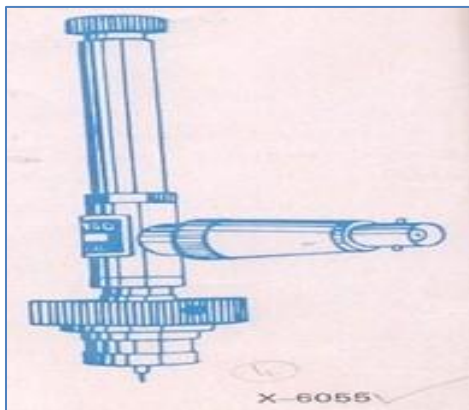


Figure: Tunable

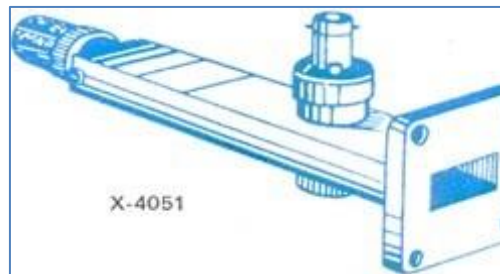


Figure: Detector Mount

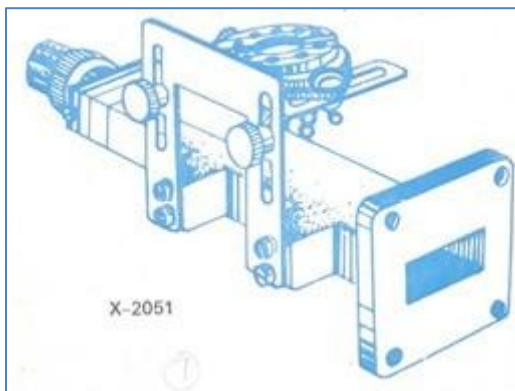


Figure: Klystron Mount

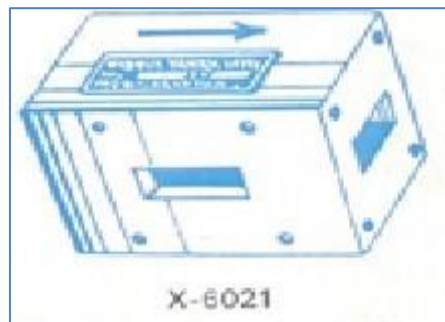


Figure: Circulator

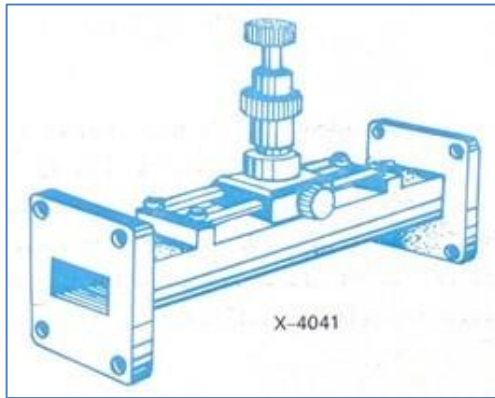


Figure: Slide Screw Tuners



Figure: Directional coupler

Setup and Configuration:

1. Power Supply:

- Ensure the power supply to the microwave bench is stable and within the specified range.

2. Connection of Components:

- Follow provided schematics to interconnect microwave components properly.
- Use high-quality coaxial cables and connectors for low-loss connections.

3. Safety Precautions:

- Adhere to safety guidelines for handling microwave equipment.
- Avoid direct exposure to microwave radiation and follow proper grounding practices.

1.1 Exercises on microwave bench set up

- 1 If the VSWR of a transmission line is 3, Calculate the reflection coefficient.
- 2 If the temperature of a circulator increases, what effect does it have on the insertion loss and isolation of the circulator.
- 3 Calculate the electron beam velocity in a reflex klystron tube with an anode voltage of 800 V and an anode-cathode separation of 1 cm.

Try:

- 1 If a Gunn diode has a length of 1 μm and an electron drift velocity of 10^7 cm/s, calculate the transit time of electrons through the diode.

2 Exercises on Reflex Klystron Characteristics

Reflex klystrons are vacuum tubes used for generating microwave signals. They are characterized by their ability to amplify microwave signals and to generate oscillations. Perform the following exercises:

2.1 Frequency-Voltage Characteristics:

- Plot a graph showing the relationship between repeller voltage and frequency as shown in the figure 2.1
- Analyze how changes in repeller voltage affect the klystron's operating frequency.

Expected Graph:

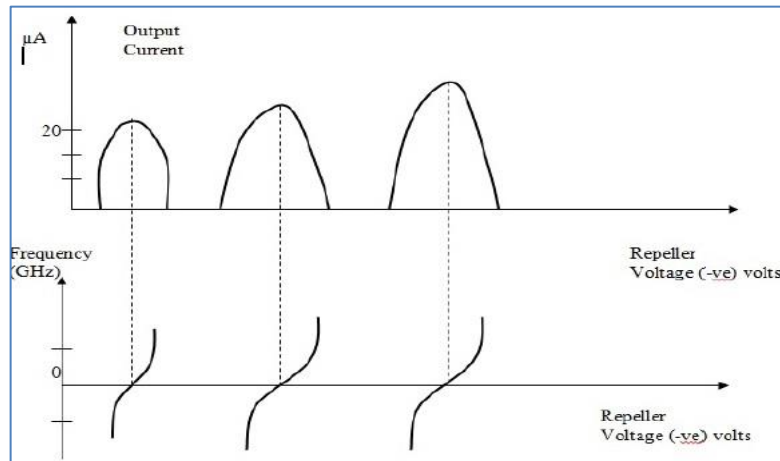


Figure 2.1 V-I Characteristics

2.2 Beam Current Modulation:

- Characterize the output voltage with repeller voltage
- If the beam voltage in a reflex klystron is 500 V and the repeller voltage is 300 V, Calculate the velocity of the electron beam as shown in the figure 2.2.

