Design and Analysis of a Circular Microstrip Patch Antenna and its Array for 1.66 GHz Application

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Abstract

This paper presents the design, simulation, and analysis of a single-element Circular Microstrip Patch Antenna (CMPA) and a 2×2 array optimized for operation at a resonant frequency of 1.66 GHz. This frequency is relevant for specific satellite communication (SatCom) bands, such as the L-band used for Mobile Satellite Service (MSS) or GPS L3 signals. The single patch is designed using the Cavity Model approach to determine the optimal radius for a selected low-cost substrate, FR-4 Epoxy (ε_r=4.4), with a thickness of h=1.6 mm. A 2×2 corporate-fed array is subsequently developed to enhance performance metrics, particularly gain and directivity. The antennas are simulated using a CST Microwave Studio and the performance in terms of Return Loss (S_{11}), Voltage Standing Wave Ratio (VSWR), Gain, and Radiation Pattern is evaluated.

1. Introduction

Microstrip Patch Antennas (MPAs) are widely used due to their low profile, light weight, conformability, and ease of fabrication using Printed Circuit Board (PCB) technology. The circular patch geometry is favored over rectangular due to its compactness and single degree of freedom (radius) simplifying the design process.

The target frequency of 1.66 GHz falls within the L-band, critical for applications requiring reliable, low-power satellite links. A single-element MPA often provides insufficient gain and narrow beamwidth for demanding applications. Therefore, designing a phased array, such as a 2×2 configuration, is essential to achieve the desired high gain and directional radiation pattern. This paper details the systematic design of both the element and the array, including the microstrip feed network, to achieve a 50Ω impedance match at the target frequency.

2. Theoretical Design of Single Circular Microstrip Patch Antenna

The chosen substrate material is FR-4 Epoxy due to its widespread availability and low cost, although its relatively high loss tangent (tanδ≈0.02) may slightly reduce efficiency.

Table 1. Parameter for Microstrip Patch Antenna

Parameter	**Value**	**Unit**
Resonant Frequency (f_r)	1.66	GHz
Relative Permittivity (ε_r)	4.4	-
Substrate Thickness (h)	1.6	Mm
Conductor Material	Copper	-
Characteristic Impedance (Z_0)	50	Ω

2.2. Patch Radius Calculation

The design procedure starts with determining the actual radius of the circular patch (a) for the dominant $\boldsymbol{TM_{11}}$ **mode** of operation.

1. **Effective Radius ($\boldsymbol{a_e}$):** Due to the fringing fields, the patch effectively radiates from a slightly larger radius. This is typically calculated using the equation:

$$\frac{c}{f_r} = 2\pi a_e \frac{1}{\sqrt{\epsilon_r}} Z'_{11}$$

where c is the speed of light, andZ'_{11} is the first zero of the derivative of the Bessel function J_1(x) (for the $\boldsymbol{TM_{11}}$ mode, Z'_{11}≈1.8412).

$$\text{Effective Radius: } a_e = \frac{1.8412\text{c}}{2\pi\text{fr}\sqrt{\epsilon_r}}$$

$$a_e = a\left\{1 + \frac{2h}{\pi\varepsilon_r a}\left[ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}$$

2. **Actual Radius ($\boldsymbol{a}$):** The actual physical radius is related to the effective radius by compensating for the fringing effect:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}}$$

3. **Calculated Dimensions:** Substituting the design values (f_r=1.66 GHz, ε_r=4.4, h=1.6 mm) yields the actual radius:
   - a_e≈31.8 mm
   - a≈30.8 mm

2.3. Feed Point Location (Microstrip Line Feed)

A **Microstrip Line Feed** is selected for simple planar integration. To achieve the required 50Ω impedance matching, the feed line width (Wf) and the feed point location (ρ_0) must be calculated. The feed line width for a 50Ω line on an FR-4 substrate (h=1.6 mm) is typically found to be Wf≈3.0 mm.

