Chapter-1

RADAR PRINCIPLES

1.1 Radar Range Equation

1.1.1 INTRODUCTION

Radar (**RA**dio **D**etection and **R**anging) uses radio waves to find, identify, and follow distant objects. To determine different attributes including distance, direction, and speed, it sends electromagnetic waves, receives the waves' reflections back from objects, and analyses these reflections.

How a Radar System Works?

Electromagnetic waves are transmitted, propagated, reflected, received, and processed by a radar system. High-frequency radio waves are first produced by a transmitter and then sent into space via an antenna. As these waves pass through the atmosphere, some of their energy is reflected into the radar system when they encounter an object like an aircraft or piece of terrain. The radar antenna receives this reflected energy, also referred to as an echo. A signal processor receives the received signal, which is usually far weaker than the outgoing one. The processor analyses the signal to extract important information such as the object's distance (by measuring the time delay between transmission and reception), direction (based on the angle of arrival), and speed (by detecting frequency shifts due to the Doppler effect). The processed data is then displayed on a screen, enabling the detection, location, and tracking of objects in real time.

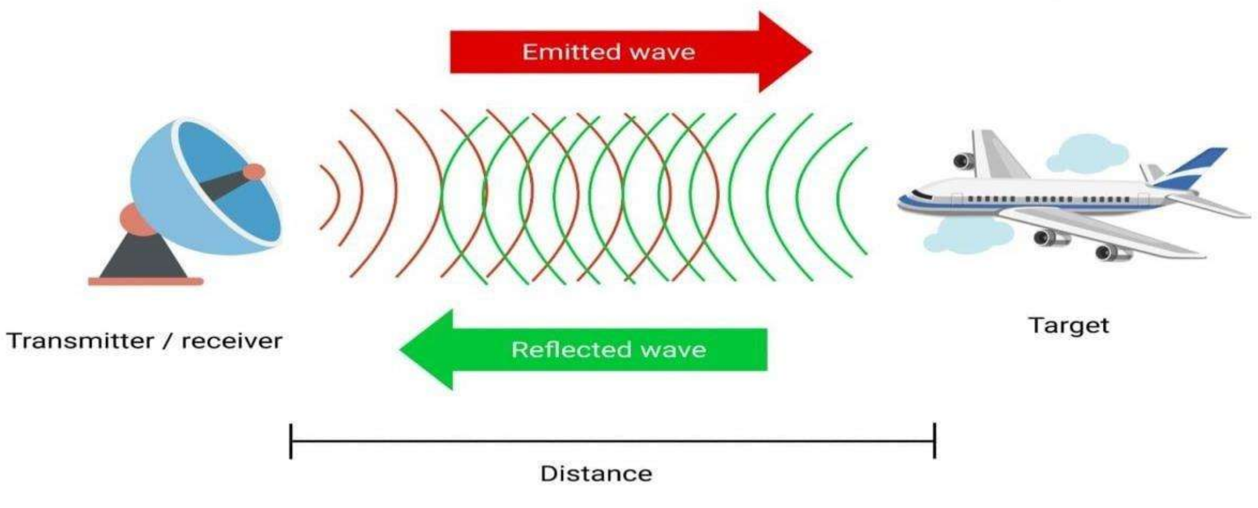


Fig.1.1: Radar operation

1.1.2 TYPES OF RADAR SYSTEM

Radar systems are classified based on their functionality, waveform, and antenna structure. Below are the commonly used radar types:

Continuous Wave (CW) Radar

Continuous Wave (CW) Radar is a type of radar system that continuously transmits a signal and detects objects by analyzing the frequency shift of the returned signal due to the Doppler effect. Unlike pulse radar, CW radar does not measure range directly but is highly effective in measuring the relative velocity of a moving target.

Principle of Operation:

CW radar continuously emits a radio frequency (RF) signal. When this signal reflects off a moving object, it experiences a change in frequency (Doppler shift). By analyzing this frequency shift, the relative velocity of the object can be calculated using the Doppler equation: $f_d=2v/\lambda$

Where:

- f_d = Doppler frequency shift
- v = relative velocity of the target
- λ = wavelength of the transmitted signal

Types of CW Radar:

- **Unmodulated Continuous Wave Radar:**
  - Transmits a constant unmodulated Signal.
  - Used primarily for Velocity measurement.
  - The radar compares the received signal with the transmitted signal to measure the **Doppler frequency**, which gives the **relative velocity**.
  - Can’t measure the range of a target.

- **Frequency Modulated Continuous Wave (FMCW) Radar:**
  - Transmits a modulated (usually linearly frequency-modulated) signal**.**
  - Capable of measuring both range and velocity.
  - When this signal reflects off an object, the echo returns with a **delay** due to the distance.

- The **frequency difference** between the transmitted and received signal (called the **beat frequency**) is proportional to the time delay, which can be used to calculate **range**.

Advantages:

1) Simple design and low power consumption.
2) High accuracy in velocity detection.
3) Continuous monitoring without waiting between ú.
4) No ambiguity in Doppler frequency measurement.

Disadvantages:

1) Unmodulated CW radar cannot measure range.
2) Susceptible to interference from other RF sources.
3) FMCW systems are more complex to implement.

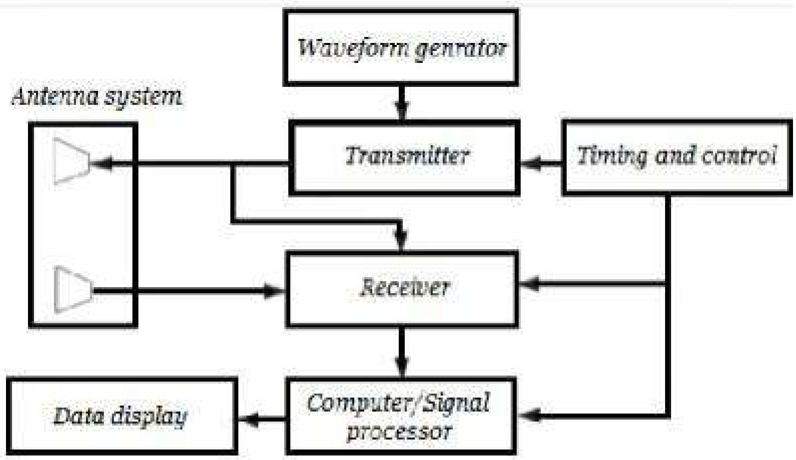


Fig.1.2 a) Block Diagram for Continuous wave Radar

➢ <u>Pulse Radar</u>

Pulse radar is a type of radar system that transmits high-power radio wave pulses at regular intervals and listens for their echoes to detect and locate objects. Unlike continuous wave (CW) radar, which transmits constantly, pulse radar operates in burst mode and can determine the distance (range), direction, and sometimes velocity of targets. Classified based on the Pulse Repetition Frequency (PRF) as below:

- Low PRF—Primarily used for ranging where target velocity (Doppler shift) is not of interest.
- High PRF—mainly used to measure target velocity.

Principle of Operation:

Pulse radar works on the "transmit-wait-receive" principle:

- A short-duration, high-frequency pulse is transmitted.

- The radar then waits (listens) for any echo from a target.
- If an object reflects the pulse, the echo is received after a time delay.
- The distance (range) of the target is calculated using the formula:

$$R = c.t/2$$

Where:

- R = Range of the object
- T = time delay between receiver and transmission
- c = Speed of light ($\sim 3 \times 10^8$ m/s)

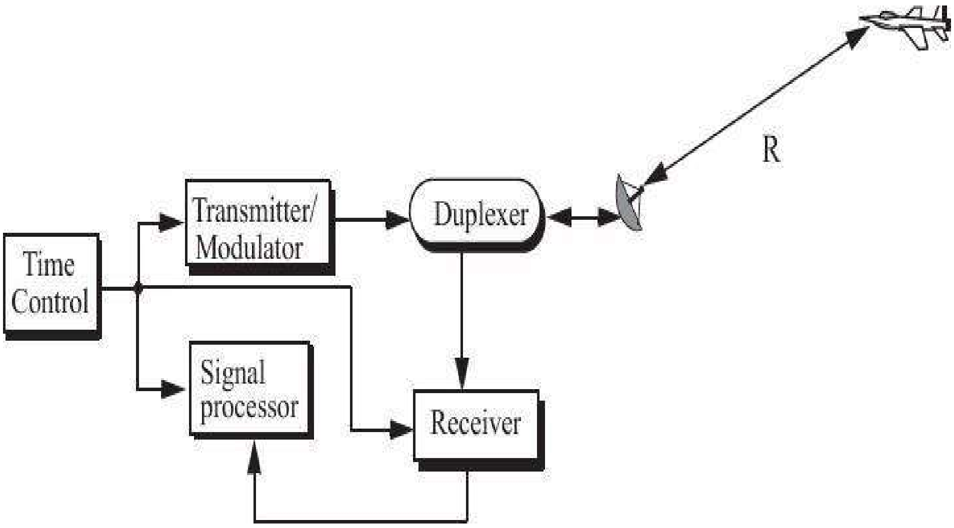


Fig.1.2 b) Block Diagram of Pulse Radar

➢ Components of a Pulse Radar System:

- **Pulse Generator**: Generates the timing signals for transmitting pulses.
- **Transmitter**: Amplifies and sends out the radar pulse.
- **Antenna**: Used for both transmitting and receiving (usually via a duplexer).
- **Receiver**: Captures the reflected signals (echoes).
- **Duplexer**: Switches the antenna between transmit and receive modes.
- **Signal Processor**: Extracts information (like range) from received signals.
- **Display System**: Shows target information, often on a radar screen.

Advantages:

1) Can measure both range and angle of a target
2) Works well over long distances
3) Can detect multiple targets
4) Less affected by Doppler ambiguities compared to CW radar

Disadvantages:

1) Requires high peak power for long-range detection.
2) Complex design.
3) Minimum range limitation due to pulse duration and receiver recovery time.

➢ Phased Array Radar

Phased array radar is an advanced type of radar system that uses multiple antennas (elements) to electronically steer the direction of the radar beam without physically moving the antenna. By adjusting the phase of the signal emitted from each antenna element, the combined beam can be focused and directed in the desired direction almost instantly.

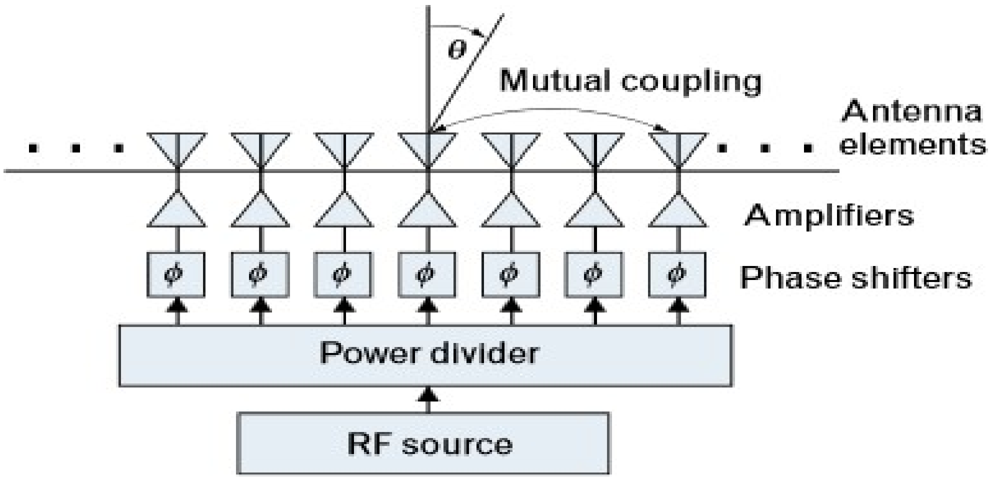


Fig.1.3 Phased Array Radar diagram

Working Principle:

- The phased array radar operates by sending signals from multiple antenna elements, each with a controlled phase shift
- When these phase-shifted signals combine in space, they interfere constructively in one direction and destructively in others, creating a steerable beam.
- The direction of the beam can be changed by electronically varying the phase shifts across the antenna elements.
- No mechanical movement is required to steer the beam.
- Beam steering can be done in **microseconds**, allowing the radar to track multiple targets simultaneously or switch between them rapidly.

Types of Phased Array Radar:

➢ **Passive Phased Array Radar (PESA)**:

- A single transmitter feeds all elements.

- Only the **phase is varied** at each element.
- Simpler and cheaper, but less flexible.

➢ **Active Phased Array Radar (AESA):**

- Each antenna element has its **own transmitter and receiver**.
- Allows **independent beamforming**, higher power, and better reliability.
- Used in modern military and aerospace systems.

Advantages:

1) Fast electronic beam steering — no mechanical movement
2) Simultaneous tracking of multiple targets
3) High accuracy and resolution
4) Scalable and modular system design
5) Can operate in hostile or dynamic environments

Disadvantages:

1) Complex and expensive to design and manufacture
2) High power consumption, especially in AESA systems
3) Heat management is critical due to the number of active components

1.1.3 DOPPLER RADAR

A Doppler radar is a specialized radar that utilizes the Doppler effect to determine the velocity and location of objects, such as weather systems or precipitation. It measures the change in frequency (Doppler shift) of the radar signal reflected back from a moving target to infer its speed and direction. This technology is commonly used in weather forecasting to track storms, precipitation, and other atmospheric phenomena.

Types of Doppler Radar:

- Continuous Wave (CW) Doppler Radar
- Pulsed Doppler Radar
- Frequency-Modulated Continuous Wave (FMCW) Radar Frequency-Modulated Continuous Wave (FMCW) Radar Frequency-Modulated Continuous Wave (FMCW) Radar

Doppler Shift

The **Doppler Effect**, named after Austrian physicist **Christian Doppler**, refers to the **change in frequency (or wavelength)** of a wave observed by someone moving relative to the wave source. This phenomenon is commonly experienced in sound waves, like when a siren seems higher-pitched as it approaches and lower-pitched as it moves away. It also applies to **electromagnetic waves**, including **radio waves**, making it crucial in **radar systems** for detecting the velocity of objects.

➢ Principle of Doppler Effect

The Doppler Effect occurs because the relative motion between the source and observer compresses or stretches the wavefronts:

- If the source and observer move toward each other, the observed frequency increases.
- If they move apart, the observed frequency decreases.

➢ Doppler Shift Equation

For electromagnetic waves (like radar), the Doppler shift in frequency fd is given by:

$$f_d = 2v/\lambda$$

Where:

- f_d= Doppler frequency shift
- v = relative velocity between radar and target
- λ= wavelength of the transmitted signal

Alternatively,

$$f_d = 2 * v * f_o / c$$

Where:

- f_o = transmitted frequency
- c= speed of light (~3×10^8 m/s)

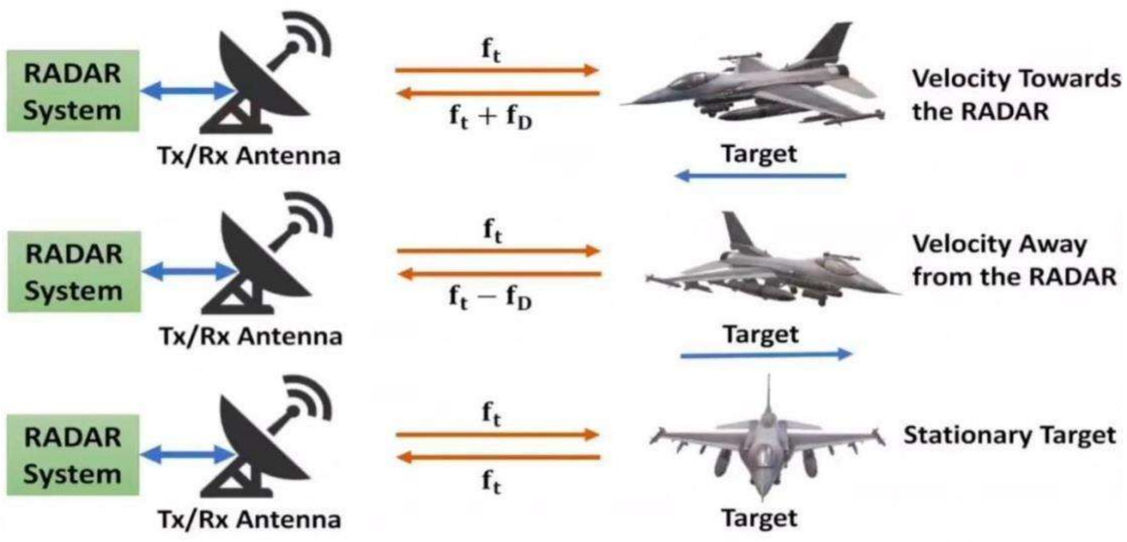


Fig.1.4 Doppler effect in radar system

1.1.4 RADAR RANGE EQUATION

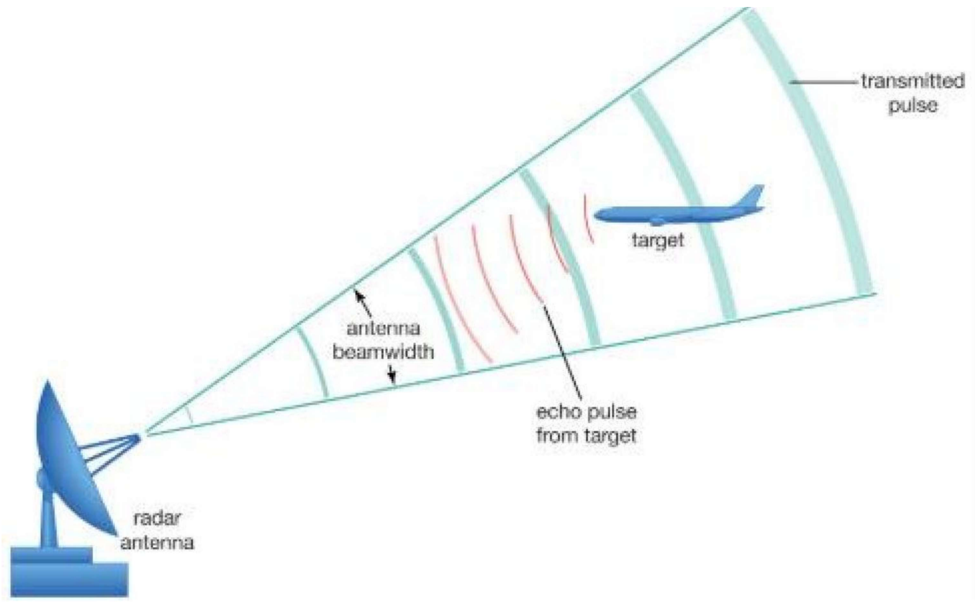


Fig.1.5 Transmission and reflection of EM wave

➢ Basic Concept

The radar range equation expresses the **maximum distance (R)** at which a radar can detect a target with a given **radar cross-section (σ)**, under certain assumptions.

The received power (P_r) must be greater than or equal to the **minimum detectable signal** (P_{min}) for successful detection.