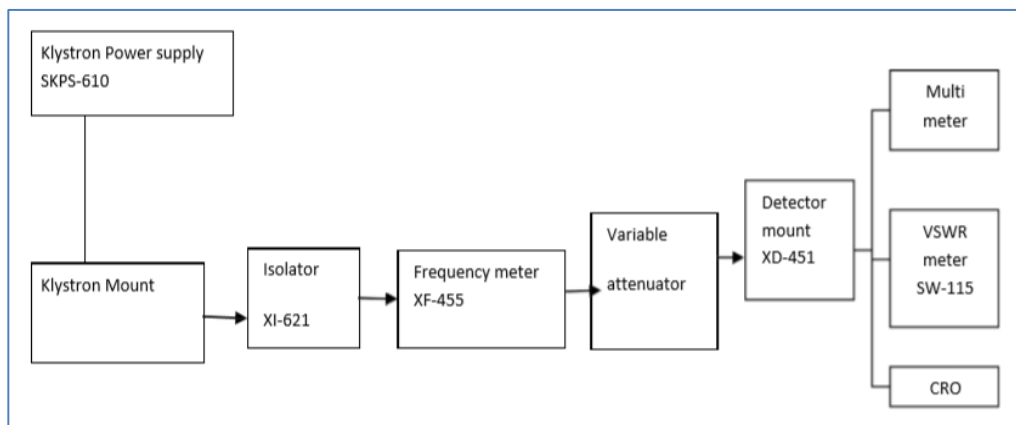


Figure 2.2: Reflex Klystron Characteristics

2.3 Modes of reflex klystron:

1. Calculate the efficiency of the reflex klystron using the formula: Efficiency = (Output Power / Input Power) * 100%.
2. Calculate resonant frequency assuming the mode of oscillation is the fundamental mode ($m = 1$).

Try:

1. A Klystron has the following parameters: $V_0 = 14.5 \text{ kV}$, $I_0 = 1.4 \text{ A}$, $f = 10 \text{ GHz}$, Calculate the dc beam current density
2. A Klystron amplifier has the following parameters: $V_0 = 18 \text{ kV}$, $I_0 = 2.25 \text{ A}$, $d = 1 \text{ cm}$, $f = 10 \text{ GHz}$, signal voltage $V_i = 10 \text{ V}$, beam coupling coefficient = 1, Calculate the dc electron velocity and plasma frequency.
3. Obtain the characteristics of Reflex Klystron by changing the frequency of operation and changing the anode voltage
4. If a reflex klystron consumes 50 mA of current at a beam voltage of 400 V and produces an output power of 5 mW, Calculate its efficiency.

3.Exercises on Gunn Diode Characteristics

Gunn diodes are semiconductor devices that exhibit negative differential resistance, making them

suitable for microwave applications. Perform the following practical exercises.

3.1 Voltage-Current Characteristics

- Plot V- I characteristics of Gunn Oscillator as shown in the figure 3.1 and determine the voltage range over which the Gunn diode exhibits negative resistance

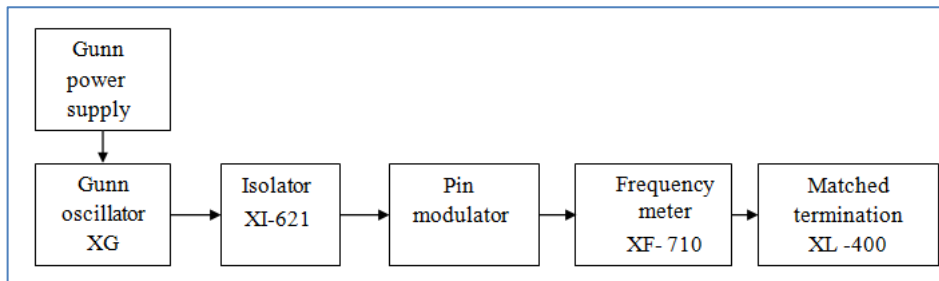


Figure 3.1: Block diagram of Gunn diode

3.2 Microwave Frequency Generation

- Plot Gunn bias vs frequency characteristics as shown in the figure 3.2 and calculate the oscillation frequency of the diode

Expected Graph:

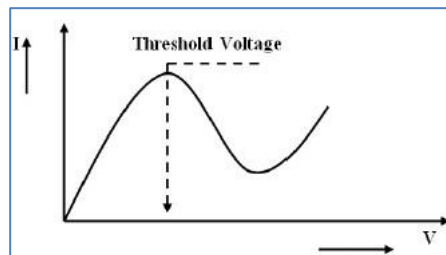


Figure 3.2: V – I characteristics of Gunn diode

3.3 Output Power Measurement

- Determine the threshold voltage and power of Gunn diode

Try:

- A Gunn diode has a resonant frequency of 10 GHz and can be tuned over a voltage range of 2 V. Calculate its frequency tuning range
- A Gunn diode has a length of 100 μm and a drift velocity of 10^7 cm/s. Calculate the oscillation frequency of the diode.
- A Gunn diode produces an output power of 1 mW with an input power of 10 mW. Calculate its efficiency

4. Exercises on Directional Coupler Characteristics

Directional couplers are crucial components in microwave systems for power splitting, combining, and signal monitoring. Perform the following exercises.