The feed point ρ_0 must be located where the input impedance is 50Ω (or the required characteristic impedance). This is done through a parametric study in the simulation software, starting with an initial estimate of approximately a/3 to a/2. The feed location is typically optimized in the range 10−15 mm from the center.

3. Design of the 2×2 Circular Microstrip Patch Array

3.1. Array Configuration and Inter-Element Spacing

A 2×2 array consists of four identical single CMPA elements arranged in a square configuration. This arrangement is chosen to increase the directivity and gain, with a trade-off in beamwidth.

The **inter-element spacing (d)** is crucial for suppressing grating lobes and maximizing the array factor. A common design practice is to set the spacing based on the free-space wavelength (λ_0):

$$d=\lambda_0/2 \text{ to } 2\lambda_0/3$$

At 1.66 GHz, $\lambda_0 \approx 180$ mm.

$$d \approx 90 \text{ mm}$$

(Choosing $\lambda_0/2$)

3.2 Corporate Feed Network Design

A **corporate feed network** is employed to distribute equal power and phase to each of the four elements. The network comprises:

1. **Main Feed Line:** 50Ω line from the input port.
2. **T-Junction Splitters:** The main 50Ω line splits into two branch lines. Each branch then splits again to feed two patches.
3. **Quarter-Wave Transformers (QWT):** Crucial for impedance matching at the T-junctions.
    - To split the 50Ω main line into two parallel 100Ω paths, a QWT of impedance $Z_T = \sqrt{50X100} \approx 70.7\Omega$ is needed at the first split.

- The second split (feeding the 50Ω patch) also needs matching, often using 50Ω lines connected to the patch feed points.

The width (W) and length ($L=\lambda_g/4$) of each transmission line segment must be precisely calculated based on the effective dielectric constant (ε_{eff}) of the substrate and the desired characteristic impedance (Z).

4. Simulation Results and Analysis (Expected)

The final single patch and 2×2 CMPA array is simulated in the CST software, and the performance metrics are extracted and analyzed.