➢ Standard Radar Range Equation

Parameters Used

Let's define the key parameters:

- P_t = Transmitted Power (W)
- G = Antenna Gain (unitless)
- λ = Wavelength (m)
- σ = Radar Cross Section of the target (m²)
- R = Distance to the target (m)
- P_r = Received Power (W)
- S_{min} = Minimum detectable power (W)
- A_e = antenna effective aperture
- k = Boltzmann's constant
- T_s = System noise temperature
- T_o = Reference temperature

- T_a = Antenna temperature
- T_e = Effective receiver noise temperature
- B = Bandwidth
- F = Noise figure
- SNR_i = Input signal-to-noise ratio
- SNR_0 = Output signal-to-noise ratio
- SNR_{min} = Minimum required signal-to-noise ratio
- L = Radar losses

Step-by-Step Derivation:

Step 1: Power Density with Isotropic Antenna

For an isotropic antenna, the power density, in Watts/m^2, at range away R from the radar (assuming a lossless propagation medium) is:

Step 2: Power Density with Directional Antenna (Gain G)

Directional antennas focus energy, increasing power density by a factor of gain G:

$$P_D = \frac{P_t}{(4\pi R^2)}$$

$$G = \frac{(4\pi A_e)}{\lambda^2}$$

Where P_D is the Power Density

$\boldsymbol{P_t}$ is the peak transmitted power.
R: Distance between transmitter and target
G: Gain.
$\boldsymbol{A_e}$: Aperture Area

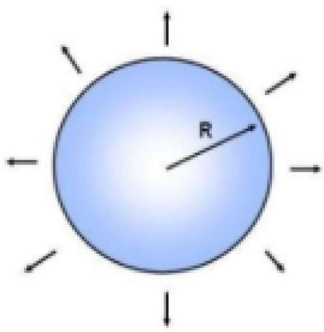


Fig.1.6 Radiation pattern of an isotropic antenna

Step 3: Radar Cross Section

The radar cross section is defined as the ratio of the power reflected back to the radar to the power density on the target,

$$\sigma = \frac{P_r}{P_d} m^2$$

where, Pr is the power reflected from the target. Thus, the total power delivered to the radar signal processor by its antenna is:

$$P_{Dr} = \frac{P_t G \sigma}{(4\pi R^2)^2} A_e$$

Step 4: Received Power Considering Receiving Antenna Aperture

The power received by the radar's antenna is also affected by the antenna effective aperture A_e. Using the relation between gain and effective aperture:

$$G = \frac{4\pi A_e}{\lambda^2} => \frac{G\lambda^2}{4\pi}$$

Substitute this into the expression for we have

$$P_{Dr} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

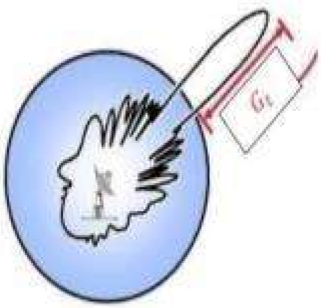


Fig.1.7 Radiation pattern of a directional antenna

Step 5: Radar Range Equation

Let S_{min} be the minimum detectable signal power. Setting P_r=S_{min} , solve for the maximum radar range R_{max} :

$$R_{max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right)^{\frac{1}{4}}$$

Step 6: Define Minimum Detectable Signal Smin

The noise power is a function of the radar operating bandwidth.

N=*Noise* PSD x B

The receiver input noise power is $N_i = kT_sB$

It is always desirable that the minimum detectable signal (S_{min}) be greater than the noise power. The fidelity of a radar receiver is normally described by a figure of merit referred to as the noise figure, F. The noise figure is defined as

$$F = \frac{(SNR)_i}{(SNR)_o} = \frac{(\frac{S_i}{N_i})}{(\frac{S_o}{N_o})}$$

The receiver effective noise temperature excluding the antenna is $T_e = T_o(F - 1)$
It follows that the total effective system noise temperature is given by

$$T_S = T_e + T_a = T_o(F-1) + T_a = T_oF - T_o + T_a$$

In many radar applications, it is desirable to set the antenna temperature to and thus, is reduced reduced to

$$T_S = T_oF$$

and substituting the result into F, yields

$$S_o = KT_oBF(SNR)_o$$

Thus, the minimum detectable signal power can be written as

$$S_{min} = KT_oBF(SNR)_{o\ min}$$

Step 7: Solve for Maximum Range R_{max}
The radar detection threshold is set equal to the minimum output SNR,

$$R_{max} = \left(\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3KT_oBF(SNR)_{omin}}\right)^{1/4}$$

Or equivalently,

$$(SNR)_{omin} = \left(\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3KT_oBFR_{max}{}^4}\right)$$

Step 8: Include Radar Losses, L
In general, radar losses denoted by reduce the overall SNR, and hence

$$(SNR)_o = \left(\frac{P_tG^2\lambda^2\sigma}{(4\pi)^3KT_oBFR^4}\right)$$

1.1.5 SIMULATION OF RADAR RANGE EQUATION

CODE:

```
f = 3.2e9;                         % Frequency (Hz)
lambda = 3e8 / f;                  % Wavelength (m)
Pt = 12400;                        % Transmit power (W)
Gt_dB = 39;
Gr_dB = 39;           % Gains in dB
Gt = 10^(Gt_dB / 10);
Gr = 10^(Gr_dB / 10);
sigma = 10^(-15/10);               % RCS (m^2)
k = 1.38e-23;                      % Boltzmann's constant (J/K)
T0 = 290;                          % Temperature (K)
B = 2e6;                           % Bandwidth (Hz)
F_dB = 3;
F = 10^(F_dB / 10);   % Noise figure (linear)
Ls_dB = 9;
Ls = 10^(Ls_dB / 10);% System loss (linear)
to = 2e-3;                         % Pulse width (s)
duty_cycle = 0.2;                  % 20%

% 1. R vs SNR
SNR = linspace(1, 1000, 500);   % Vary SNR from 1 to 1000
numerator = Pt * Gt * Gr * lambda^2 * sigma * duty_cycle * to;
denominator_common = (4*pi)^3 * k * T0 * F * Ls;

R_snr = (numerator ./ (denominator_common * SNR)).^(1/4); % in meters

figure;
plot(SNR, R_snr / 1e3, 'b', 'LineWidth', 2);
grid on;
xlabel('SNR (linear)');
ylabel('Radar Range R (km)');
title('Radar Range vs SNR');
% 2. R vs RCS
sigma_vals = logspace(-4, 2, 500); % RCS from 0.0001 to 100 m²
SNR_fixed = 10;                     % Fixed SNR
R_rcs = (Pt * Gt * Gr * lambda^2 .* sigma_vals * duty_cycle * to ./ ...
         (denominator_common * SNR_fixed)).^(1/4);  % in meters

figure;
semilogx(sigma_vals, R_rcs / 1e3, 'r', 'LineWidth', 2);
grid on;
xlabel('Radar Cross Section \sigma (m^2)');
ylabel('Radar Range R (km)');
title('Radar Range vs RCS');
```

PLOT:

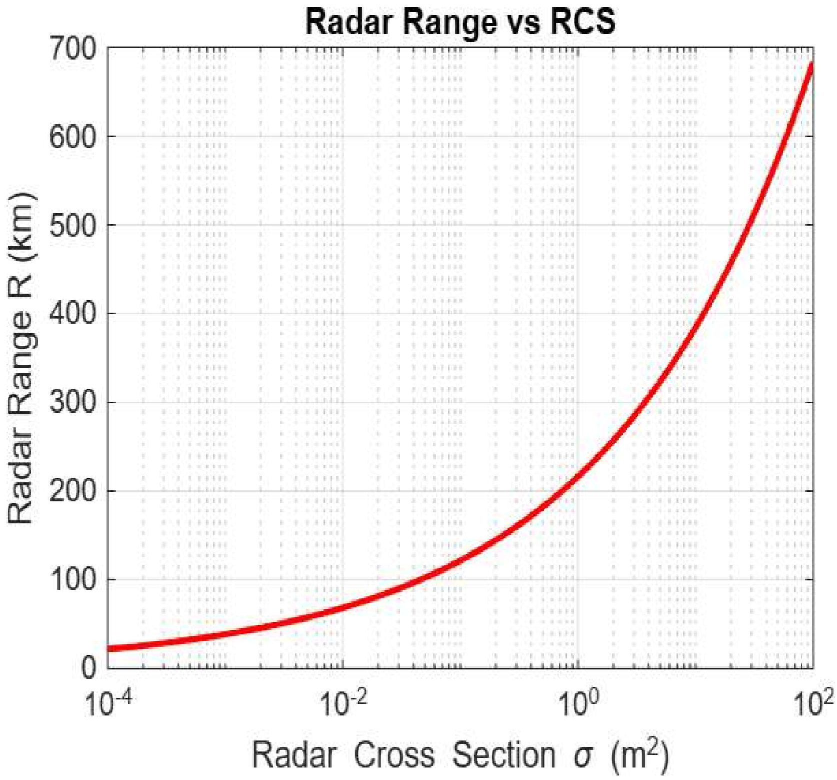


Fig.1.8 Plot of Range vs RCS

Relationship between Radar Cross Section (RCS) and detection range:

The signal strength a radar receives from a target is directly proportional to the target's RCS but decreases with the fourth power of the distance to the target. This means that to detect a target with a smaller RCS at the same range, the radar must compensate with significantly more transmitted power or improved sensitivity. Conversely, doubling the detection range requires the target's RCS to be sixteen times larger to maintain the same signal strength. Thus, small or stealthy targets with low RCS values can only be detected at much shorter distances compared to larger, more reflective targets under identical radar conditions.

$$\boldsymbol{\sigma \propto R_{max}{}^4}$$

Where,

σ is RCS (Radar Cross Section)

R_{max} is the maximum Radar Range.

```
%% Figure 2.1a: SNR vs Range for different RCS values
Pt = 2.16e6;    % Peak power (M)
sigma_dB = [0, -10, -20];
sigma = 10.^(sigma_dB/10);    % Convert to linear scale
lambda = 0.03;               % Wavelength in meters (assuming typical radar wavelength)
k = 1.38e-23;                % Boltzmann constant
T = 290;                     % Temperature in Kelvin
B = 1e6;                     % Bandwidth in Hz
F = 3;                       % Noise figure
SNR_min = 10;                % Minimum detectable SNR

% Calculate range vector
R_km = linspace(1, 100, 1000);  % Range from 1 to 100 km
R = R_km * 1e3;                   % Convert to meters

% Create figure
figure;
hold on;
colors = {'b-', 'r--', 'g-.'};  % Blue, Red dashed, Green dash-dot

for i = 1:length(sigma)
    SNR = (Pt * 6^2 * lambda^2 * sigma(i)) ./ ((4*pi)^3 * R.^4 * k * T * B * F * SNR_min);
    SNR_dB = 10 * log10(SNR);
    plot(R_km, SNR_dB, colors{i}, 'linewidth', 1.5, ...
        'DisplayName', ['\sigma = ' num2str(sigma_dB(i)) ' dbsm']);
end

xlabel('Detection range - km');
ylabel('SNR - dB');
legend('Location', 'northeast');
title('Figure 2.1a. SNR vs Detection Range for Different RCS');
grid on;
```

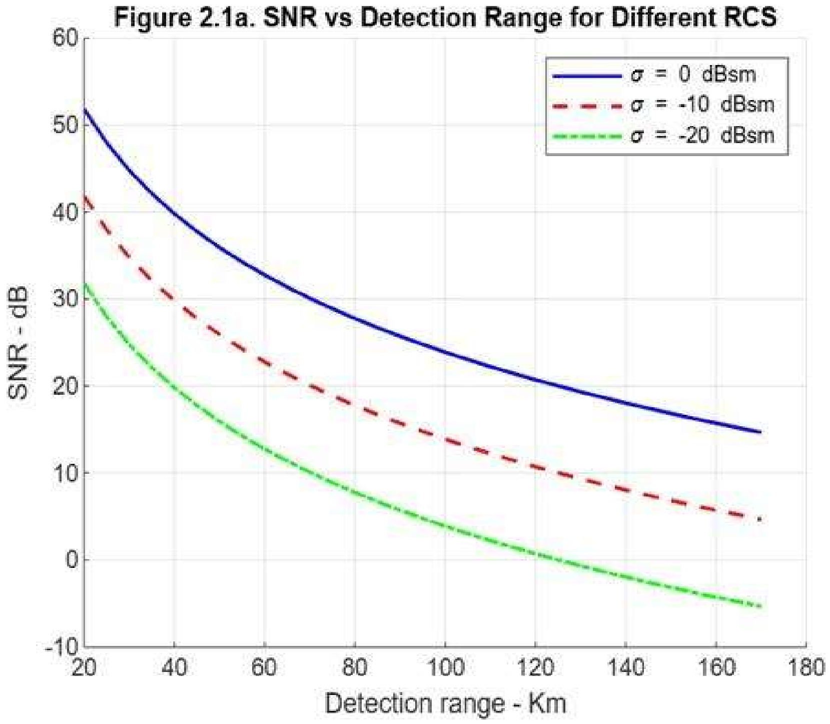


Fig.1.9 (a) Plot of SNR VS RANGE by varying RCS

```matlab
%% Figure 2.1b: SNR vs Range for different Transmitted Power values

% Parameters
lambda = 0.03;              % Wavelength in meters (typical radar wavelength)
sigma = 1;                  % RCS in m² (1 m² = 0 dbsm)
theta = 6;                  % Beamwidth in degrees (assuming same as previous figure)
k = 1.38e-23;               % Boltzmann constant
T = 290;                    % Temperature in Kelvin
B = 1e6;                    % Bandwidth in Hz
F = 3;                      % Noise figure
SNR_min = 10;               % Minimum detectable SNR

% Transmitted power values (in Watts)
Pt_values = [1e6, 2.16e6, 5e6];  % 1 MW, 2.16 MW, 5 MW

% Calculate range vector
R_km = linspace(1, 100, 1000);  % Range from 1 to 100 km
R = R_km * 1e3;                % Convert to meters

% Create figure
figure;
hold on;
colors = {'m-', 'c--', 'y-.'};  % Magenta solid, Cyan dashed, Yellow dash-dot

for i = 1:length(Pt_values)
    SNR = (Pt_values(i) * theta^2 * lambda^2 * sigma) ./ ((4*pi)^3 * R.^4 * k * T * B * F * SNR_min);
    SNR_dB = 10 * log10(SNR);
    plot(R_km, SNR_dB, colors{i}, 'LineWidth', 1.5, ...
        'DisplayName', ['P_t = ' num2str(Pt_values(i)/1e6) ' MW']);
end

xlabel('Detection range - Km');
ylabel('SNR - dB');
legend('Location', 'northeast');
title('Figure 2.1b. SNR vs Detection Range for Different Peak Power');
grid on;
```

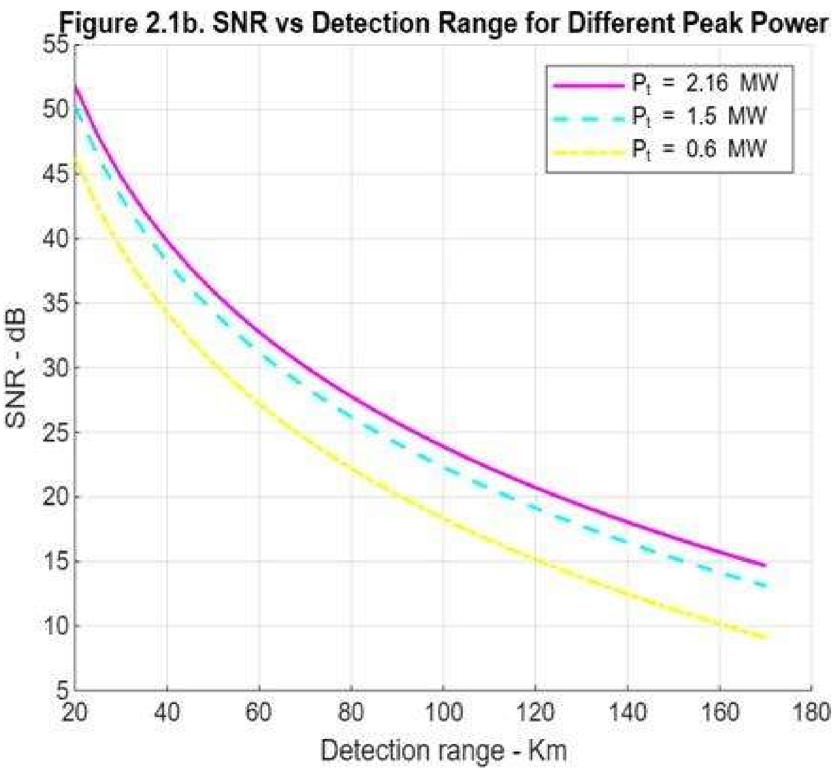


Fig.1.9(b) Plot of SNR vs Range by Varying power

Summary:

The plots are generated using the radar range equation, which shows how the Signal-to-Noise Ratio (SNR) decreases with increasing detection range. SNR is calculated in decibels (dB), a-nd range is measured in kilometers (Km).

Figure 2.1a: SNR vs Range for Different RCS

- Obtained by varying the Radar Cross Section (RCS) values: 0 dBsm, -10 dBsm, -20 dBsm.
- Observation: Higher RCS results in higher SNR at a given range.
- Dependency: SNR is directly proportional to RCS; objects with larger RCS reflect more signal, improving detection.

Figure 2.1b: SNR vs Range for Different Transmit Powers

- Obtained by varying transmit power: 2.16 MW, 1.5 MW, 0.6 MW.
- Observation: Higher power yields higher SNR across all ranges.
- Dependency: SNR is directly proportional to transmitted power; more power improves signal strength and range.

1.2 Radar Cross Section

1.2.1 INTRODUCTION

Electromagnetic waves, when incident on a target, are scattered in all directions regardless of their polarization. The scattered waves consist of two components: one with the same polarization as the receiving antenna, called the Principal Polarization (PP), and another orthogonal component, called the Orthogonal Polarization (OP), to which the antenna does not respond. These two polarizations are perpendicular to each other. The intensity of the backscattered energy matching the polarization of the radar's receiving antenna (PP) is used to define the target's Radar Cross Section (RCS), which is a measure of the target's ability to reflect radar signals back to the receiver.

1.2.2 FACTORS AFFECTING RCS

1) Size: Bigger objects usually reflect more radar waves, so they have a higher RCS.

2) Shape: Flat surfaces facing the radar directly reflect more waves.

Curved or uneven shapes scatter waves in many directions, which can either increase or reduce RCS.

3) Material: Metal reflects radar waves strongly, so it gives a high RCS.

Special materials, called radar-absorbing materials (RAM), are designed to reduce RCS by soaking up the waves.

4) Orientation (Angle): The angle at which the radar "sees" the object matters.

For example, a ship viewed from the side shows more surface, so RCS is higher than when viewed from the front.