4.1 Measurement of Directivity

- Calculate the directivity of the three directional couplers as shown in the figure 4.1.

- Directivity, $D = 20 \log (V_3 / V_{3r})$ dB.

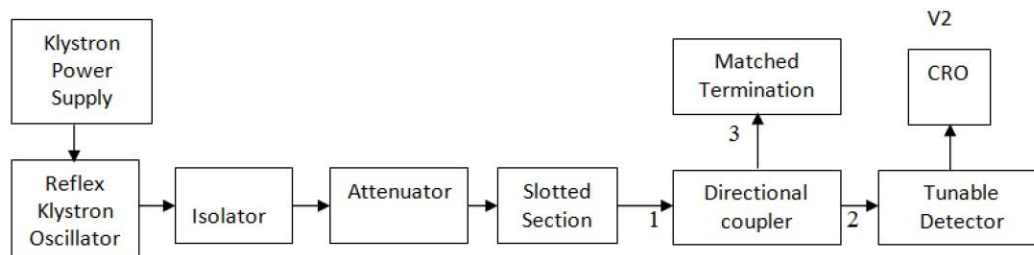


Figure 4.1: Measurement of directivity

4.2 Measurement of coupling factor

- Determine the Coupling Factor of a three-port directional coupler
- Calculate Coupling Factor (Coupling Ratio): Use the following formula to calculate the coupling factor (k): $k = 20 \log P_{\text{coupled}} / P_{\text{through}}$

4.3 Measurement of Isolation and Insertion Loss

- Determine the Isolation of a directional coupler
- Calculate Isolation (ISO): $ISO = P_{\text{without load}} - P_{\text{with load}}$
- Measure the Insertion Loss of a directional coupler
- Calculate Insertion Loss (IL): $IL = P_{\text{input}} - P_{\text{through}}$

Try:

1. A directional coupler with a forward coupling of -10 dB and a reverse coupling of -30 dB is used. Calculate the coupling ratio.
2. If a directional coupler has an insertion loss of 0.5 dB, what percentage of power is lost as the signal passes through the coupler
3. Observe the characteristics of the directional coupler by replacing klystron with gunn setup.
4. Determine the coupling factor and directivity of a four port directional coupler.

5. Exercises on Measurement of VSWR

The Voltage Standing Wave Ratio (VSWR) is a key parameter in RF and microwave systems, indicating the efficiency of power transfer between a transmission line and an antenna or load. Perform the following exercises.

5.1 Measurement of reflection coefficient:

- 1 Measure the incident and reflected power. Connect a power meter or a directional coupler to measure the incident and reflected power as shown in the figure 5.1
- 2 Calculate the VSWR using the formula
- 3 Obtain the reflection coefficient of any load attached to the waveguide using slotted line and VSWR meter.
- 4 Compute SWR increasing the distance between two successive minima positions of the probe

5.2 Measurement of low and high VSWR:

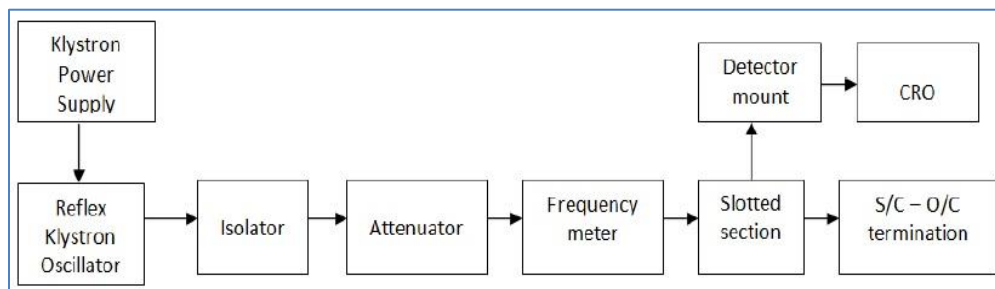


Figure 5.1: Measurement of VSWR

1. Measure low and high VSWR using slotted section as shown in the figure 5.1
2. Find guide wavelength and VSWR using the formula $VSWR = (1 + \sqrt{P_{refl}/P_{inci}}) / (1 - \sqrt{P_{refl}/P_{inci}})$.
3. Calculate the return loss using the formula: $Return\ Loss\ (dB) = -20 * \log_{10}(\sqrt{P_{refl}/P_{inci}})$.

Try:

1. Apply a known power level (e.g., 1 watt) to the input of the transmission line and measure the incident power using the VSWR meter.
2. Introduce a mismatch at the end of the transmission line to create reflections. Measure the reflected power using the VSWR meter.

6. Exercises on Circulator Characteristics

A circulator is a three-port device that is used to control the direction of signal flow in a microwave circuit. Perform the following practical exercises

6.1 Measurement of Insertion loss and Isolation loss:

- Calculate the insertion loss of a circulator as shown in the figure 6.1 using the formula:
 $Insertion\ Loss = 10 * \log_{10}(P_{in} / P_{out2})$.
- Calculate the isolation between port 2 and port 3 using the formula: $Isolation = 10 * \log_{10}(P_{out2} / P_{out3})$.
- Compute the S-matrix of a 3-port circulator.