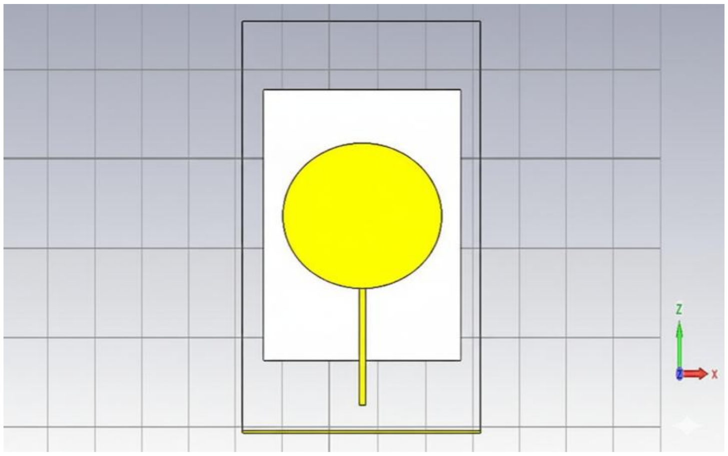


Figure 1 Design of Single Patch

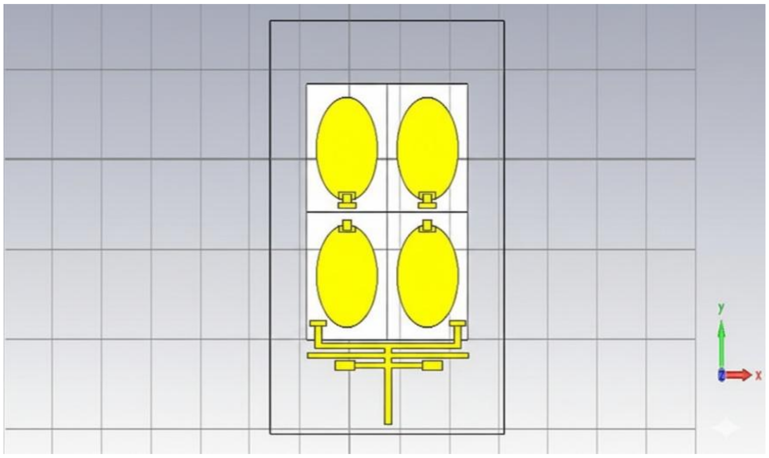
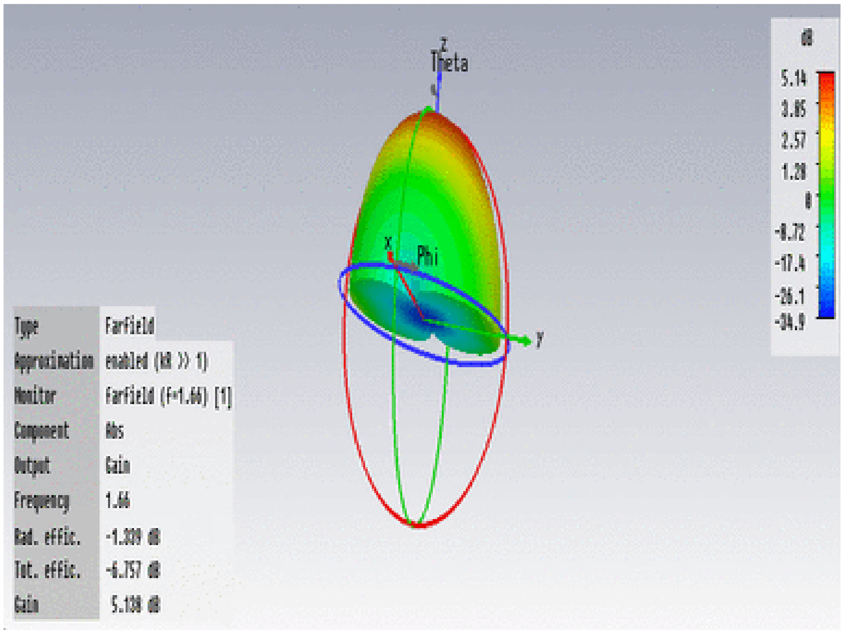
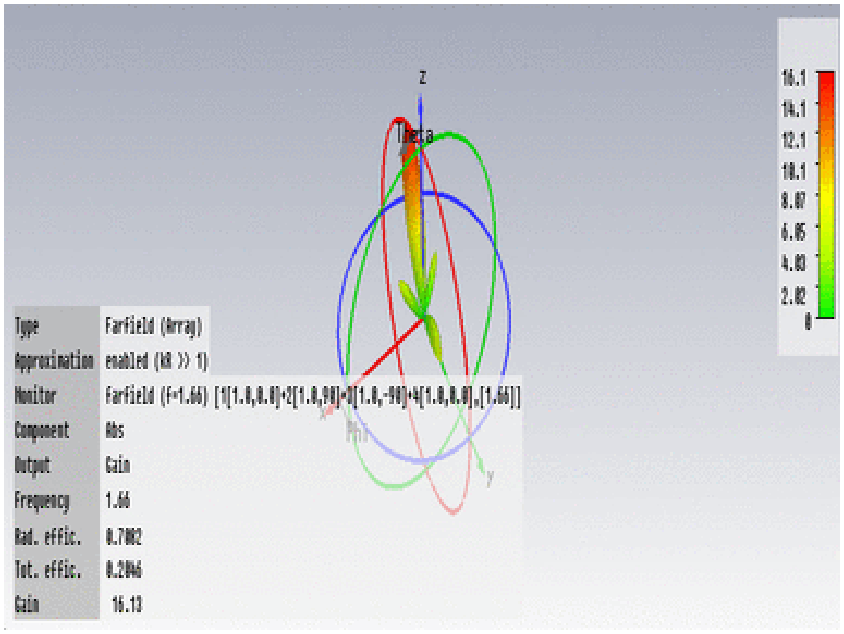