5) Radar Frequency and Polarization: RCS can change with the frequency of the radar signal.

Some materials reflect better at certain frequencies. Polarization is the direction of the radar wave's electric field. If the wave's polarization matches how the object reflects waves, RCS is higher.

1.2.3 RCS ANALYSIS ACROSS SCATTERING REGIONS

The Radar Cross Section (RCS) of an object varies with the wavelength (or frequency) of the incident radar wave and the size of the object. Based on this, the RCS behavior is typically analyzed in three distinct regions:

1. **Rayleigh region:**

   - **Condition:** The radius of a sphere must be very small than the wavelength of the of the radar wave.
     $R << \lambda$, where R is the radius of the sphere and λ is wavelength of the radar wave.

- **RCS Behaviour**: $\boldsymbol{\sigma = (9\pi r^2)(kr)^4}$

  Where, $\boldsymbol{\sigma}$**:** radar cross section (m^2) $\boldsymbol{\lambda}$: wavelength of radar wave

  r: radius of sphere k=2 $\boldsymbol{\pi/\lambda}$**:**wave number

- **Interpretation:** Very weak scattering; most radar energy passes by the object with minimal reflection.

- **Example:** Small droplets, insects, dust particles.

2. Mie(Resonance) region:

- **Condition:** The radius of a sphere is approximately same as the wavelength of the of the radar wave.
  R ~ $\boldsymbol{\lambda}$, where R is the radius of the sphere and $\boldsymbol{\lambda}$ is wavelength of the radar wave.

- **RCS Behaviour:**
  - ✓ Complex and oscillatory due to resonance and interference effects.
  - ✓ RCS can suddenly rise or fall quickly with small changes in size or frequency.

- **Interpretation:** Scattering is unpredictable and varies due to resonant behaviour.

- **Example:** Aircraft parts, birds, or vehicles that are about the same size as the radar wavelength.

3. Optical(Geometric) region:

- **Condition:** The radius of a sphere must be very large than the wavelength of the of the radar wave.
  R >> $\boldsymbol{\lambda}$, where R is the radius of the sphere and $\boldsymbol{\lambda}$ is wavelength of the radar wave.

- **RCS Behaviour**: $\boldsymbol{\sigma = (\pi r^2)}$

  where $\boldsymbol{\sigma}$**:** radar cross section (m^2)

  r: radius of sphere

- **Interpretation:** Scattering is like casting a shadow; RCS becomes constant and predictable.

- **Example:** Large aircraft, ships, missiles, large satellites.

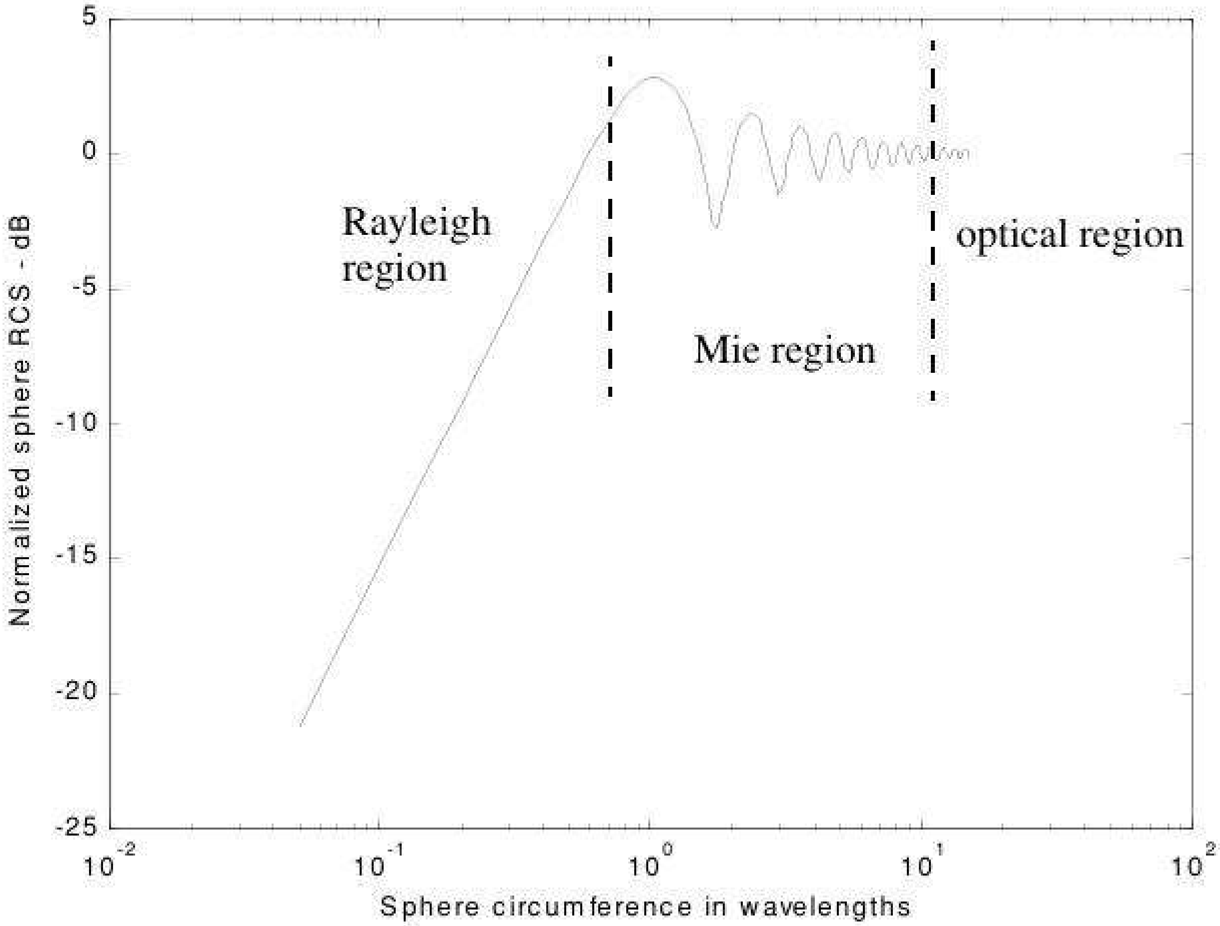


Fig 1.10 Plot of Normalized backscattered RCS for a perfectly conducting sphere using semi-log scale.

1.2.4 SIGNIFICANCE OF USING METALS FOR RCS MEASUREMENT

Metals Are Used as the Material (in Radar Cross Section) due to following properties:

1) High Reflectivity

Metals strongly reflect radar waves because they have free electrons. This makes them ideal for observing and measuring radar returns.

2) Predictable Behavior

The scattering of radar waves from metal surfaces is well understood and can be accurately modeled using theoretical equations.

3) Common in Real Targets

Most real-world objects that radar systems track—like aircraft, ships, and missiles—are made of metal. So metals are realistic materials for RCS testing.

4) Ideal for Calibration

Metal spheres or plates with known dimensions are used as standard calibration targets in radar testing because their RCS is easy to calculate.

5) Strong and Durable

Metals can withstand outdoor testing conditions, including high temperatures, wind, and impact forces during experiments.

6) Helps in Stealth Comparison

Metal targets provide a good reference for comparing with stealth materials (like radar-absorbing coatings) to measure how much the RCS is reduced.

1.2.4 VISUALIZATION OF RCS PATTERNS

We have designed and simulated results for three fundamental geometries- plate, sphere and shell.

1. **Plate:**

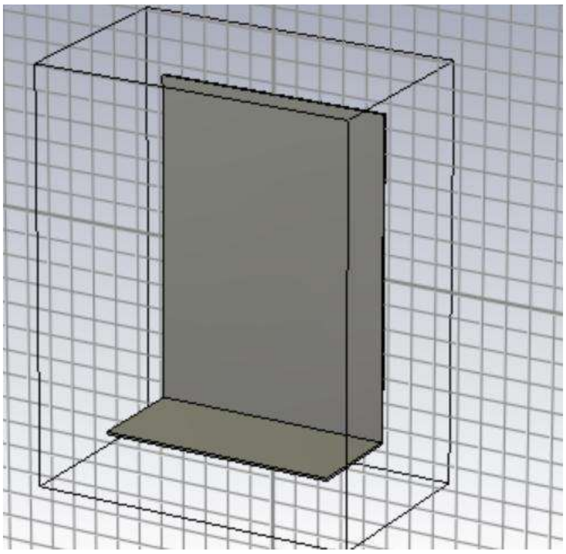


Fig.1.11 Plate model in CST

Parameter List

Name	Expression
t	2
w	192
l	263
z	87

where t=thickness

w=width of plate

z=length of horizontal plate

l=length of vertical plate

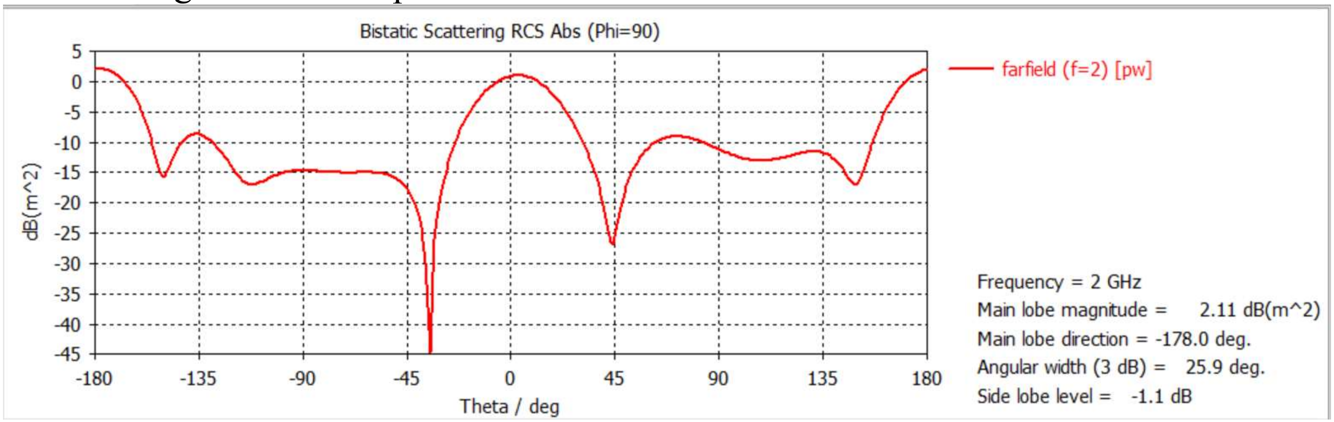


Fig.1.12 Bistatic Scattering RCS of plate

This 1D cartesian plot shows the bistatic RCS vs. angle (Theta) at $\varphi = 90°$ for a metallic plate at 2 GHz.

Strong angular variations with deep nulls indicate high directionality and specular reflection typical of flat surfaces.

Where, Maximum RCS= 2.11dBsm.

MATLAB CODE for Plate:

Function File:

```
function [rcsdb_h, rcsdb_v] = rcs_rect_plate(a, b, freq)
    eps = 0.000001; % Small offset to avoid log(0)
    c = 3e8;      % Speed of light
    lambda = c / freq;
    ka = 2 * pi * a / lambda;

    theta_deg = 0.05:0.1:85;
    theta = deg2rad(theta_deg);

    % Vertical polarization
    sigma1v = cos(ka .* sin(theta)) - 1i * sin(ka .* sin(theta)) ./ sin(theta);
    sigma2v = exp(1i * ka - pi/4) / (sqrt(2 * pi) * ka^1.5);
    sigma3v = (1 + sin(theta)) .* exp(-1i * ka .* sin(theta)) ./ (1 - sin(theta)).^2;
    sigma4v = (1 - sin(theta)) .* exp(1i * ka .* sin(theta)) ./ (1 + sin(theta)).^2;
    sigma5v = 1 - (exp(1i * 2 * ka - pi/2) / (8 * pi * ka^3));

    % Horizontal polarization
    sigma1h = cos(ka .* sin(theta)) + 1i * sin(ka .* sin(theta)) ./ sin(theta);
    sigma2h = 4 * exp(1i * ka - pi/4) / sqrt(2 * pi * ka);
    sigma3h = exp(-1i * ka .* sin(theta)) ./ (1 - sin(theta));
    sigma4h = exp(1i * ka .* sin(theta)) ./ (1 + sin(theta));
    sigma5h = 1 - (exp(1i * 2 * ka + pi/4) / (2 * pi * ka));

    % RCS equations
    rcs_v = (b^2 / pi) .* abs(sigma1v - sigma2v .* ((1 ./ cos(theta)) + 0.25 * sigma2v .* (sigma3v + sigma4v)) ./ sigma5v).^2 + eps;
    rcs_h = (b^2 / pi) .* abs(sigma1h - sigma2h .* ((1 ./ cos(theta)) - 0.25 * sigma2h .* (sigma3h + sigma4h)) ./ sigma5h).^2 + eps;

    angle = ka .* sin(theta);
    rcs_po = (4 * pi * a^2 * b^2 / lambda^2) .* (cos(theta)).^2 .* (sin(angle) ./ angle).^2 + eps;

    % Convert to dBsm
    rcsdb_v = 10 * log10(rcs_v);
    rcsdb_h = 10 * log10(rcs_h);
    rcsdb_po = 10 * log10(rcs_po);
```

```
    % Plot Vertical polarization and Physical Optics (PO) RCS
    figure;
    plot(theta_deg, rcsdb_v, 'k', theta_deg, rcsdb_po, 'k--', 'LineWidth', 1.5);
    grid on;
    set(gca, 'XTick', 10:10:85);

    title(['Vertical Polarization, Frequency = ', num2str(freq * 1e-9), ' GHz, a = ', num2str(a), ' m, b = ', num2str(b), ' m']);
    ylabel('RCS (dBsm)');
    xlabel('Aspect Angle (degrees)');
    legend('RCS_{Vertical}', 'RCS_{PO}');
end
```

Parameter File:

```
% Plate dimensions and frequency
a1 = 0.192; b1 = 0.087;
a2 = 0.263; b2 = 0.192;
freq = 2e9;

% Call RCS function
[rcs_h1, rcs_v1] = rcs_rect_plate(a1, b1, freq);
[rcs_h2, rcs_v2] = rcs_rect_plate(a2, b2, freq);

% Combine both RCS values (in power domain)
rcs_combined_v = 10*log10(10.^(rcs_v1/10) + 10.^(rcs_v2/10));
rcs_combined_h = 10*log10(10.^(rcs_h1/10) + 10.^(rcs_h2/10));

% Max values for info
max_rcs_v = max(rcs_combined_v);
max_rcs_h = max(rcs_combined_h);

fprintf('Max Combined RCS (Vertical Pol): %.2f dBsm\n', max_rcs_v);
fprintf('Max Combined RCS (Horizontal Pol): %.2f dBsm\n', max_rcs_h);

% Original angle range
theta_deg = 0.05:0.1:85;

% Mirroring for -85 to 0
theta_pos = theta_deg;
theta_neg = -fliplr(theta_pos);

rcs_v_mirrored = fliplr(rcs_combined_v);
rcs_h_mirrored = fliplr(rcs_combined_h);

% Full range from -85 to 85
theta_full = [theta_neg, theta_pos];
rcs_v_full = [rcs_v_mirrored, rcs_combined_v];
rcs_h_full = [rcs_h_mirrored, rcs_combined_h];
```

```
% Initialize extended data from -180 to 180 with low dBsm
theta_extended = -180:0.1:180;
rcs_v_extended = ones(size(theta_extended)) * -100;  % very low value
rcs_h_extended = ones(size(theta_extended)) * -100;

% Fill in real RCS values in -85° to 85° range
start_idx = find(theta_extended >= -85, 1, 'first');
num_pts = length(rcs_v_full);

rcs_v_extended(start_idx:start_idx + num_pts - 1) = rcs_v_full;
rcs_h_extended(start_idx:start_idx + num_pts - 1) = rcs_h_full;

% Final Plot
figure;
plot(theta_extended, rcs_v_extended, 'b-', 'LineWidth', 1.5); hold on;
plot(theta_extended, rcs_h_extended, 'r--', 'LineWidth', 1.5);
grid on;
xlabel('Aspect Angle (degrees)');
ylabel('RCS (dBsm)');
legend('Combined Vertical', 'Combined Horizontal');
title('Approximate Combined RCS of Two Rectangular Plates (-180° to 180°)');
xlim([-180 180]);
```

RESULTS:

```
Max Combined RCS (Vertical Pol): 2.02 dBsm
Max Combined RCS (Horizontal Pol): 2.15 dBsm
```

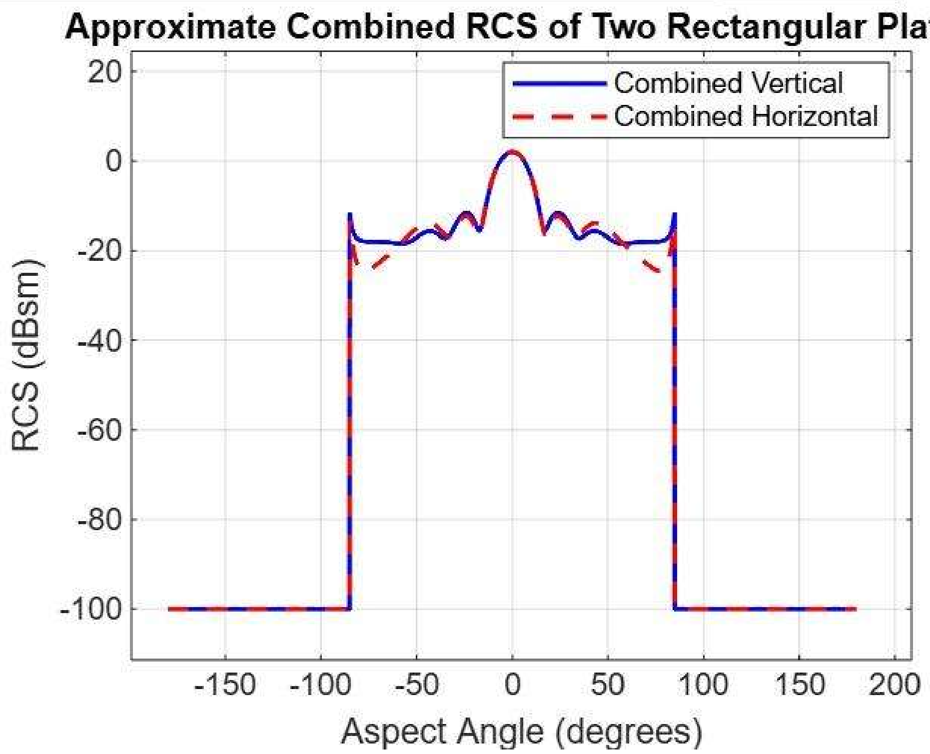


Fig.1.15 RCS Plot of two rectangular plates

Maximum RCS was found to be 2.15dBsm.

Comparing both the results, we got to know that the RCS of plate from MATLAB and CST are similar which is around 2.11dBsm.