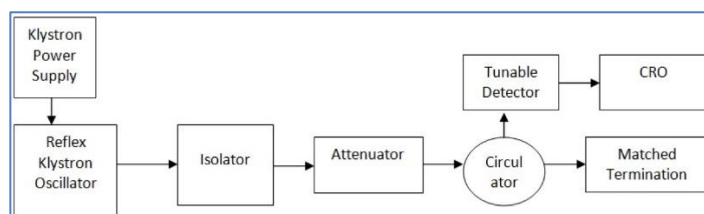


Figure 6.1: Circulator block diagram

6.2 Measurement of return loss:

Measure the power reflected back from port 2 (S11 parameter) and calculate the return loss using the formula:

$$Return\ Loss = -20 * \log_{10}(|S_{11}|).$$

Try:

1. A circulator has an isolation of 25 dB between port 1 and port 2. If a signal of 1 mW is incident on port 1, what is the power level at port 2.

2. A circulator has a return loss of 20 dB at port 3. Calculate the percentage of reflected power at port 3.
3. A circulator is specified to operate in the frequency range of 2-4 GHz. Calculate the bandwidth of the circulator.

7. Exercises on measurement of scattering parameters of magic TEE

A magic tee is a type of waveguide component used in microwave systems for power splitting and combining. Perform the following practical exercises.

7.1 Isolation coefficient and coupling coefficient measurement:

- For a given magic tee, determine the isolation between ports C and D by comparing the power at port D to the input power as shown in the figure 7.1
- Measure the coupling coefficient and determine the S – matrix of a magic – Tee.

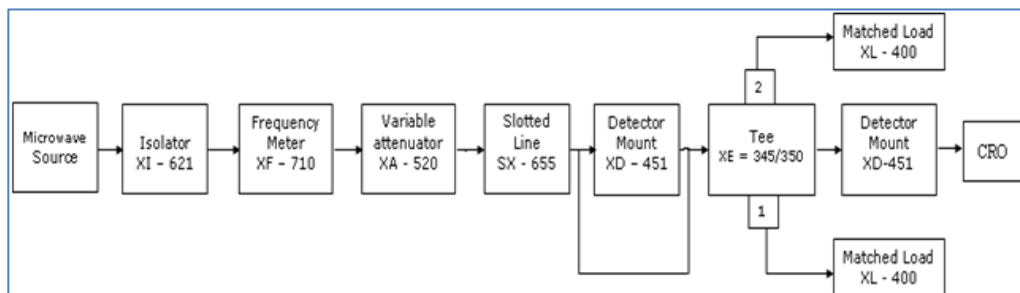


Figure 7.1: Block diagram of magic tee

Try:

1. If a Magic Tee divides an input signal equally between ports A and B, what is the power at each output port if a 10 dBm signal is input at port 1.
2. A Magic Tee has an isolation of 30 dB between ports C and D. If a signal is input at port 1, what is the power level at port D
3. For a Magic Tee operating at a frequency of 10 GHz, calculate the minimum cross-sectional dimensions of the waveguide.

8. Introduction to HFSS

HFSS, which stands for High-Frequency Structure Simulator, is powerful electromagnetic simulation software developed by Ansys. It is widely used in the field of radio frequency (RF) and microwave engineering for designing and analyzing high-frequency electronic components and systems. The software is particularly popular for its ability to simulate and optimize complex three-dimensional structures, making it an invaluable tool in the development of antennas, microwave circuits, and other RF devices.

Here is an introduction to the HFSS laboratory, which typically involves hands-on exercises and experiments using the HFSS software:

Overview of HFSS:

- Start with an introduction to the HFSS software, discussing its capabilities and applications in the field of electromagnetic simulation.
- Understand the importance of accurate simulation in the design and optimization of high-frequency devices.

Software Interface:

- Familiarize students with the HFSS user interface, including menus, toolbars, and navigation options.
- Learn how to set up a new project and define the necessary parameters.

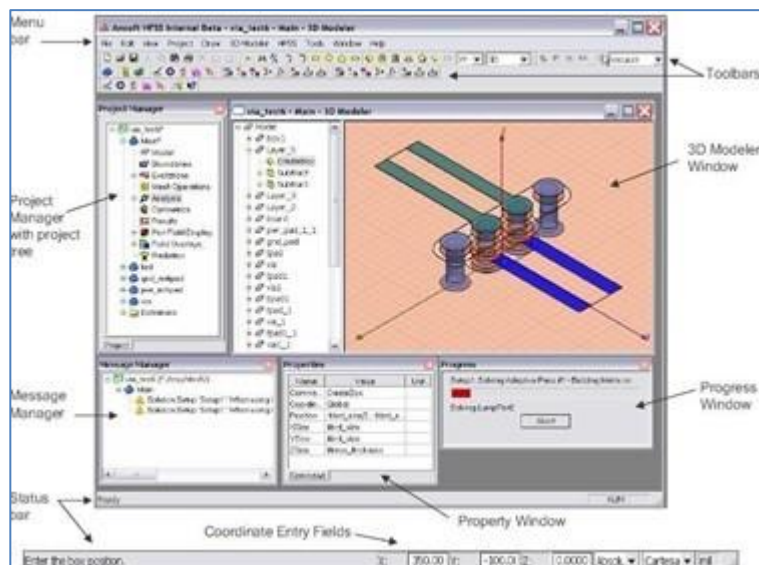


Figure 8.1: HFSS window

Geometry Creation:

- Explore the geometry creation tools in HFSS to build three-dimensional structures.
- Understand how to import existing CAD models or create simple shapes within HFSS.