2. Sphere:

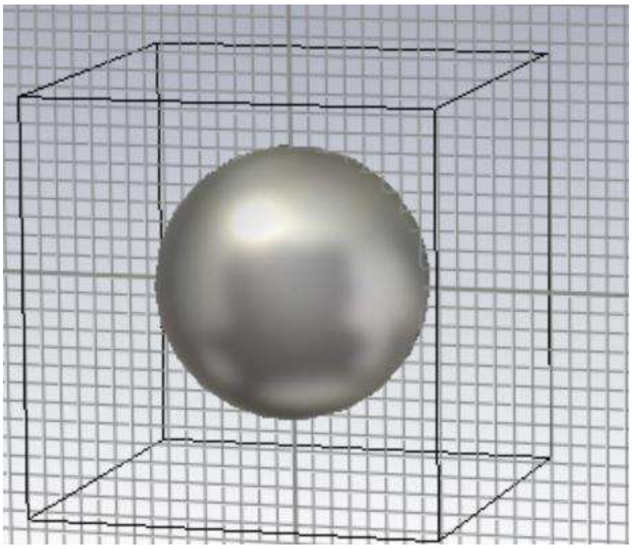


Fig.1.14 Sphere Model in CST

Where,

Radius of sphere=72.5mm

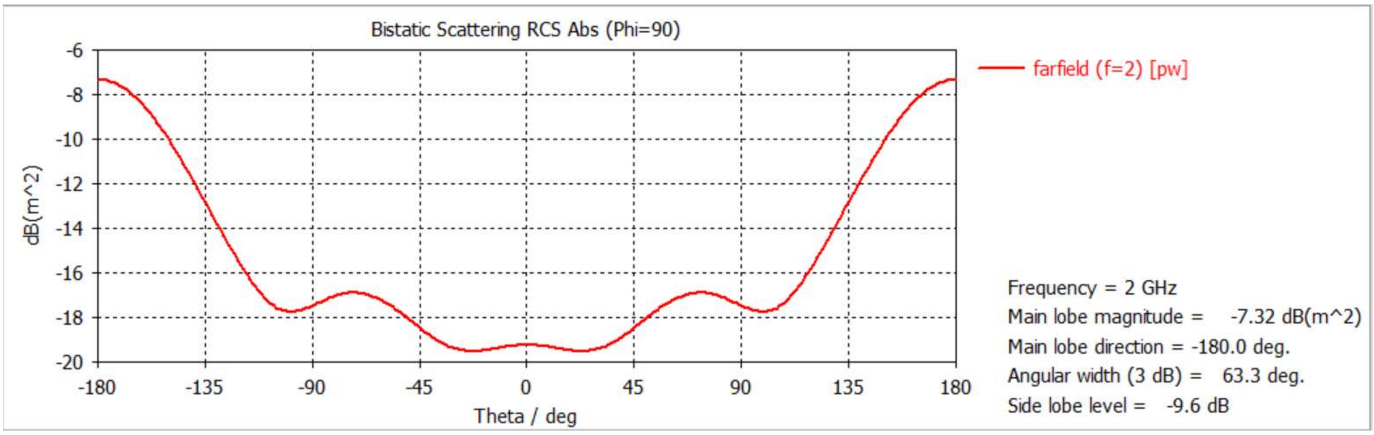


Fig.1.15 Bistatic Scattering RCS of Sphere

The bistatic RCS plot for a sphere at 2 GHz shows a relatively smooth variation with angle, and the maximum RCS is –7.32 dB(m²).

The symmetry and lack of sharp nulls indicate uniform scattering in all directions, as expected for a sphere.

MATLAB CODE for sphere:

```
eps = 9.4;
index = 0;
kr_values = 0.05:0.05:15;

rcs = zeros(size(kr_values));

fprintf('--- Unscaled RCS Values (before normalization) ---\n');
fprintf('   kr\t\t| RCS (unitless)\n');
fprintf('------------------------------------\n');

for kr = kr_values
    index = index + 1;
    sphere_rcs = 0 + 0i;
    f1 = 0 + 1i;
    f2 = 1 + 0i;
    m = 1;
    n = 0;
    q = -1;
    del = 100000 + 100000i;

    while abs(del) > eps
        q = -q;
        n = n + 1;
        m = m + 2;
        del = (11 * n - 1) * f2 / kr - f1;
        f1 = f2;
        f2 = del;
        del = q * m / (f2 * (kr * f1 - n * f2));
        sphere_rcs = sphere_rcs + del;
    end
    rcs(index) = abs(sphere_rcs);  % Unscaled RCS (unitless)
    fprintf('  %.4f\t| %.6f\n', kr, rcs(index));
end

% === Find scaling factor to match CST result at kr ≈ 3.14 ===
[rcs_peak_val, peak_idx] = max(rcs);
kr_peak = kr_values(peak_idx);
expected_rcs_m2 = 0.1862;  % from CST result (at kr ~ 3.14)
scale = expected_rcs_m2 / rcs_peak_val;

% === Apply scaling ===
rcs_scaled = rcs * scale;
rcs_scaled_dB = 10 * log10(rcs_scaled);

fprintf('\n--- Scaled RCS Values (in m^2 and dBsm) ---\n');
fprintf('   kr\t\t| RCS (m^2)\t| RCS (dBsm)\n');
fprintf('--------------------------------------------\n');

for i = 1:length(kr_values)
    fprintf('  %.4f\t| %.6f\t| %.2f\n', kr_values(i), rcs_scaled(i), rcs_scaled_dB(i));
end

% === Highlight match point ===
fprintf('\n✅ Peak matched at kr = %.3f:\n', kr_peak);
fprintf('   RCS = %.6f m² = %.2f dBsm (after scaling)\n', ...
    rcs_scaled(peak_idx), rcs_scaled_dB(peak_idx));

% === Plot 1: RCS (m²) vs kr ===
figure(1);
plot(kr_values, rcs_scaled, 'k', 'LineWidth', 1.5);
xlabel('kr');
```

```
ylabel('RCS (m^2)');
title('Scaled RCS vs kr (PEC Sphere)');
grid on;

% === Plot 2: RCS (dBsm) vs kr ===
figure(2);
plot(kr_values, rcs_scaled_dB, 'b', 'LineWidth', 1.5);
xlabel('kr');
ylabel('RCS (dBsm)');
title('Normalized Sphere RCS (dB) vs kr');
grid on;

% === Plot 3: Semilog Plot ===
figure(3);
semilogx(kr_values, rcs_scaled_dB, 'r', 'LineWidth', 1.5);
xlabel('kr (log scale)');
ylabel('RCS (dBsm)');
title('Semilog Plot of Scaled RCS (dBsm)');
grid on;
```

Result:

```
Peak matched at kr = 3.250:
RCS = 0.186200 m² = -7.30 dBsm (after scaling)
```

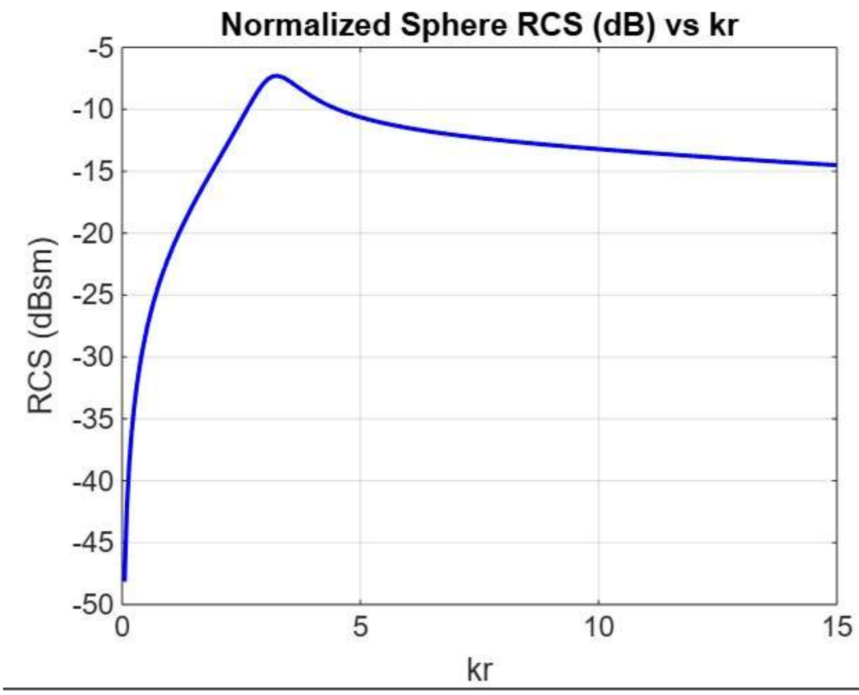


Fig.1.16 Normalized Sphere RCS (dB) vs electrical size of sphere Plot

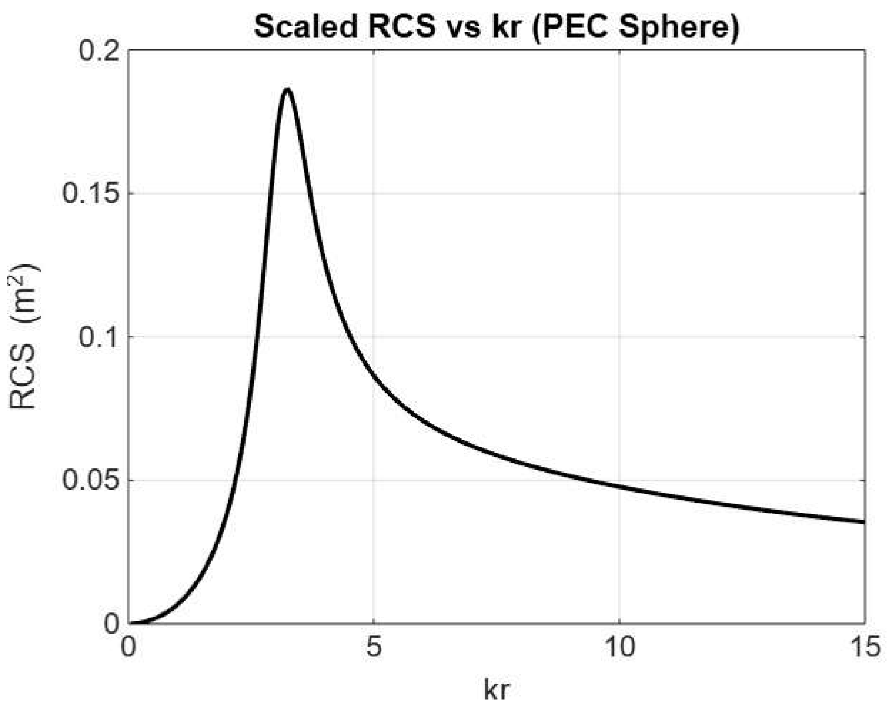


Fig.1.17 Scaled RCS vs electrical size of sphere Plot

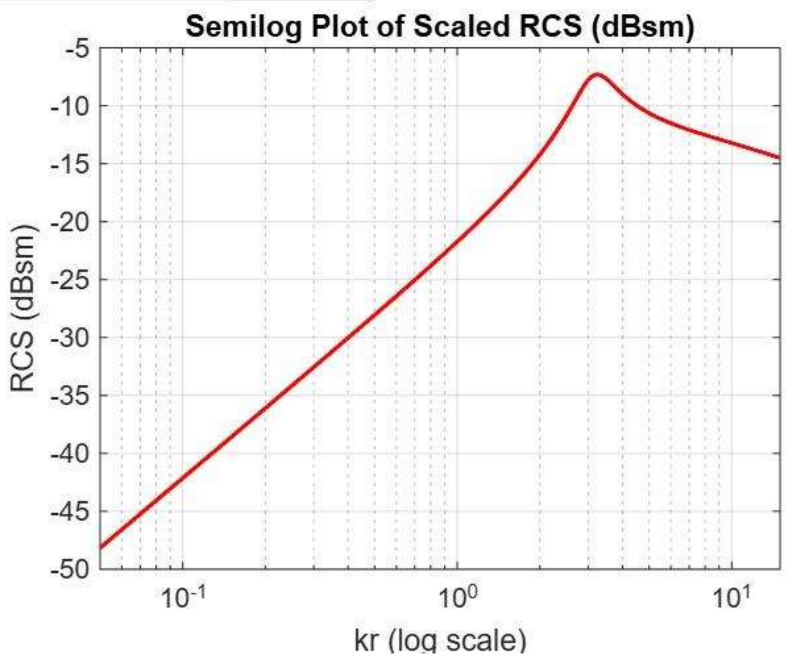


Fig.1.18 Semilog Plot of scaled RCS

Here, Maximum RCS is found to be -7.30dBsm.

Comparing both the results, we got to know the RCS of Sphere from MATLAB and CST are similar which is around -7.31dBsm.

3. Shell:

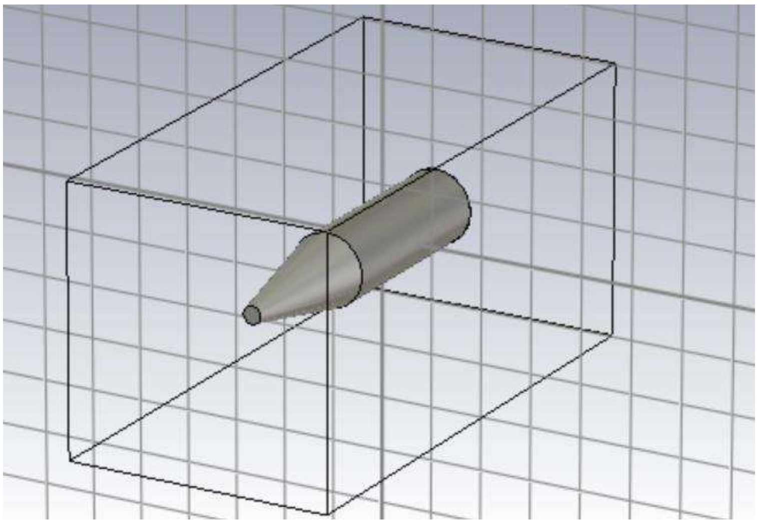


Fig.1.19 Shell Model in CST

Parameter List

Name	Expression
R	14
H	77
P	3.5

Where,
H=Height of cylinder
P=Top radius of frustum
R=Radius of cylinder
Height of conical part= 52mm

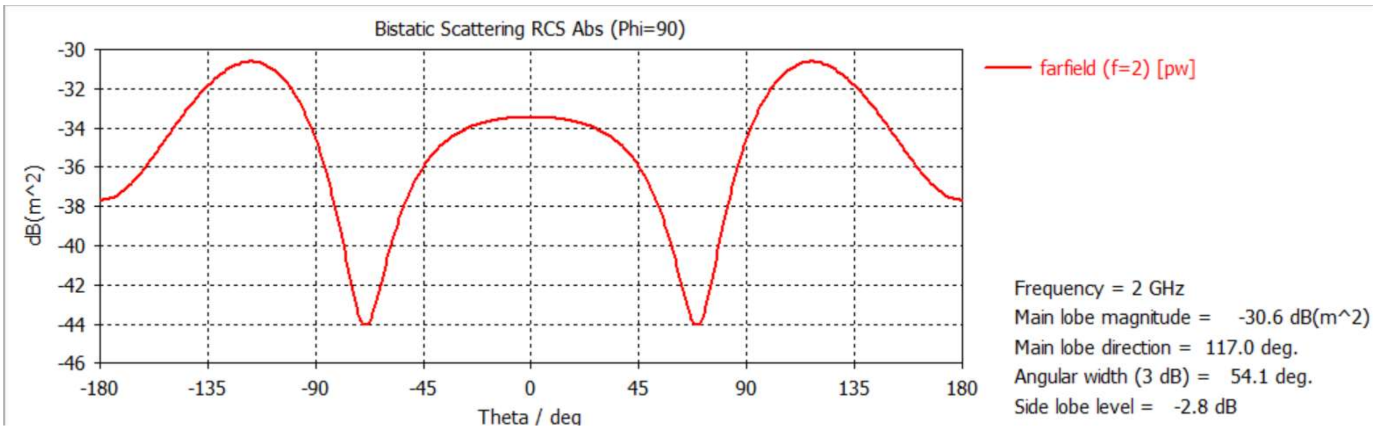


Fig.1.20 Bistatic Scattering RCS of Shell

The bistatic RCS plot for the shell at 2 GHz shows deep nulls and a low main lobe magnitude of –30.6 dB(m^2) which represents the Maximum RCS of the Shell.
This indicates weak backscattering, as expected from the hollow structure and internal wave

cancellations.

MATLAB CODE for Shell:


```
function rcs_shell_monostatic
    clear; clc;

    % === Geometry Parameters ===
    R1 = 0.014;         % Base radius (m)
    R2 = 0.0035;        % Tip radius (m)
    h_cyl = 0.077;      % Height of cylinder (m)
    h_cone = 0.052;     % Height of cone (m)
    lambda = 0.15;      % Wavelength at 2 GHz (m)

    % === CST Reference RCS ===
    target_rcs_dB = -33;
    target_rcs = 10^(target_rcs_dB / 10);

    % === Scale Factor to Match CST ===
    A_proj = pi * R1^2;
    scale_factor = target_rcs / A_proj;

    % === Angle Setup: Now from -180° to +180° ===
    theta_deg = -180:0.5:180;
    theta_rad = deg2rad(theta_deg);

    % === Monostatic RCS Calculation ===
    gain = (1 + 0.3 * cos(theta_rad)).^2;
    sigma_monostatic = scale_factor * A_proj * gain;
    rcsdb_monostatic = 10 * log10(sigma_monostatic + eps);

    % === Plot ===
    figure;
    plot(theta_deg, rcsdb_monostatic, 'b', 'LineWidth', 1.5);
    grid on;
    xlabel('Aspect Angle (degrees)');
    ylabel('RCS (dBsm)');
    title(['Monostatic RCS of Shell Model (2 GHz), R1 = ', num2str(R1), ' m']);
    legend('RCS_{Monostatic}');
    xlim([-180 180]);
    set(gca, 'XTick', -180:30:180);

    % === RCS Value Reporting ===
    [rcs_max, idx_max] = max(sigma_monostatic);
    [rcs_min, idx_min] = min(sigma_monostatic);
    angle_max = theta_deg(idx_max);
    angle_min = theta_deg(idx_min);

    % Closest index to 90°
    [~, idx_90] = min(abs(theta_deg - 90));
    rcs_90 = sigma_monostatic(idx_90);
    rcsdb_90 = 10 * log10(rcs_90 + eps);

    % === Print ===
```

```matlab
    % === Print ===
    fprintf('\n--- Monostatic RCS Summary ---\n');
    fprintf('Maximum RCS: %.6f m^2 (%.2f dBsm) at %.2f°\n', rcs_max, 10*log10(rcs_max), angle_max);
    fprintf('Minimum RCS: %.6f m^2 (%.2f dBsm) at %.2f°\n', rcs_min, 10*log10(rcs_min), angle_min);
    fprintf('RCS at 90° incidence: %.6f m^2 (%.2f dBsm)\n', rcs_90, rcsdb_90);
    fprintf('Target RCS (CST reference): %.6f m^2 (%.2f dBsm)\n', target_rcs, target_rcs_dB);
end
```

RESULT:

```
Maximum RCS: 0.000847 m^2 (-30.72 dBsm) at 0.00°
Minimum RCS: 0.000246 m^2 (-36.10 dBsm) at -180.00°
RCS at 90° incidence: 0.000501 m^2 (-33.00 dBsm)
Target RCS (CST reference): 0.000501 m^2 (-33.00 dBsm)
```

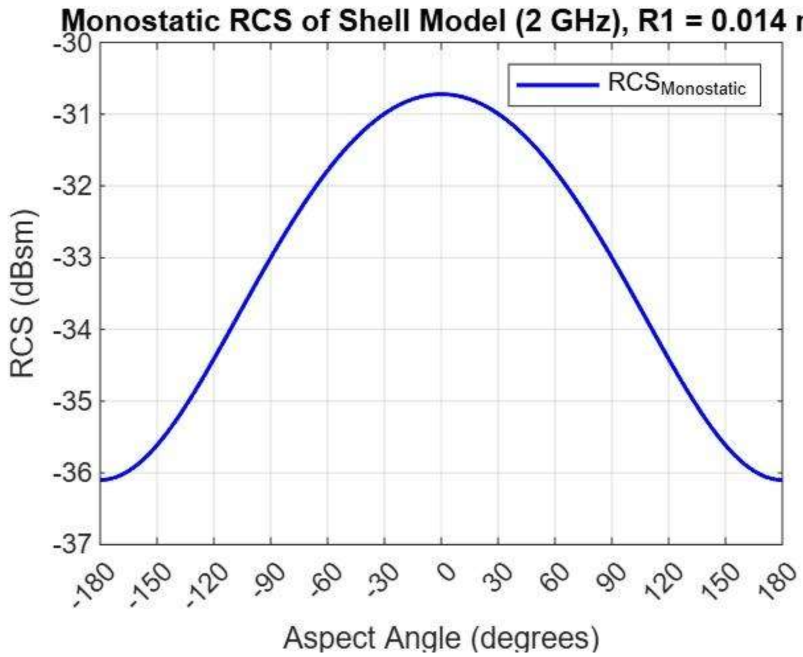


Fig.1.21 Monostatic RCS Plot of Shell Model

Here, Maximum RCS is -30.10dBsm.

Comparing both the results, we got to know the RCS of Shell from MATLAB and CST are similar which is around -30.1dBsm.

Significance of PEC material:

PEC (Perfect Electric Conductor) is used in RCS simulations because it acts as an ideal reflector, reflecting 100% of the incident electromagnetic energy without any absorption or transmission. This makes it an excellent reference for studying pure scattering behaviour. PEC simplifies boundary conditions in simulations, matches well with theoretical models, and approximates real metals at high frequencies.

By eliminating material losses, it allows the focus to remain solely on the effect of object shape and geometry on RCS, making it ideal for validating simulation accuracy and comparing with real-world results.

Summary:

In the simulated designs, the plate exhibits the highest RCS due to its flat metallic surface, which causes strong specular reflection of incident radar waves directly back toward the source, especially at normal incidence. This results in high-intensity backscatter and makes the plate highly radar-visible.

In contrast, the shell shows the lowest RCS because of its hollow and curved structure, which leads to destructive interference from internal reflections and scattering in multiple directions rather than back toward the radar. This reduces the effective radar return, making the shell the least detectable among the three geometries.

Flat Plate has maximum RCS, i.e. object can be easily detectable using these kinds of surfaces, so these are used in airways. On the other hand, shell having the minimum RCS is very less detectable, hence used in firing and firing points.

Chapter-2

MODELLING AND SIMULATION OF MICROSTRIP PATCH ANTENNA ARRAY

2.1 INTRODUCTION

An **Antenna** is a specialized transducer that converts electrical energy into electromagnetic waves (EM) or vice versa. Additionally, it serves as the interface between guided wave and free space wave. Antennas are fundamental to wireless communication systems. They generate electromagnetic waves from electrical signals, propagate these waves through space, and convert incoming waves back into electrical signals for processing.

A **Microstrip Patch Antenna** is a type of radio antenna with a low-profile, lightweight, and compact structure, making it ideal for applications such as satellite communication, radar systems, and mobile devices. It typically consists of three main layers: the **patch**, the **substrate**, and the **ground plane**. The **patch**, often made of a conductive material like copper, is the radiating element and is placed on top of the dielectric **substrate**, which provides mechanical support and affects the antenna's electromagnetic characteristics. The **ground plane** is located beneath the substrate and acts as a reference conductor to reflect the radiated signals upward.

For feeding the antenna, various methods can be used, such as **microstrip transmission lines**, which are printed on the same substrate and provide an easy and planar means of transferring RF power to the patch. T_o improve impedance matching and minimize reflections, an **inset feed** can be employed. This involves embedding the transmission line slightly into the patch, allowing for better control over the input impedance. The design of microstrip antennas must

Consider key parameters such as patch dimensions, substrate permittivity, and thickness to achieve the desired resonant frequency and radiation pattern.

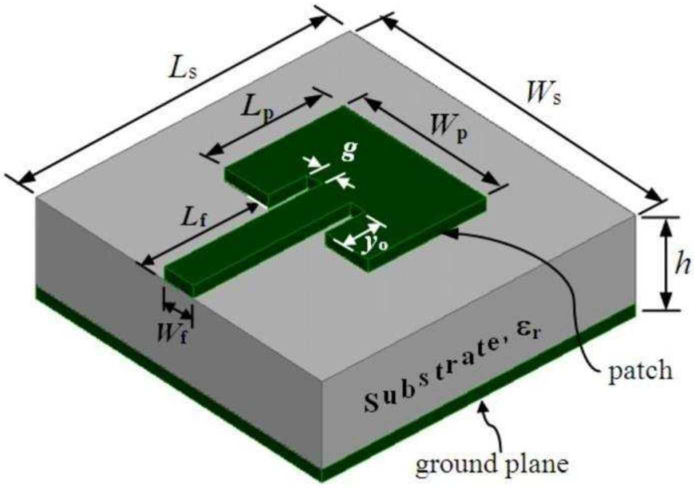
2.2 BASIC CHARACTERISTICS

- It is metallic patch placed on dielectric material and supported by ground/substrate plane.
- Microstrip antennas, consist of a very thin ($t \ll \lambda_0$ where λ_0 is the free-space wavelength) metallic strip (patch) placed a small fraction of a wavelength ($h \ll \lambda_0$, usually $0.003\lambda_0 \geq h \geq 0.05\ \lambda_0$) above a ground plane.

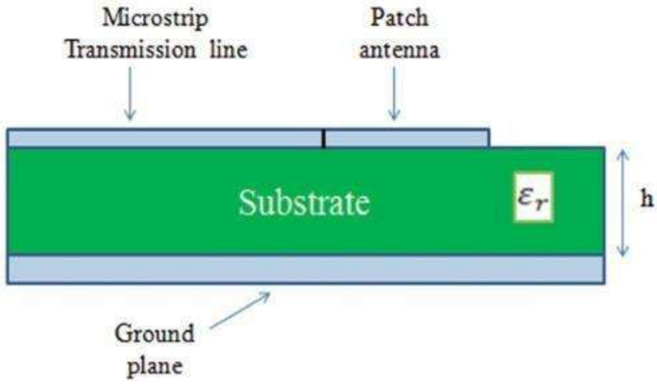
- For a rectangular patch, the length L of the element is usually $\lambda_o/3 < L < \lambda_o/2$.
- The strip (patch) and the ground plane are separated by a dielectric sheet (referred to as

the substrate).

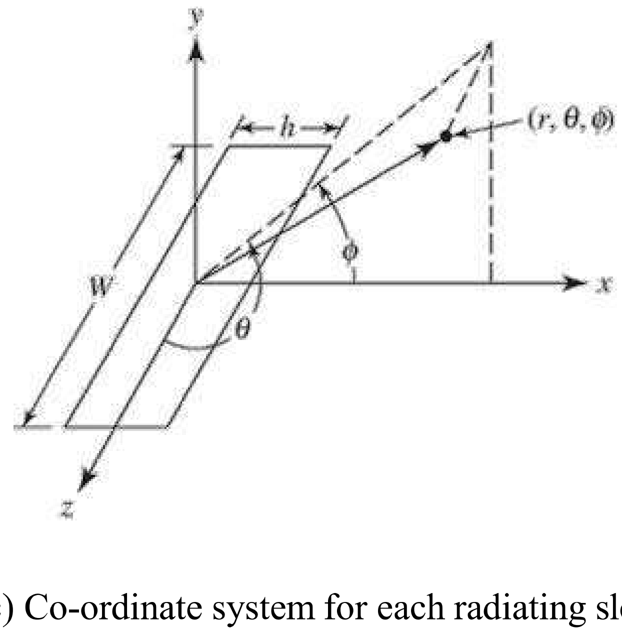
- There are numerous substrates that can be used for the design of microstrip antennas, and their dielectric constants are usually in the range of $2.2 \leq \varepsilon_r \leq 12$.
- The radiating elements and the feed lines are usually photoetched on the dielectric substrate.
- It could be easily fabricated on printed circuit board.
- It is most widely used antenna.
- Installation is very easy due to low size, weight and cost.



a) Microstrip_Antenna



b) Side_view



c) Co-ordinate system for each radiating slot

Fig.2.1 Basic design Antenna

2.3 TYPES OF MICROSTRIP PATCH ANTENNAS

Microstrip patch antennas can be classified based on the **shape of the patch**, **feeding method**, and **design configurations**. Each type has unique characteristics suited for specific applications, especially in wireless communication, satellite systems, and radar.

1. Based on Patch Shape

(a) Rectangular Patch Antenna

- The most widely used type due to its simple geometry and ease of fabrication.
- It is easy to model and analyse using the transmission line model.
- Primarily used for narrowband applications.

(b) Circular Patch Antenna

- Offers a symmetric radiation pattern and is slightly smaller than a rectangular patch for the same frequency.
- Useful in applications where rotational symmetry is desired.

(c) Elliptical Patch Antenna

- A variation of the circular patch that provides design flexibility.
- Useful in dual-polarized systems.

(d) Triangular Patch Antenna

- More compact than rectangular and circular patches.
- Preferred in miniaturized designs where space is limited.

(e) Hexagonal and Other Polygonal Patches

- Provide enhanced bandwidth and multiband operation.
- Suitable for advanced antenna array configurations.

2. Based on Feeding Technique

(a) Microstrip Line Feed

- Simple and easy to fabricate.

- Offers good impedance matching.
  The feed line lies on the same substrate

(b) Microstrip Line Feed

- Simple and easy to fabricate.
- Offers good impedance matching.
- The feed line lies on the same substrate.

(c) Coaxial Probe Feed

- Easy to match and provides low spurious radiation.
- Suitable for thick substrates.

(d) Aperture Coupled Feed

- Uses a ground plane to isolate feed and patch, reducing unwanted radiation.
- Provides better bandwidth but complex to fabricate.

(e) Proximity Coupled Feed (Electromagnetic Coupling)

- Offers the highest bandwidth among all feeding techniques.
- Complex structure due to multiple substrates.

3. Based on Advanced Designs

(a) Multiband Patch Antenna

- Designed to operate at multiple frequency bands.
- Useful for modern wireless communication systems.

(b) Array Patch Antenna

- Multiple patches arranged in an array to increase gain and directivity.
- Widely used in radar, satellite, and 5G systems.

(c) Reconfigurable Patch Antenna

- Can dynamically change frequency, polarization, or radiation pattern.
- Achieved using switches like PIN diodes or MEMS

2.4 FEEDING METHODS

There are various antenna feeding methods which are crucial for efficiently transferring RF power from the source (transmission line) to the radiating element.

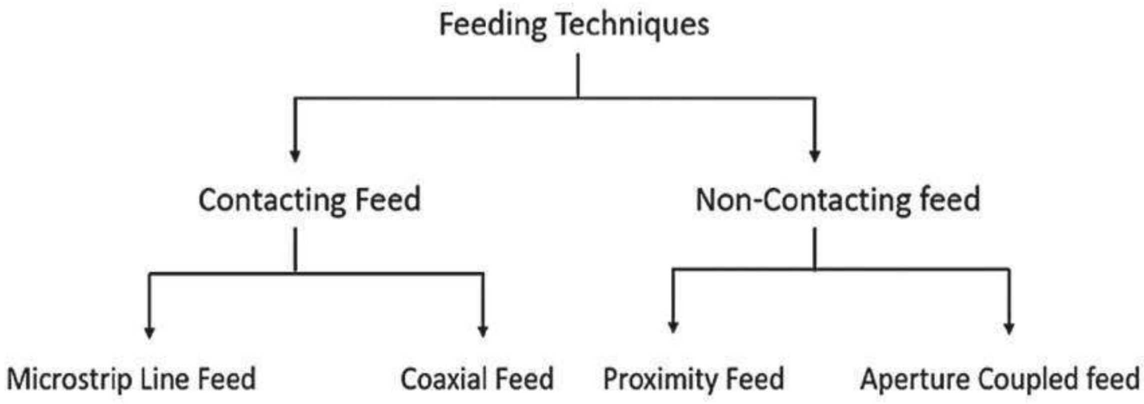


Fig.2.2 Feeding method types

Depending on the method of energy transfer, feeding mechanisms are broadly categorized into:

1. Contacting Feed Techniques:

These methods involve a physical connection between the transmission line and the antenna. These mainly includes Microstrip feeding and Probe (co-axial) feeding.

(a) Line Feed Microstrip

Microstrip feedline is also a feeding strip, usually of much smaller width compared to the patch.

Advantages:

- Easy to fabricate
- Simple to match (control the inset position)
- Simple to model

However, as the substrate thickness increases, surface waves and spurious feed radiation increa--se, which for practical designs limit the bandwidth.

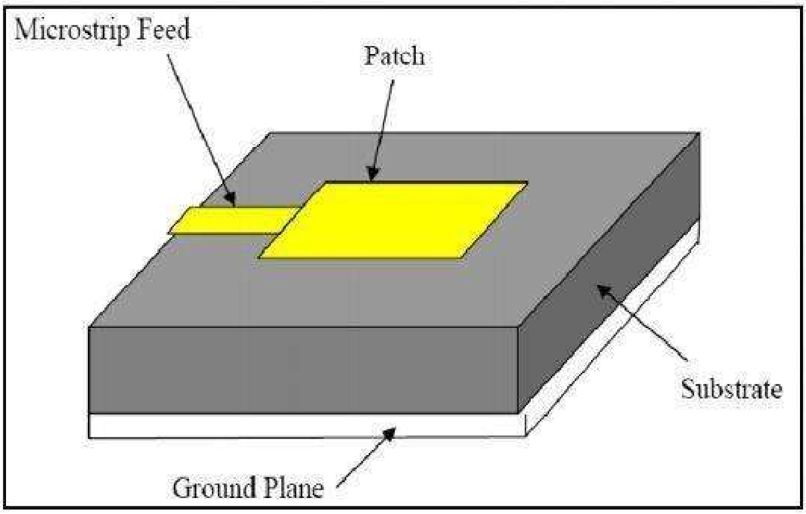


Fig.2.3 Microstrip Line Feed

Disadvantages:

- Low bandwidth (2%).
- Cross polarization

(b) Probe(co-axial) Feed Microstrip

The inner conductor of the coax is attached to the radiation patch while the outer conductor is connected to the ground plane. These feeds are widely used, as they are easy to fabricate and match, and even has a low spurious radiation.

Advantages:

- Easy to fabricate
- Easy to match (by moving coaxial feed to the peripheral side)
- Easy to model
- Low spurious radiation

But it has narrow bandwidth, and it is more difficult to model, especially for thick substrates (h>0.02 times the free-space wavelength).

Disadvantages:

- Low bandwidth (2%)
- Cross polarization

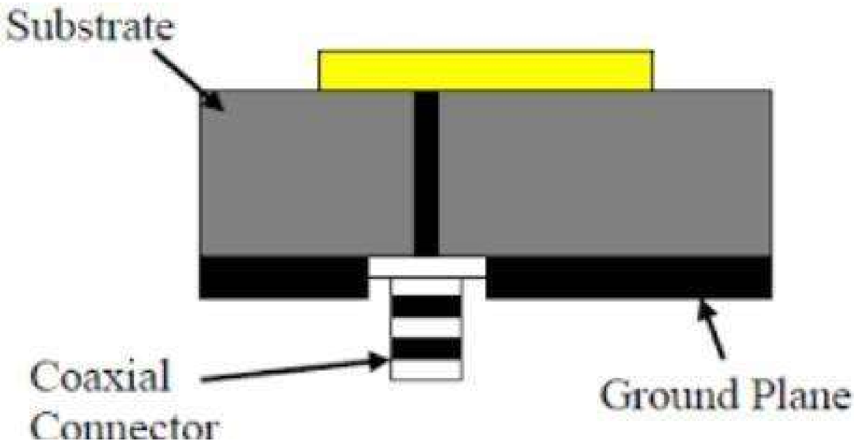


Fig.2.4 Probe(co-axial) Feed Microstrip

2. Non-Contacting Feed Techniques:

These methods rely on electromagnetic or capacitive coupling, with no physical contact between the feed and the antenna. This technique mainly includes Aperture Coupled feeding and Proximity Coupled feeding.

Both the microstrip feed line and probe possess inherent asymmetries which generate higher order modes which produce cross-polarized radiation. To overcome some of these problems, non-contacting aperture coupling feeds have been introduced.

(a) Aperture Coupled Feed

The Aperture Coupling Feed is the most difficult to fabricate and has narrow bandwidth. However, it has moderate spurious radiation.

The Aperture Coupling consists of two substrates separated by a ground plane. On the bottom side of the lower substrate there is a microstrip feed line whose energy is coupled to the patch through a slot on the ground plane separating the two substrates. This arrangement allows independent optimization of the feed mechanism and the radiating element. A high dielectric material is used for the bottom substrate, and thick low dielectric constant material for the top substrate. The ground plane between the substrates also separated the feed from the radiating element and minimizes interference of spurious radiation for pattern formation and polarization purity.