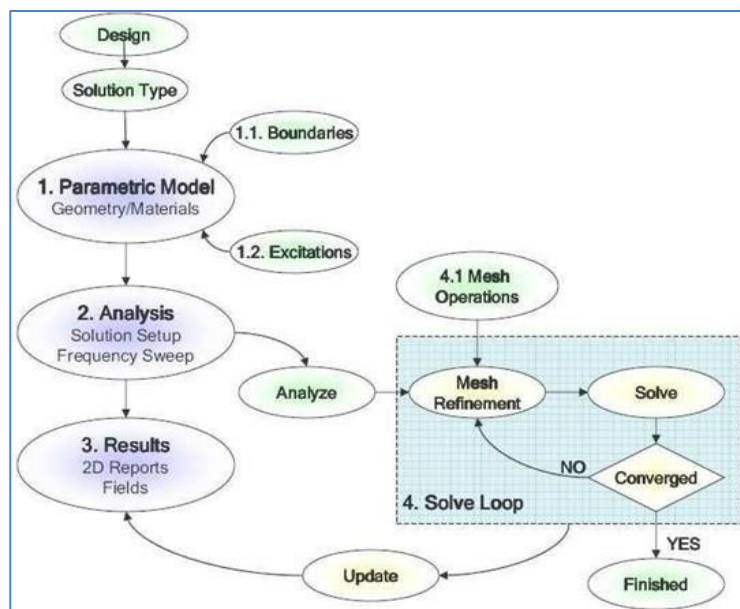


Figure 8.2: HFSS model

Material Assignment:

- Learn how to assign material properties to different parts of the geometry.
- Understand the impact of material properties on electromagnetic behavior.

Boundary Conditions:

- Explore different types of boundary conditions used in HFSS simulations.
- Understand how boundary conditions affect the accuracy of simulations.

Setup and Solution:

- Set up the simulation by defining frequency ranges, excitations, and other relevant parameters.
- Run simulations and analyze the results.

Post-Processing:

- Learn how to interpret simulation results using various post-processing tools.
- Visualize electromagnetic fields, S-parameters, and other relevant data

Parameter Sweeps and Optimization:

- Understand the concept of parameter sweeps to analyze the performance of a structure under different conditions.
- Explore optimization techniques to improve the design based on simulation results.

Antenna Design and Analysis:

- Focus on designing and analyzing antennas using HFSS.
- Explore different antenna types, such as patch antennas, dipole antennas, and array antennas.

8.1 Exercises on Yagi-Uda and rhombic antenna:

1. Create a Yagi-Uda antenna with a driven element, reflector, and directors. Optimize the lengths and spacing of the elements for maximum gain and desired radiation pattern.
2. Create a simple rectangular waveguide structure with specified dimensions.
3. A rhombic antenna consists of four sides, typically with unequal lengths, forming a diamond shape. Draw the rhombic antenna structure.

Try:

1. Design a basic V antenna and plot the radiation pattern
2. Design an omni-directional antenna and plot the radiation pattern

9. Exercises on monopole and dipole antenna

A monopole antenna is a class of radio antenna consisting of a straight rod-shaped conductor, often mounted perpendicularly over some type of conductive surface, called a ground plane. A dipole antenna is the simplest type of radio antenna, consisting of a conductive wire rod that is half the length of the maximum wavelength the antenna is to generate. Perform the following practical exercises.

9.1 Gain and efficiency for simple monopole:

1. Create a Monopole Antenna Geometry as shown in the figure 9.1. Calculate the radiation efficiency of the monopole antenna using the simulated radiation pattern and the input power.
2. Calculate the gain of a monopole antenna with a length of 1 meter operating at 500 MHz.
3. Design a monopole antenna for a frequency of 2.4 GHz with a quarter-wavelength vertical element above a ground plane. Calculate the length of the monopole.

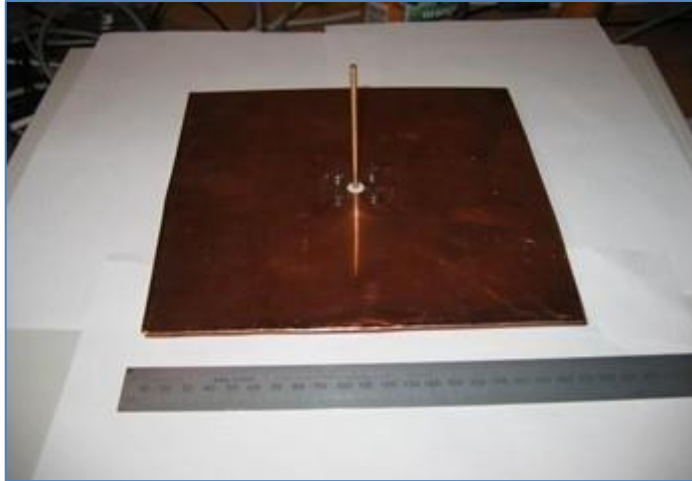


Figure 9.1: Monopole antenna

9.3 Radiation pattern and directivity using HFSS modeling tool:

1. Analyze the radiation pattern and measure the antenna's gain and directivity.
2. Calculate the directivity of a dipole antenna as shown in the figure 9.2 with a radiation efficiency of 95% operating at 900 MHz.
3. The gain (G) of the antenna can be calculated using the formula $G = 4\pi \times \text{directivity}$.
4. The directivity (D) of the antenna can be calculated using the formula: $D = 4\pi \times (\text{Radiated power} / \text{total power})$.