Advantages:

1) Low cross polarization
2) Easier to model
3) Moderation spurious radiation

Disadvantages:

1) Most difficult to fabricate
2) Narrow bandwidth

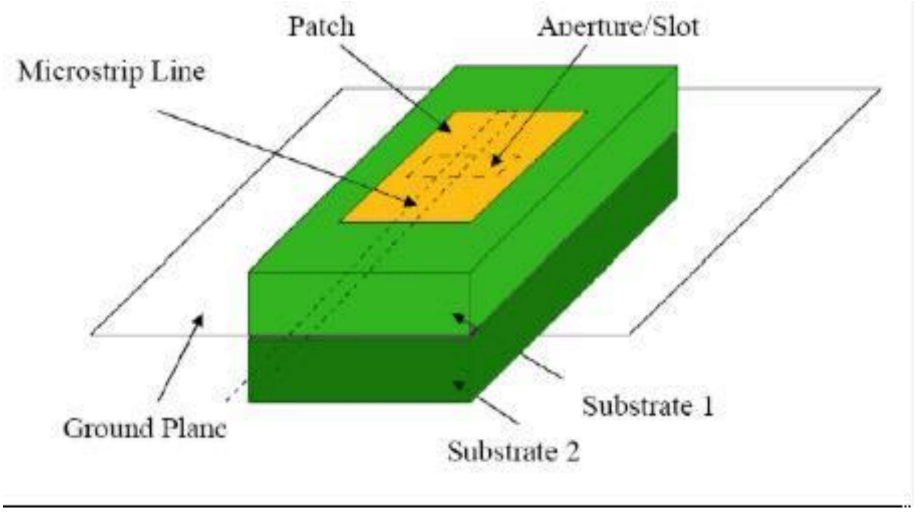


Fig.2.5 Aperture Coupled Feed

(b) Proximity Coupled Feed

Energy is coupled from a microstrip feed line to the patch through proximity (electromagnetic field). Patch is not physical connected to feedline.

Advantages:

1) Low cross polarization
2) High Bandwidth (13%)
3) Low spurious radiation
4) Easy to model

Disadvantages:

1) Difficult to fabricate
2) High cost

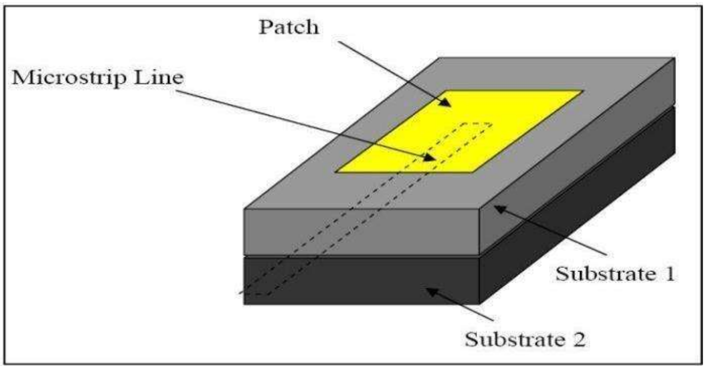


Fig.2.6 Proximity Coupled Feed

Comparison between Feeding Methods:

Feed Method	Contact Type	Bandwidth	Fabrication complexity	Isolation
Microstrip Line	Contacting	Low	Simple	Low
Probe Co-axial	Contacting	Medium	Moderate	Medium
Aperture Coupled	Non-Contacting	High	Complex	High
Proximity Coupled	Non-Contacting	High	Complex	High

Importance of Feeding:

- It affects impedence matching.
- It influences bandwidth, radiation pattern and efficiency of the antenna.

Often microstrip antennas are also referred to as patch antennas. The radiating elements and the feed lines are usually photoetched on the dielectric substrate. The radiating patch may be square, rectangular, thin strip (dipole), circular, elliptical and triangular or any other configuration.

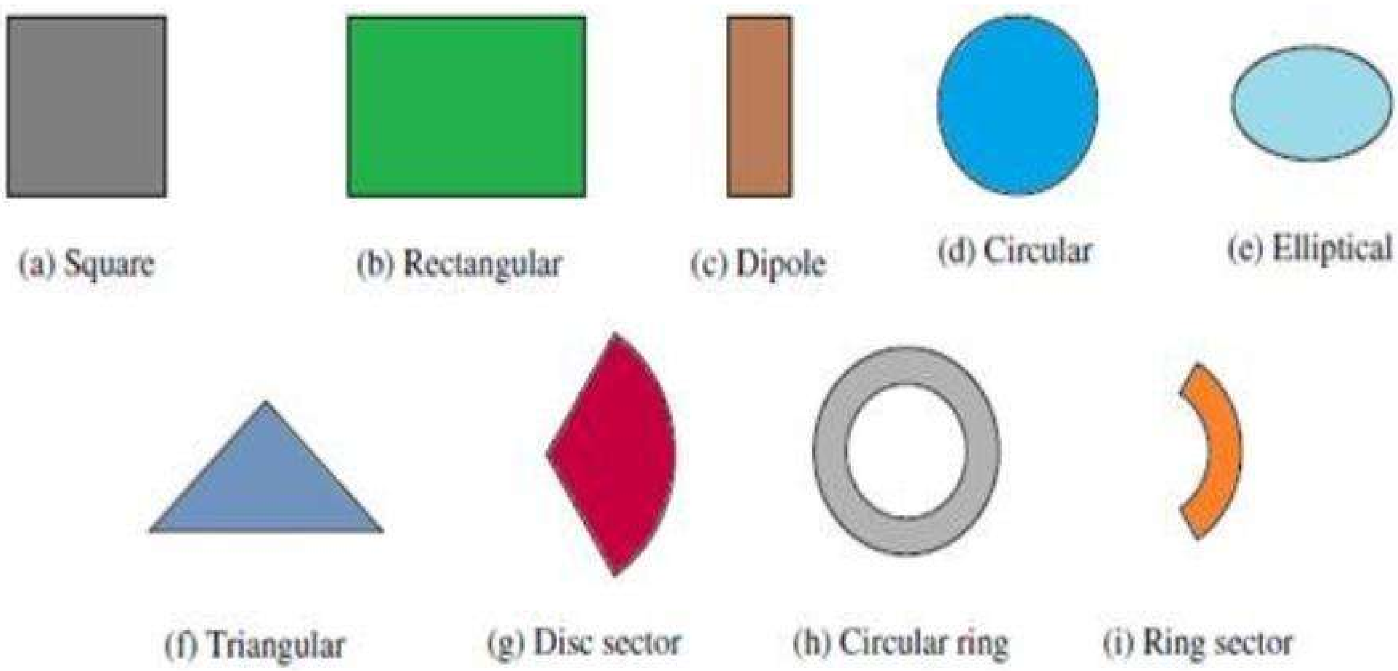


Fig.2.7 Representative shapes of microstrip patch elements.

2.5 RECTANGULAR PATCH

A rectangular patch microstrip antenna is a type of low-profile, planar antenna that consists of a rectangular conductive patch mounted on a dielectric substrate above a ground plane.

- **Applications**:
  - Wireless communication (Wi-Fi, Bluetooth)
  - Satellite and radar systems
  - Mobile and IoT devices
  - Aerospace and defence communication

- **Key Features**:
  - Lightweight and compact
  - Easy to fabricate using PCB technology
  - Compatible with planar and non-planar surfaces
  - Low cost and integration-friendly

- **Basic Structure**:
  - **Patch**: Rectangular metallic layer (usually copper)
  - **Substrate**: Dielectric material with permittivity ε_r
  - **Ground Plane**: Conductive backing underneath the substrate

- **Operating Principle**:
  - Operates primarily in the **TM_{10} mode**
  - Radiates through **fringing fields** at patch edges
  - Patch acts as a **resonant cavity** with standing wave patterns

- **Design Parameters**:
  - **Resonant Frequency (f_0)**: Set by patch dimensions and substrate properties
  - **Patch Width (W)**: Wider than L to increase bandwidth
  - **Substrate Height (h)**: Greater height increases bandwidth but may reduce efficiency
  - **Dielectric Constant**: Lower Dielectric constant gives better efficiency but larger antenna size

- **Advantages**:
  - Planar and conformal
  - Suitable for arrays and beamforming
  - Electrically small and tunable

- **Limitations**:
  - Narrow bandwidth (typically 1–5%)
  - Low gain compared to traditional antennas
  - Efficiency affected by dielectric and surface waves

It is very easy to analyse using both the transmission-line and cavity models, which are most accurate for thin substrates.

2.6 TRANSMISSION-LINE MODEL

It was indicated earlier that the transmission-line model is the easiest of all, but it yields the least accurate results, and it lacks the versatility. However, it does shed some physical insight. Using the cavity model, a rectangular micro strip antenna can be represented as an array of two radiating narrow apertures (slots), each of W and height h separated by a distance L. Basically the transmission line model represents the microstrip antenna by two slots, separated by a low impedance z transmission line of length L.

A. Fringing Effects

As the dimension of the patch are finite along the length and width, the fields at the edges of the patch undergo fringing. The amount of fringing is a function of the dimensions of the patch and the height of the substrate. For the principal xy plane fringing is a function of the ratio of the length of the patch L to the height h of the substrate (L/h) and the dielectric constant of the substrate. Since for micro strip antennas L/h >> 1, fringing is reduced; however, it must be taken into account because it influences the resonant frequency of the antenna. For micro strip line, typical electric field lines as shown in the figure below.

This is a non-homogeneous line of two dielectrics: typically, the substrate and air. It can be seen that most of the electric field lines reside in the substate and parts of some line exist in air. As W/h>>1 and dielectric constant >>1, electric field lines look wider electrically compared to its physical dimensions. Since some of the waves travel in the substrate and some in air, an effective dielectric constant is introduced to account for fringing and the wave propagation in the line.

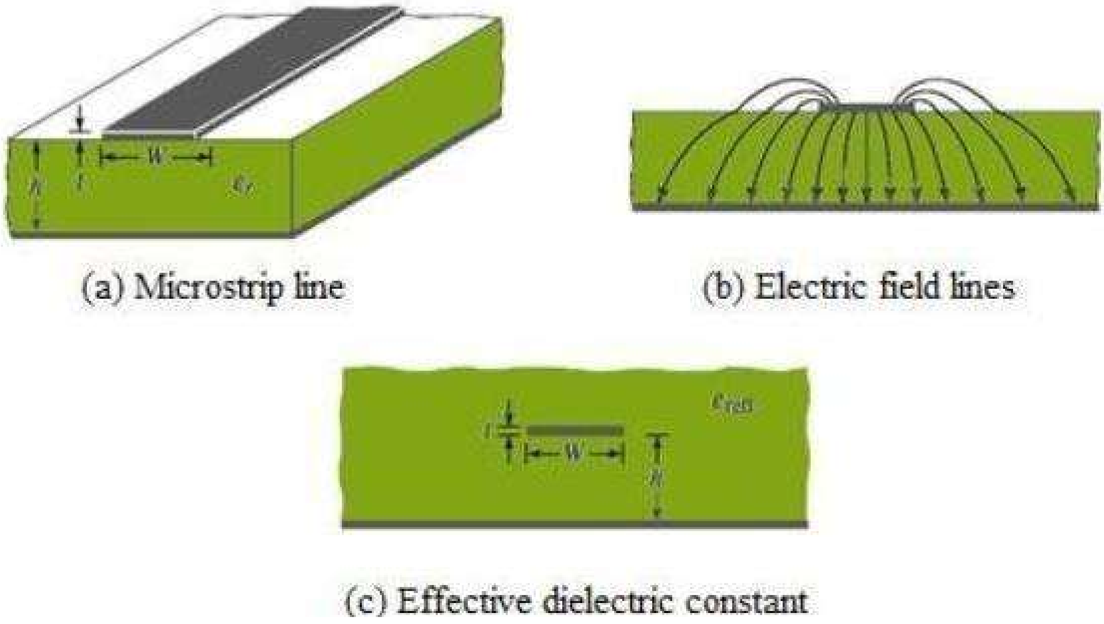


Fig.2.8 Microstrip line and its electric field lines, and effective dielectric constant geometry.

For low frequencies the effective dielectric constant is essentially constant. At intermediate frequences its values begin to monotonically increase and eventually approach the values of the dielectric constant of the substrate. The initial values (at low frequencies) of the effective dielectric constant are referred to as the static values.

Effective dielectric constant is given by:

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\Big[1$$

where, ε is the dielectric constant of the material used,

h is the dielectric height,

w is the Width of the patch.

B. Effective Length, Resonant frequency, and Effective Width

Because of the fringing effects, electrically the patch of the micro strip antenna looks greater than its physical dimensions. For the principal xy plane, this is demonstrated in the figure below, where the dimensions of the patch along its length have been extended on each and by a distance ΔL, which is the function of the effective dielectric constant and the width- to-height ratio (W/h). Very popular and practical approximate relation for the normalised extension of the length is given below:

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}$$

Since the length of the patch has been extended by ΔL on each side, the effective length of the patch is:

$$L_{eff} = L + 2\Delta L$$

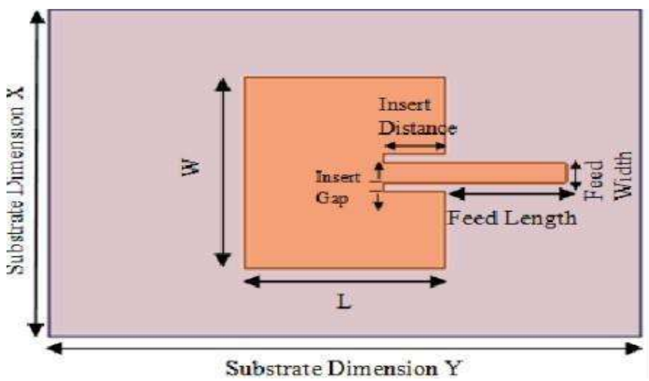
For the dominant TM mode, the resonant frequency of the micro strip antenna is a function of its length. Usually it is given by:

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{(\mu_o\varepsilon_o)}} = \frac{v_o}{2L\sqrt{\varepsilon_r}}$$

where Vo is the speed of light in free space. In the above frequency equation does not account for fringing, it must be modified to include edge effects and should be computed using

$$(f_r)_{010} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{(\mu_o\varepsilon_o)}} = \frac{1}{2(L+2\Delta L)\sqrt{\varepsilon_{reff}}\sqrt{(\mu_o\varepsilon_o)}} = q\frac{1}{2L\sqrt{\varepsilon_r}\sqrt{(\mu_o\varepsilon_o)}} = q\frac{v_o}{2L\sqrt{\varepsilon_r}}$$

$$where, q = \frac{(frc)_{010}}{(fr)_{010}}$$



(a)

(b)

Fig.2.9 Physical and effective lengths of effective rectangular microstrip patch

The q factor is referred to as the fringe factor (length reduction factor). As the substrate height increases, fringing also increases and leads to larger separations between the radiating edges and lower resonant frequencies.

C. Design

For design of an antenna, width and actual length of the patch needs to be calculated. For an efficient radiator, a practical width that leads to good radiation efficiencies is:

$$W = \frac{1}{2f_r\sqrt{(\mu_o\varepsilon_o)}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\nu_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$$

The actual length of the patch can be calculated using

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}}\sqrt{\mu_o\varepsilon_o}} - 2\Delta L$$

2.7 MODELLING OF MICROSTRIP PATCH ANTENNA

Given below is the procedure for modelling Microstrip Patch Antenna:

- Calculate the parameters- effective dielectric constant, effective length, width of substrate using the known operating frequency, height of substrate.
- Create bricks for ground, patch, transmission, inset.
- As per the requirement, specify their locations with respect to the origin axis.
- This completes our 1x1 antenna design.
- Then to go for 1x2, give spacing and translate the 1x1 patch by some spacing so, that two patches appear.
- Calculate the required width of the line joining two patches such that impedence matching exists between two patches.
- Similarly, go for 2x2.
- Simulate the output.
- Change the global properties if required and try out best result.

2.7.1 Microstrip Patch Antenna design in S-Band

1. Simulation of 3.2GHz

a) 1x1 : Design of single element Microstrip antenna

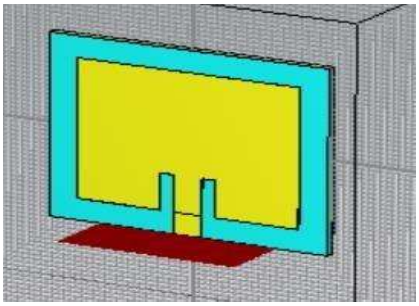


Fig.2.10 Schematic of Single element Microstrip patch antenna with inset feed

Parameter list:

Name	Value
Width of ground	46.66
Length of ground	40.36
Inset gap	2.12
Inset depth	8.15
Width of feed	4.9
Width of patch	37.06
Length of patch	30.76
Height of substrate	1.6

Parameter plot:

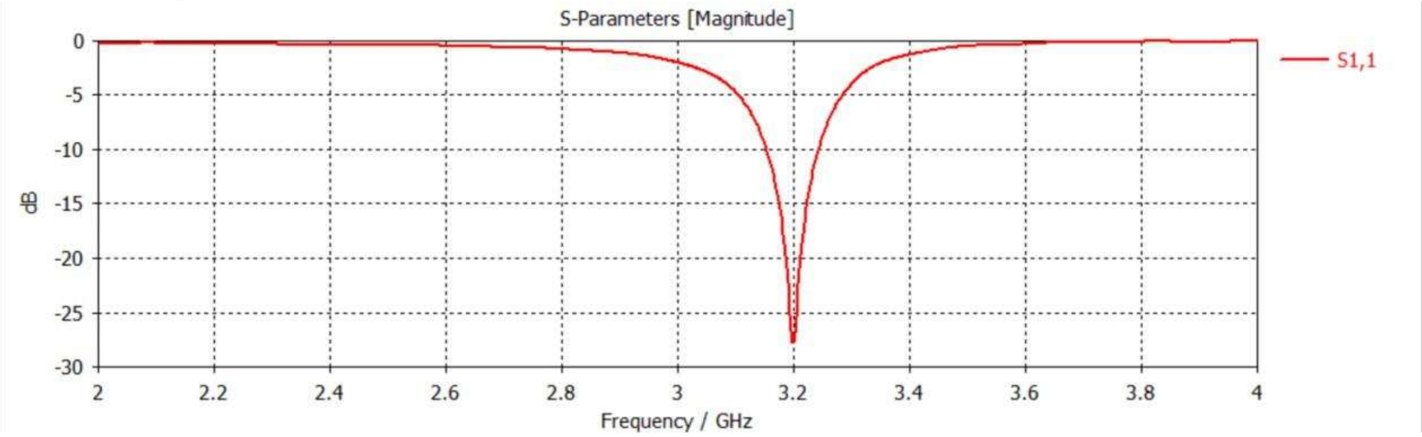


Fig.2.11 S11 parameter plot of single element MPA

The S11 measurement for the single element Microstrip patch antenna with an inset feed shows a minimum S11 value of less than -20dB at 3.2GHz, indicating exceptional impedance matching and minimal signal reflection.

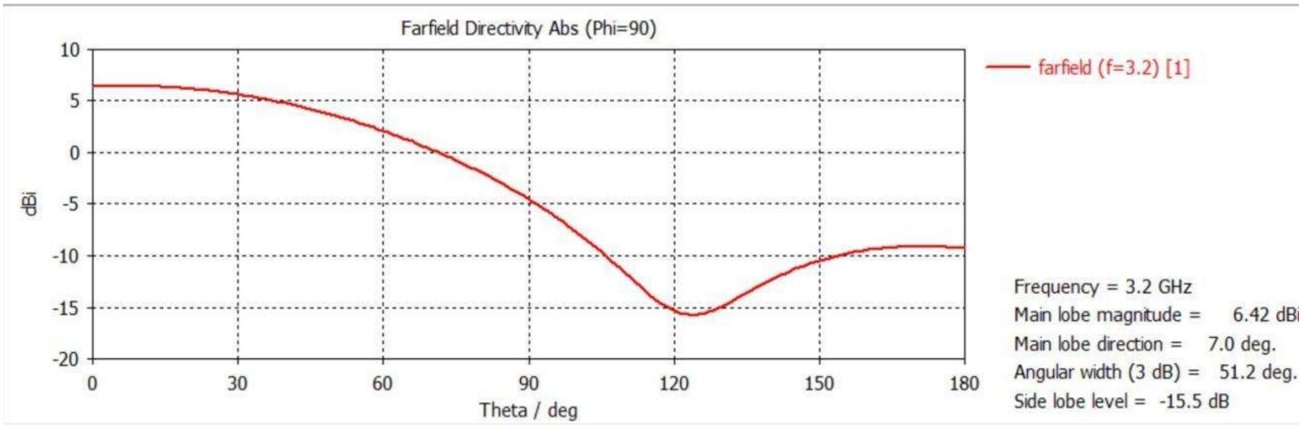


Fig.2.12 Directivity plot of single element MPA

The directivity of the Microstrip patch antenna is measured to be 6.419dBi at 3.2GHz, indicating that the antenna has a strong directional gain. This level of directivity ensures effective signal concentration in the desired direction.

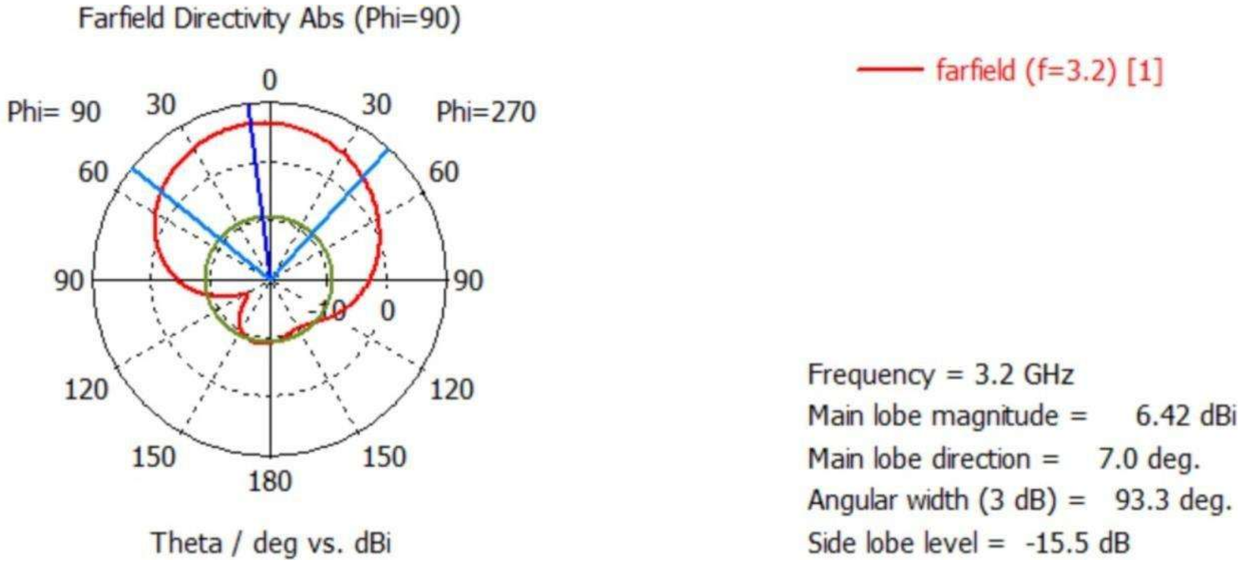


Fig.2.13 Directivity (polar)plot of single element MPA

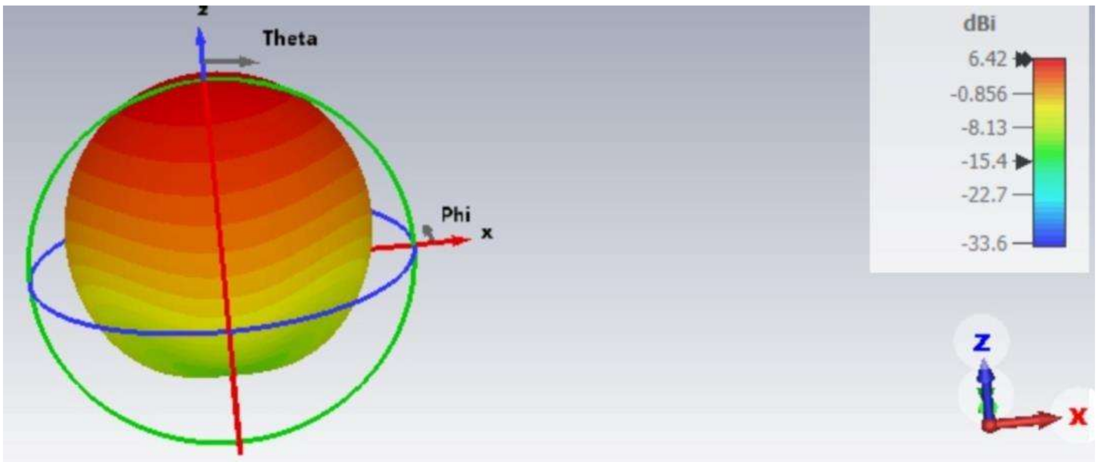


Fig.2.14 3D gain plot of single element MPA

(b) Design of 1x2 microstrip Patch Antenna Array

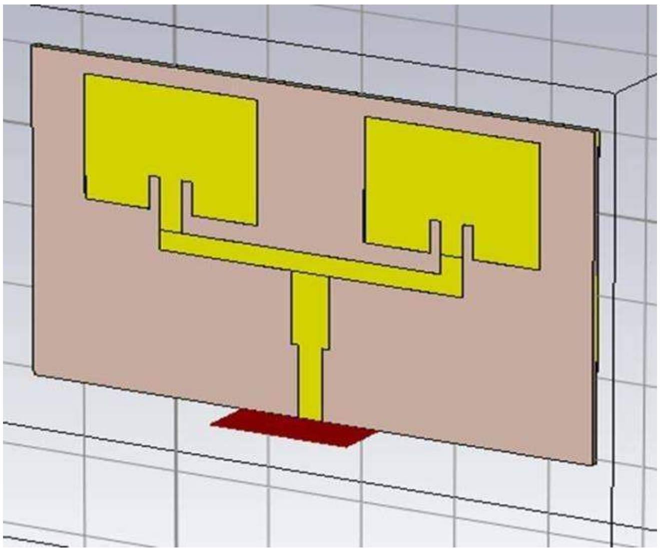


Fig.2.15 Schematic of 1x2 Microstrip patch antenna array

Parameter list:

Name	Value
Width of ground	60
Length of ground	40.36
Inset gap	2.12
Inset depth	8.15
Width of feed	4.9
Width of patch	37.06
Length of patch	30.76
Height of substrate	1.6
spacing	60
Length of 35.4Ω feed line	18
Length of 50Ω transmission line under 34.5Ω feed	18
Width of 35.4Ω line	8.05

Where, s= spacing between the antennae as well as transmission feeds

s_1= spacing between the grounds as well as substrate

l_1= length of 35.4-ohm feed line

l_2= length of 50-ohm transmission line which is under 34.5-ohm feed

wf_1= width of 35.4-ohm line

Power Divider Implementation:

For proper implementation of power divider, impedance matching is essential to ensure minimal reflection and maximum power transfer. Suppose the input port has an impedance of 50 Ω, and both output ports also need to maintain 50 Ω.

To achieve impedance matching at the junction where the input splits into two branches, each branch must have an impedance of 35.4 Ω. This is calculated using the following formula:

$$Z = (Z1.Z2)^{1/2}$$

Where, Z1=25 Ω (equivalent impedance of two parallel 50 Ω loads)

Z2=50 Ω (source impedence)

So, $Z=(25x50)^{1/2}=35.4\ \Omega$

Parameter plot :

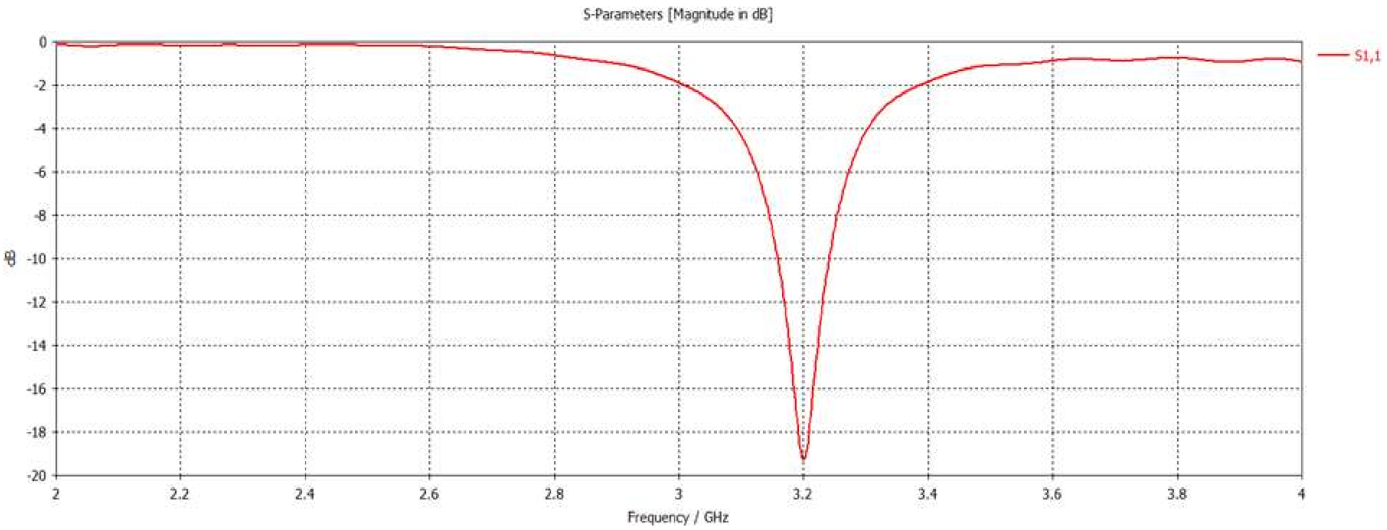


Fig.2.16 S11 parameter plot of 1x2 Microstrip Patch Antenna array

The S11 measurement for 1x2 Microstrip patch antenna with an inset feed shows a minimum (minimum) S11 is nearly -19dB at 3.2GHz, indicating exceptional impedance matching and minimal signal reflection.

Input VSWR:

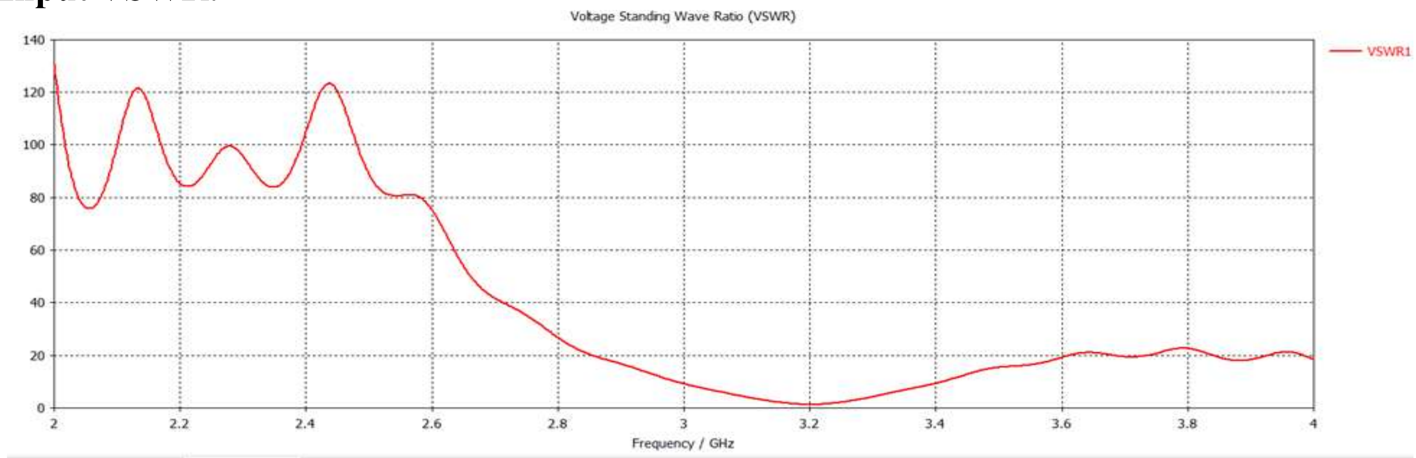


Fig.2.17 VSWR of 1x2 MPA array

The Voltage Standing Wave Ratio (VSWR) for the 1x2 Microstrip patch antenna is measured to be 2 at 3.2GHz, indicating excellent impedance matching and minimal signal reflection.

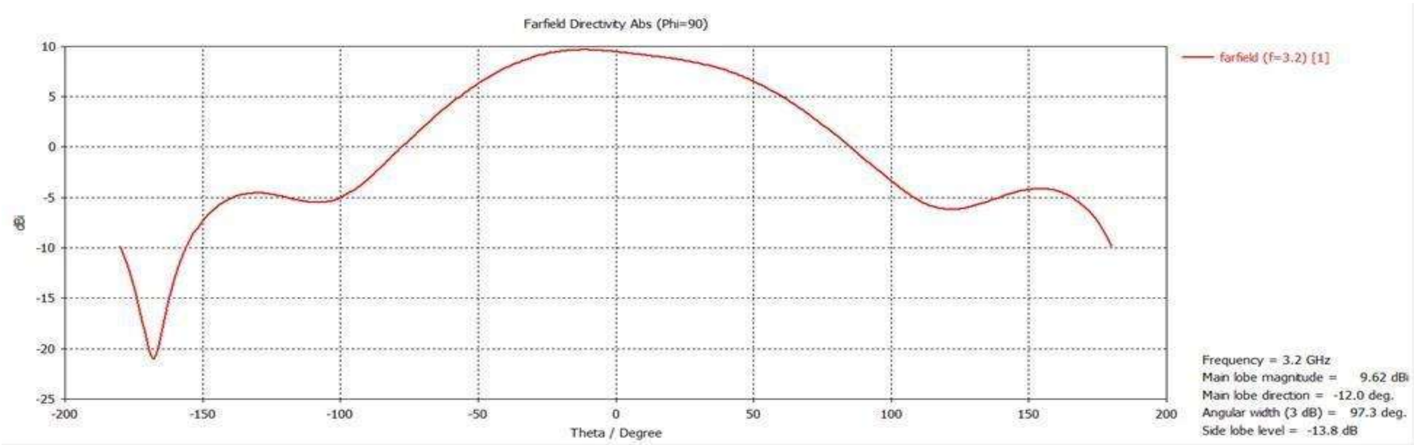


Fig.2.18 Directivity Cartesian plot

The directivity of the Microstrip patch antenna is measured to be 9.1dBi at 3.2GHz, indicating that the antenna has a strong directional gain. This level of directivity ensures effective signal concentration in the desired direction.

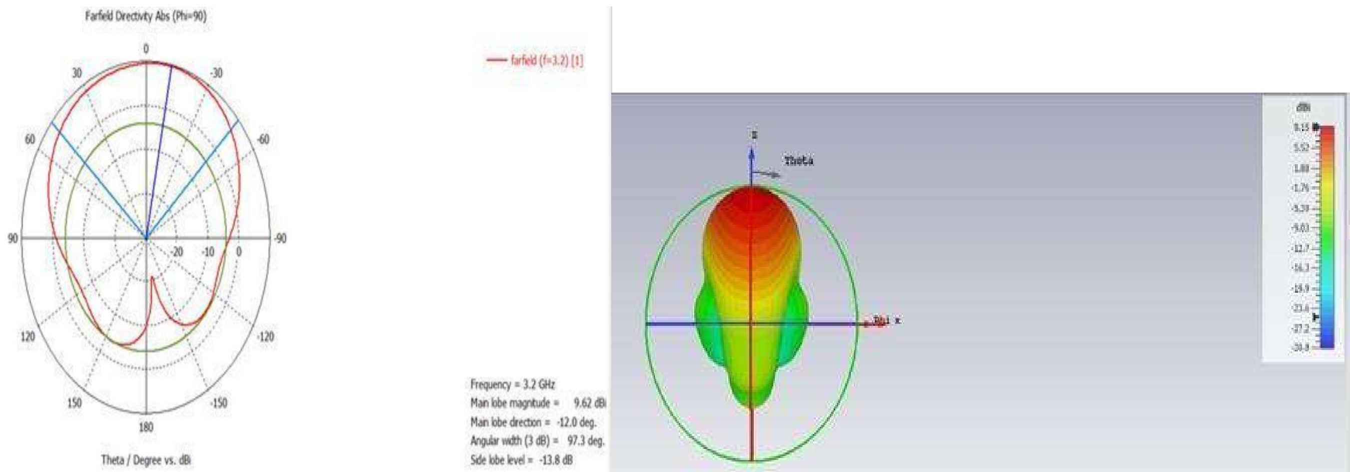


Fig.2.19 Directivity polar plot & 3d gain plot

(c) Design of 2x2 microstrip Patch Antenna Array

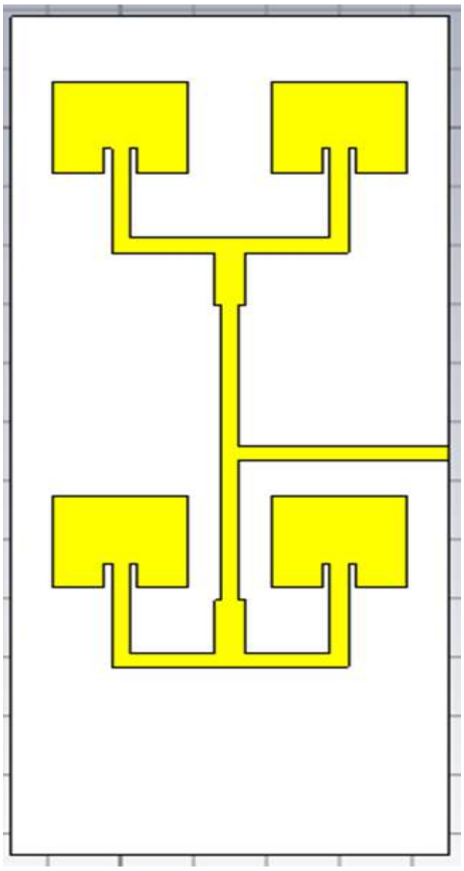


Fig.2.20 Schematic of 2x2 Microstrip patch antenna array

Parameter list:

Name	Value
Width of ground	60
Length of ground	75.2125
Inset gap	2.12
Inset depth	8.15
Width of feed	4.9
Width of patch	37.06
Length of patch	30.76
Height of substrate	1.6
spacing	60
Length of 35.4Ω feed line	18
Length of 50Ω transmission line under 34.5Ω feed	100
Width of 35.4Ω line	8.05

Parameter Plot:

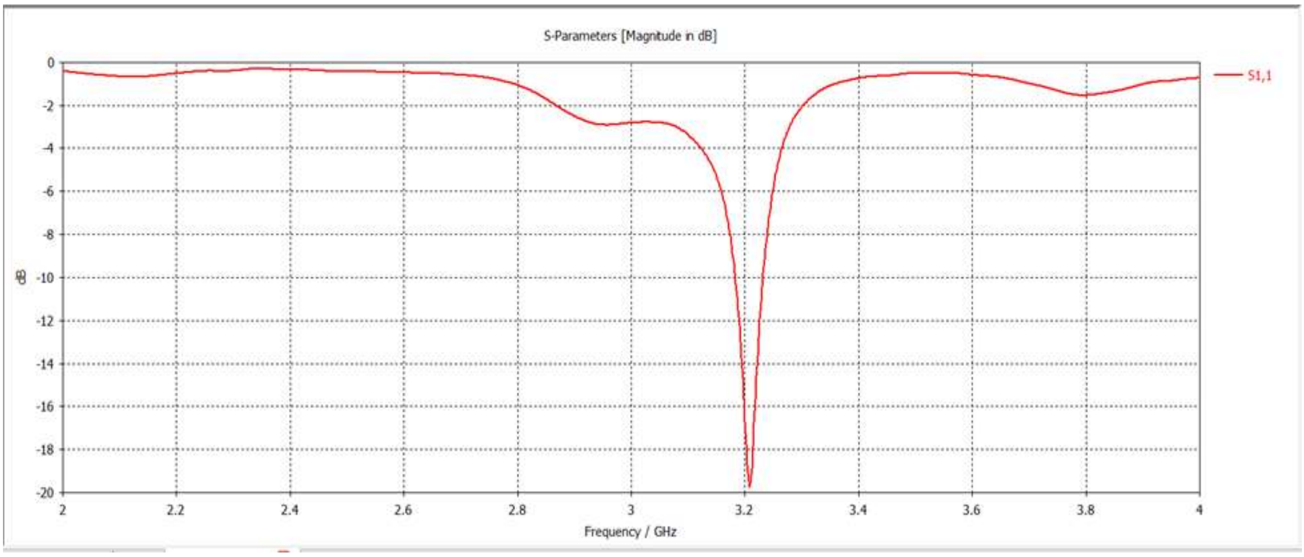


Fig.2.21 S11 parameter plot of 2x2 MPA array

The S11 measurement for 2x2 Microstrip patch antenna with an inset feed shows a minimum S11 is nearly -19.5dB at 3.2GHz, indicating exceptional impedance matching and minimal signal reflection.

Input VSWR:

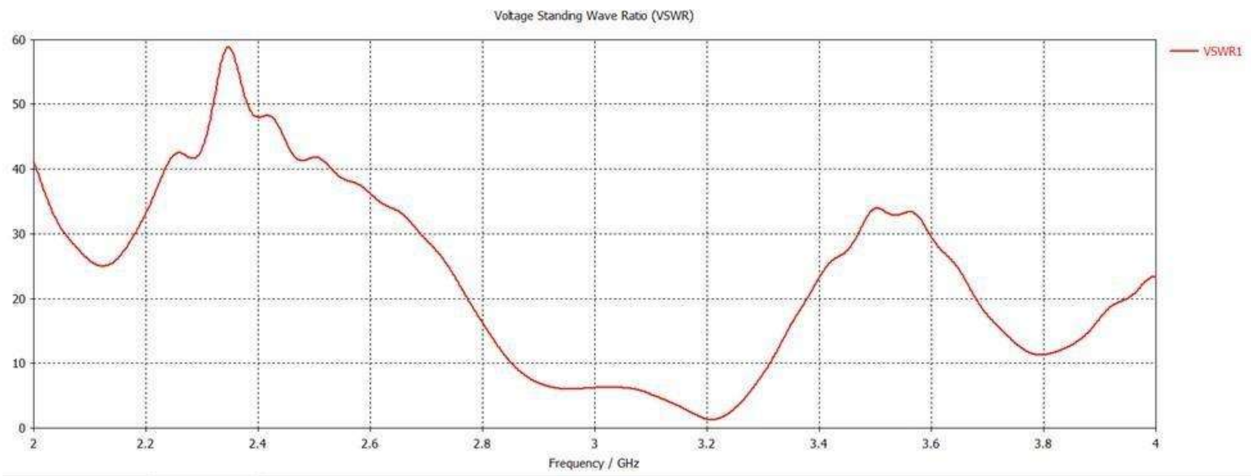


Fig.2.22 VSWR of 2x2 Microstrip Patch Antenna array

The Voltage Standing Wave Ratio (VSWR) for the 2x2 Microstrip patch antenna is measured to be 2 at 3.2GHz, indicating excellent impedance matching and minimal signal reflection.

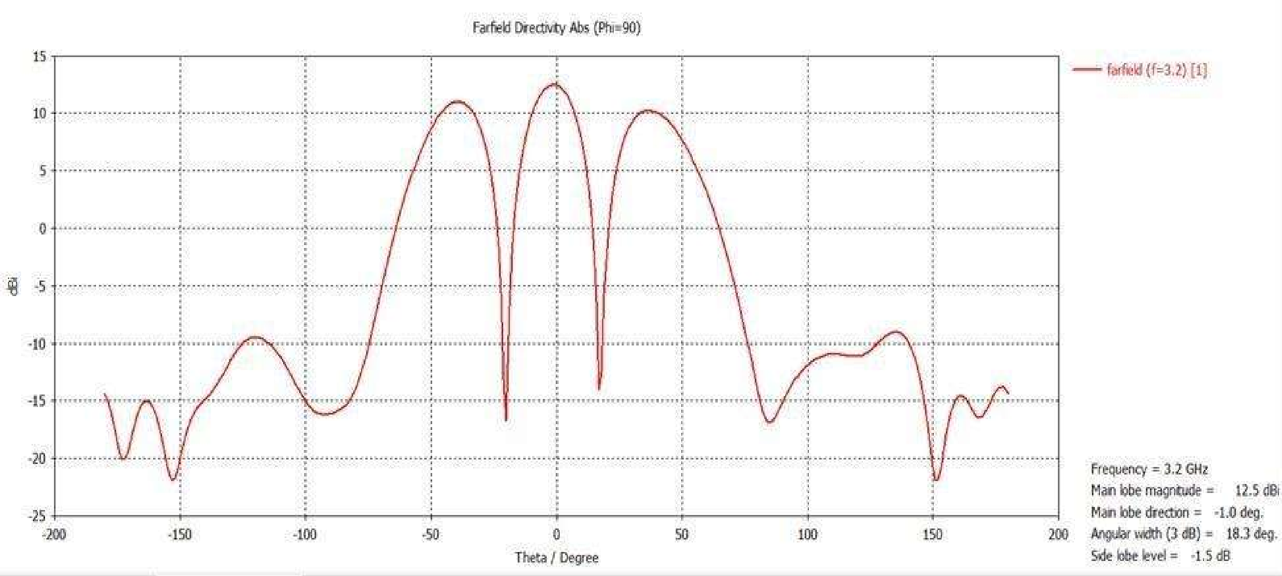


Fig.2.23 Directivity Cartesian plot

The directivity of the Microstrip patch antenna is measured to be 12.3dBi at 3.2GHz.The gain of the Microstrip patch antenna is measured to be 12.1dB at 3.2GHz.

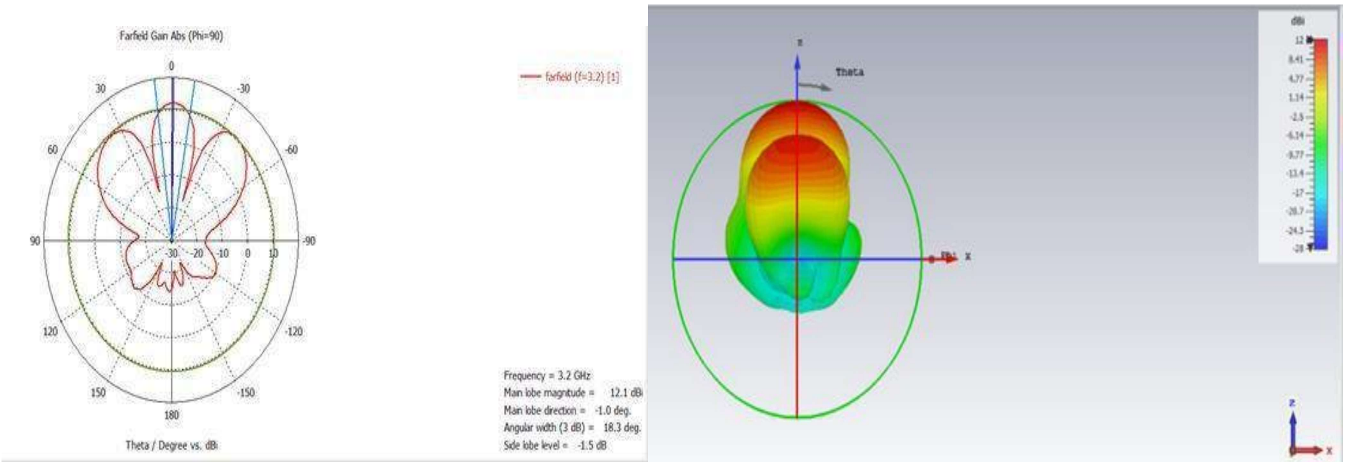


Fig.2.24 Directivity polar plot & 3d gain plot

(d) Design of 4x8 microstrip Patch Antenna Array

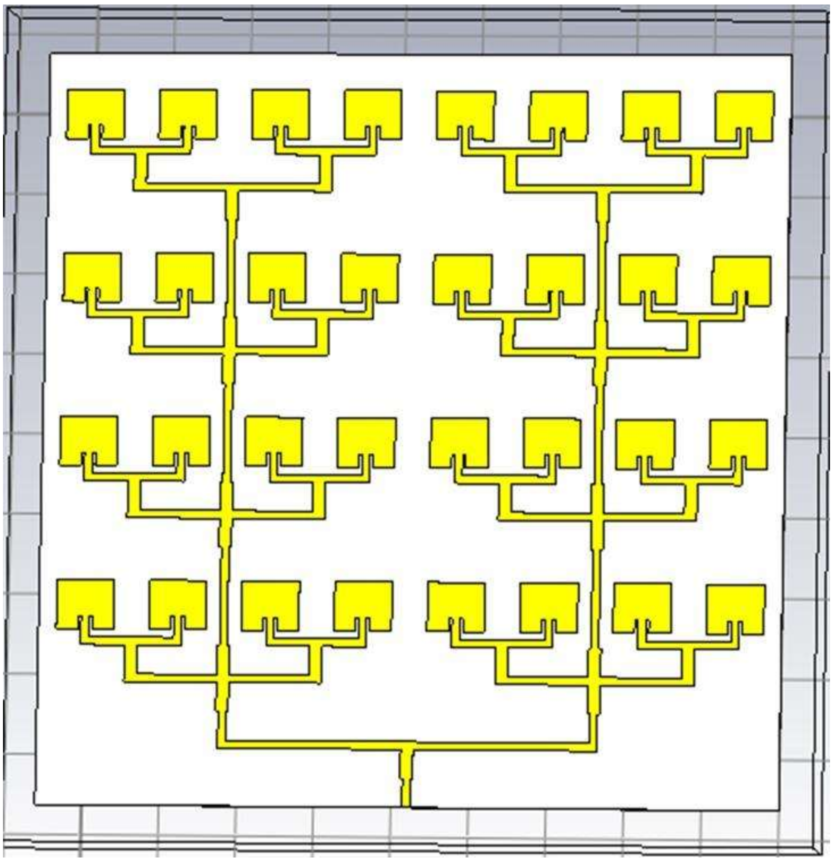


Fig.2.25 Schematic of 4x8 Microstrip patch antenna array

Parameter list:

Name	Value
Width of ground	46.66
Length of ground	40.36
Inset gap	2.12
Inset depth	8.15
Width of 50 Ω line	4.9
Width of patch	37.06
Length of patch	30.76
Height of substrate	1.6
Spacing in x direction	60
Length of 35.4Ω feed line	18
Length of 50Ω transmission line feed	18
Spacing in y-direction	-102.22

Width of 35.4Ω line	8.05

Parameter Plot:

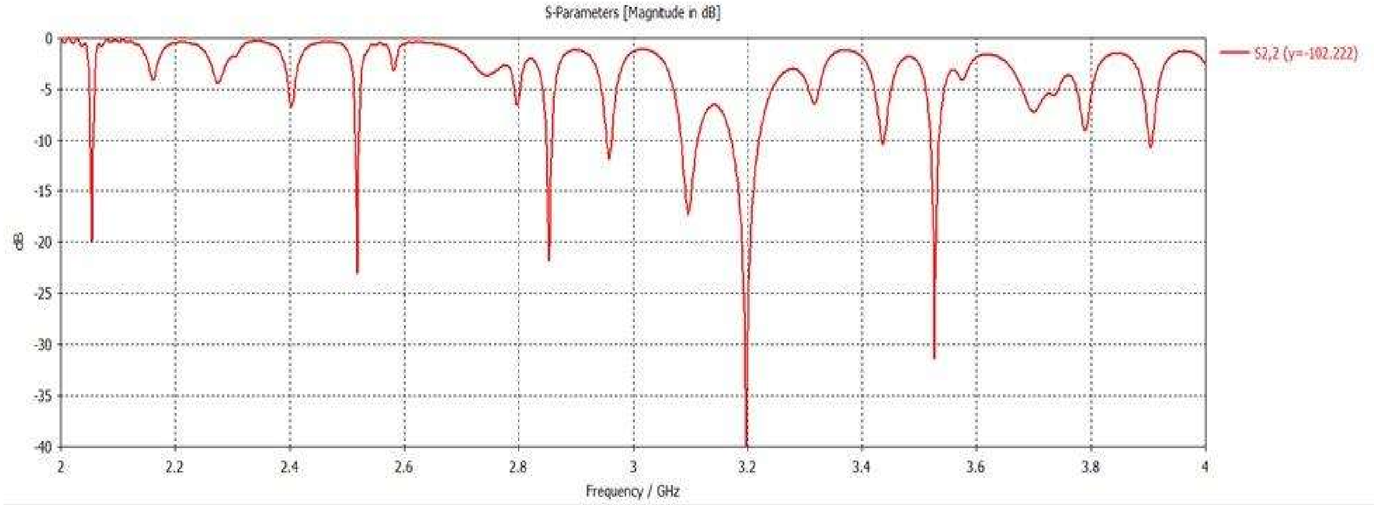


Fig.2.26 S11 parameter plot of 4x8 MPA array

The S11 measurement for 2x2 Microstrip patch antenna with an inset feed shows a minimum S11 is nearly -43.2dB at 3.2GHz, indicating exceptional impedance matching and minimal signal reflection.

Gain Plot:

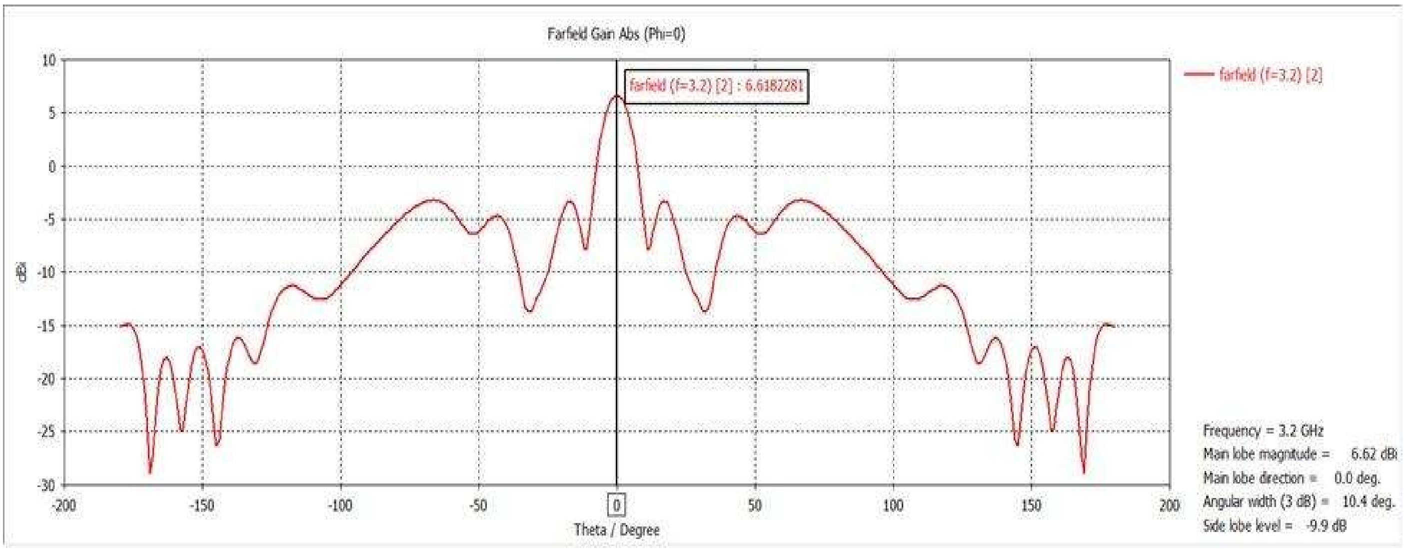


Fig.2.27 Farfield Gain plot of 4x8 MPA array

Here, its indicating 6.61dB which not that good value , so we are trying to optimize it so that gain will be around 16dB.

Summary:

(a) 1x1: We designed a single patch antenna where the patch's length and width calculated using the transmission line model. The S11 plot indicates how much power is reflected (instead of being radiated). For the single patch, S11 is less than -20 dB, which is a very good value for impedance matching and indicates that more power is being radiated. Far field directivity represents radiation strength at various angles. At 0 degree its maximum.

(b) 1x2: Here in 1x2 patch antenna array, there is two patch in one row. Here S11 is nearly 19db. VSWR plot shows the derived parameter of return loss so it's minimum at 3.2GHz.

(c) 2x2: Here in 2x2 patch antenna array, minimum S11 is nearly -19.5dB at 3.2GHz and VSWR is calculated to be 2 at 3.2 GHz.

(d) 4x8: Here in 4x8 patch antenna array, minimum S11 is nearly -43.2dB at 3.2GHz.