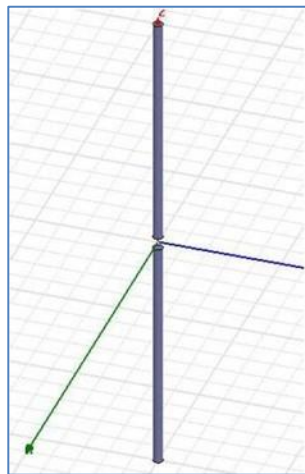


Figure 9.2: Dipole antenna

Try:

1. Simulate the radiation pattern of the dipole antenna as shown in the figure 9.2 in the azimuth plane ($\phi=0$) and the elevation plane ($\theta=90$). Measure the beamwidth and directivity of the antenna.
2. Perform a frequency sweep from 2.3 GHz to 2.5 GHz and analyze the bandwidth of the dipole antenna. Calculate the -10 dB and -3 dB bandwidths.

10. Exercises on Loop antenna

Loop antennas are commonly used for receiving and transmitting signals in the radio frequency range. Perform the following practical exercises.

10.1 Radiation pattern of Loop Antenna:

1. Design a small loop antenna as shown in the figure 10.1 for a specific frequency, such as 100 MHz.
2. Calculate the dimensions of the loop using the formula for the circumference of a circle and adjust for the desired frequency
3. Measure the radiation pattern of the loop antenna in the horizontal and vertical planes using a rotating antenna measurement setup
4. Construct loop antennas of different sizes (e.g., $1/4$ wavelength, $1/2$ wavelength) for the same frequency.
5. Measure the radiation pattern of the loop antenna at different distances from the antenna (near field and far field).

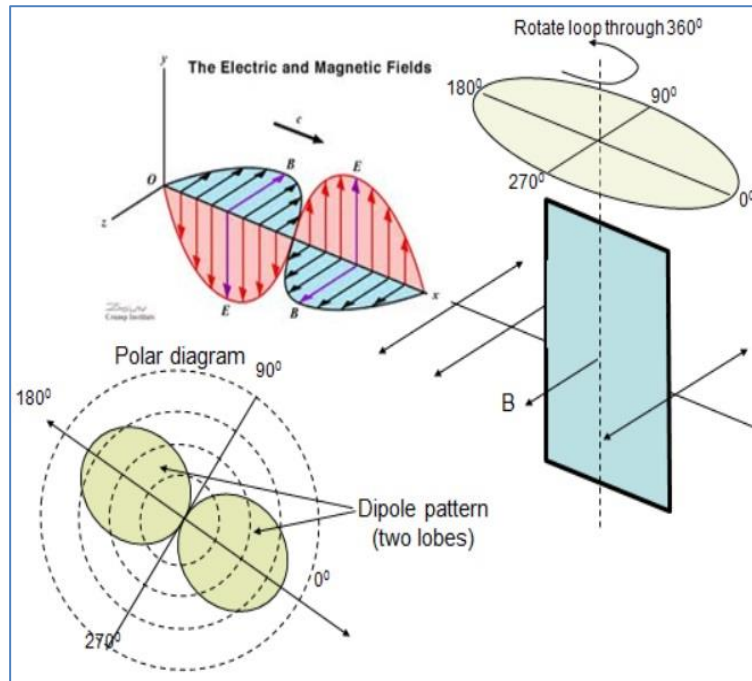


Figure 10.1: Loop antenna

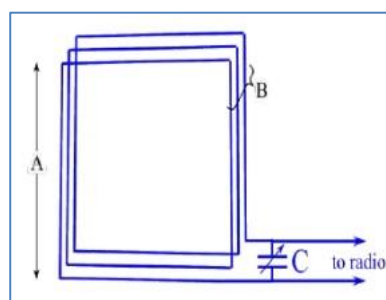


Figure 10.2: Square Loop antenna

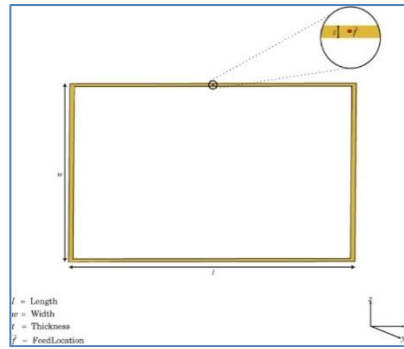


Figure 10.3: Rectangular Loop antenna

Try:

1. Design a matching network (e.g., a series capacitor) for a square loop antenna as shown in the figure 10.2 to achieve a 50-ohm impedance match at the operating frequency. Calculate the value of the matching component.
2. Given a frequency of operation (e.g., 100 MHz) and desired loop circumference-to-wavelength ratio (e.g., 0.1), calculate the dimensions (radius, diameter, or side length for a square loop) of the loop antenna.
3. Calculate the bandwidth of a rectangular loop antenna as shown in the figure 10.3 based on its physical dimensions and the Q factor of the antenna. Determine the percentage bandwidth for a given Q factor.

11. Exercises on microstrip feed antenna design

A microstrip feed antenna is an antenna design that uses a microstrip transmission line to feed electromagnetic energy to the antenna element. Perform the following practical exercises.

11.1 Microstrip Antenna Design and Simulation:

1. Simulate the radiation pattern of the microstrip patch antenna as shown in the figure 11.1 in the azimuth plane ($\phi=0$) and the elevation plane ($\theta=90$). Measure the beamwidth and directivity of the antenna.
2. Calculate the bandwidth of the antenna using the formula: $\text{Bandwidth} = f_{\text{upper}} - f_{\text{lower}}$, where f_{upper} and f_{lower} are the frequencies
3. Calculate the radiation efficiency of the microstrip patch antenna using the simulated radiation pattern and the input power.
4. The radiation efficiency of a microstrip patch antenna can be calculated using the formula:

$$\eta = P_{\text{rad}} / P_{\text{in}}$$

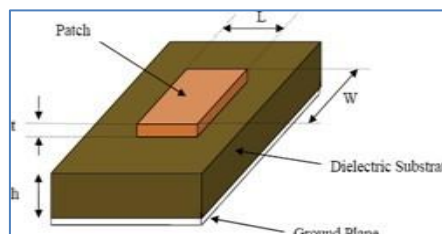


Figure 11.1: Microstrip patch antenna

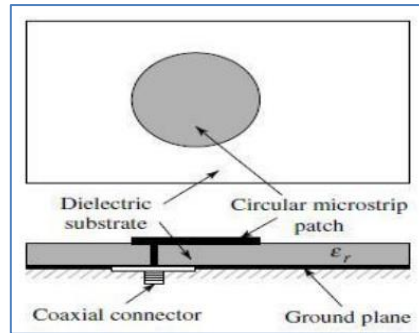


Figure 11.2: Circular patch antenna

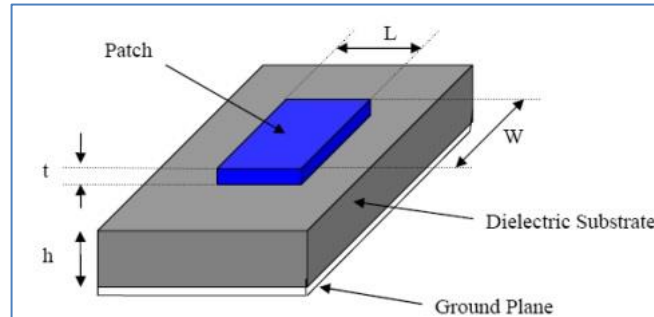


Figure 11.3: Square patch antenna

Try:

1. Perform a frequency sweep from 2.3 GHz to 2.5 GHz and analyze the bandwidth of a circular patch antenna as shown in the figure 11.2. Calculate the -10 dB and -3 dB bandwidths.
2. Given an operating frequency 2.3 GHz and radiation pattern requirements, calculate the dimensions (side lengths and angles) of a circular patch antenna for optimal performance.
3. Design a microstrip patch antenna for a frequency of 2.4 GHz with a square patch shown in the figure 11.3 on a substrate material. Calculate the dimensions of the patch and the feed line.

12. Exercises on slot coupled patch antenna

A slot-coupled patch antenna is a type of microstrip antenna that uses a slot in the patch to couple electromagnetic energy between the patch and the feed line. Perform the following lab exercises using HFSS.

12.1 Slot Antenna-Radiation efficiency:

1. Determine the resonant length and width of the patch based on the operating frequency using the formula for a square patch.
2. Calculate the radiation efficiency of the slot-coupled patch antenna using the simulated radiation pattern and the input power.
3. Use the formula below to calculate the radiation efficiency of the slot-coupled patch antenna

$$\eta = P_{\text{rad}} / P_{\text{in}}$$

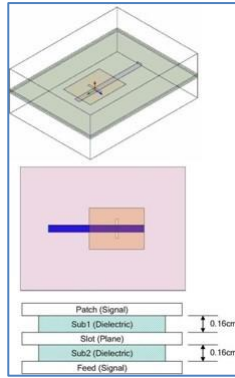


Figure 12.1: Slot coupled patch antenna

12.2 Bandwidth Enhancement:

1. Measure resonance frequency, impedance, and radiation pattern
2. Calculate the bandwidth by finding the difference between the highest and lowest frequencies at which the return loss is -10 dB or lower.

Try:

1. Design a slot-coupled patch antenna for a center frequency of 2.4 GHz. The substrate material has a relative permittivity of 4. Calculate the dimensions of the patch and the slot.
2. Perform a frequency sweep from 2.3 GHz to 2.5 GHz and analyze the bandwidth of the slot-coupled patch antenna. Calculate the -10 dB and -3 dB bandwidths.
3. Compare the simulated results (e.g., resonance frequency, impedance matching, radiation pattern) with the theoretical expectations for a slot-coupled patch antenna.

13. Exercises on probe feed patch antenna design

Designing and experimenting with probe-fed patch antennas using HFSS involves a combination of simulation and practical measurements. Perform the following practical exercises.

13.1 Basic Probe-Fed Patch Antenna Design:

- Design a probe feed patch antenna for a frequency of 2.4 GHz with a rectangular patch on a substrate material
- Determine the probe position for the desired impedance matching. The probe is typically placed at a distance of around 0.25 to 0.3 times the patch width from the edge of the patch.
- Measure the beamwidth and directivity of the antenna
- Calculate the Effective Dielectric Constant.

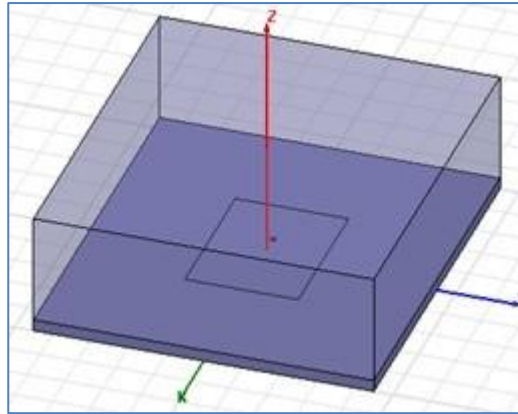


Figure 13.1: Probe feed patch antenna

Try:

1. Design a probe feed patch antenna for a frequency of 2.4 GHz. Calculate the dimensions of the patch (length and width) for a substrate with a relative permittivity of 4 and a thickness of 1.6 mm.
2. Calculate the bandwidth of the probe feed patch antenna based on the -10 dB return loss bandwidth. Given that the antenna has a return loss of -10 dB at 2.4 GHz and -20 dB at 2.5 GHz, Calculate the bandwidth.
3. Calculate the radiation efficiency of the probe feed patch antenna based on the input power and the total radiated power

14. Exercises on Horn Antenna design

Microstrip line is a type of transmission line used in microwave engineering and high-frequency electronics. Perform the following practical exercises.

14.1 Design of pyramidal horn antenna:

1. Design and test a pyramidal horn antenna as shown in the figure 14.1 operating at a frequency of 3 GHz with the following specifications:
2. Operating frequency: 3 GHz
3. Horn aperture size: 100 mm x 100 mm
4. Flare angle: 20 degrees
5. Measure the radiated power at various angles around the antenna.

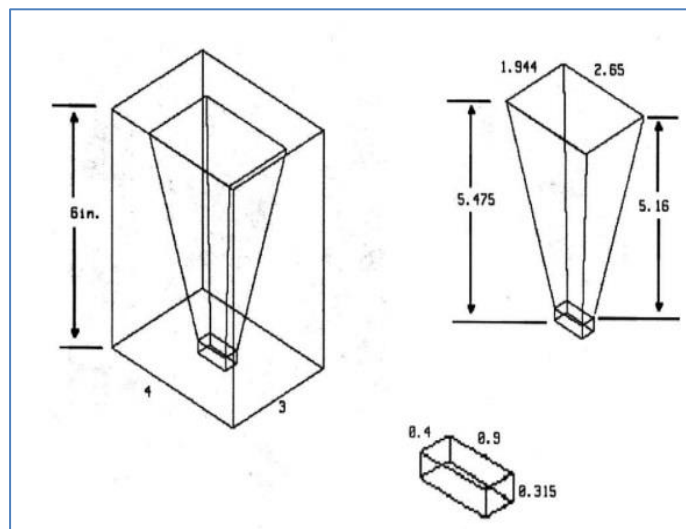


Figure 14.1: Horn antenna

14.2 Frequency Response Analysis:

1. Calculate the beamwidth of the horn antenna as shown in the figure 14.1 based on its dimensions and operating frequency. Compare the calculated beamwidth with the measured beamwidth from the radiation pattern measurement.



Figure 14.2 E plane sectoral horn antenna

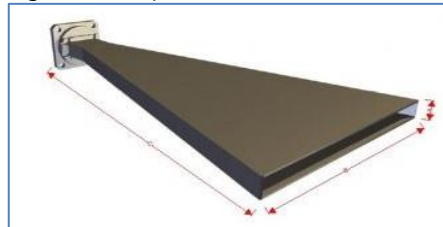


Figure 14.3 H plane sectoral horn antenna

Try:

1. Measure the radiation pattern of the sectoral horn antenna as shown in the figures 14.2 and 14.3 in both E-plane and H-plane. Compare the measured patterns with the simulated patterns from HFSS.
2. Given the operating frequency of 10 GHz and the desired beamwidth of 20 degrees, calculate the dimensions of a sectoral horn antenna with a rectangular aperture as shown in the figure 14.3.

V. TEXT BOOKS:

1. John D. Kraus, Ronald J. Marhefka, Ahmad S. Khan, “Antennas and Wave Propagation”, TMH, 4th edition, 2010.
2. Samuel Y. Liao, “Microwave Devices and Circuits”, Pearson, 3rd edition, 2003.

VI. REFERENCE BOOKS:

1. Herbert J. Reich, J.G. Skolnik, P.F. Ordung and H.L. Krauss, “Microwave Principles CBS Publishers and Distributors, New Delhi, 1st edition, 2004.
2. F.E. Terman, “Electronic and Radio Engineering”, McGraw-Hill, 4th edition, 1955.

VII. ELECTRONICS RESOURCES:

1. <https://www.slac.stanford.edu/pubs/slacpubs/7500/slac-pub-7731.pdf>
2. https://www.onlinecourses.nptel.ac.in/noc20_ee63/preview
3. <http://nptel.ac.in/courses/antennas>

VIII. MATERIALS ONLINE

1. Course template
2. Lab manual