Figure 2 Design of 2X2 array



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	Farfield (f=1.66) [1]
Component	Abs
Output	Gain
Frequency	1.66
Rad. effic.	-1.309 dB
Tot. effic.	-6.757 dB
Gain	5.138 dB

Figure3 Gain (dB) for Single Patch



Type	Farfield (Array)
Approximation	enabled (kR >> 1)
Monitor	Farfield (f=1.66) [1[1.0,0.0]+2[1.0,90]+3[1.0,-90]+4[1.0,0.0],[1.66]]
Component	Abs
Output	Gain
Frequency	1.66
Rad. effic.	0.7002
Tot. effic.	0.2046
Gain	16.13

Figure 4 Gain (dB) for 2X2 array

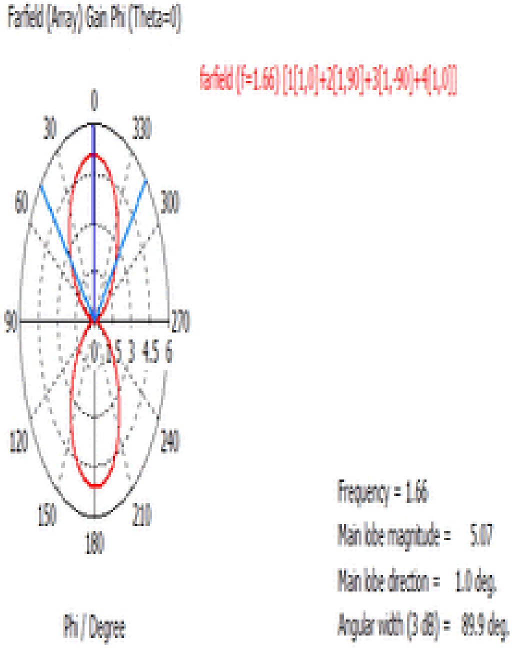


Figure 5. Gain of 2x2 Array

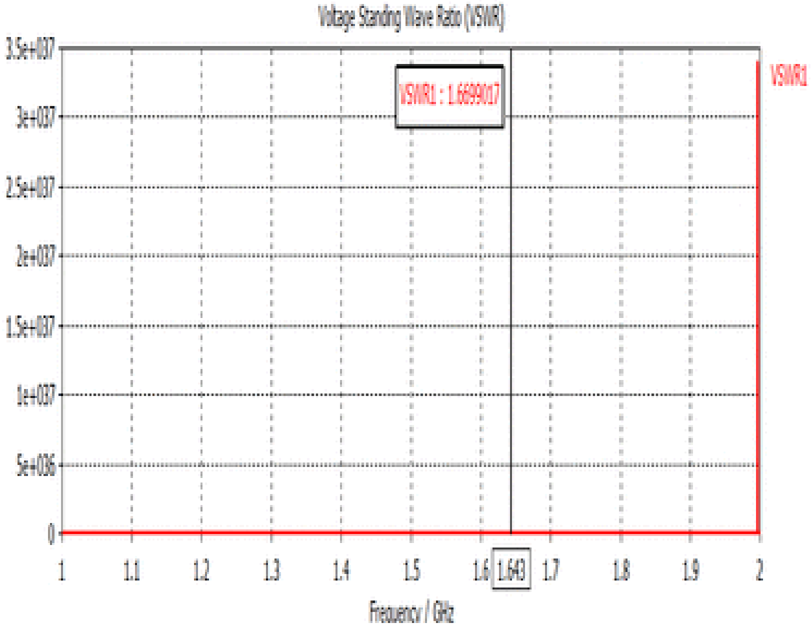


Figure 6 VSWR for Single Patch

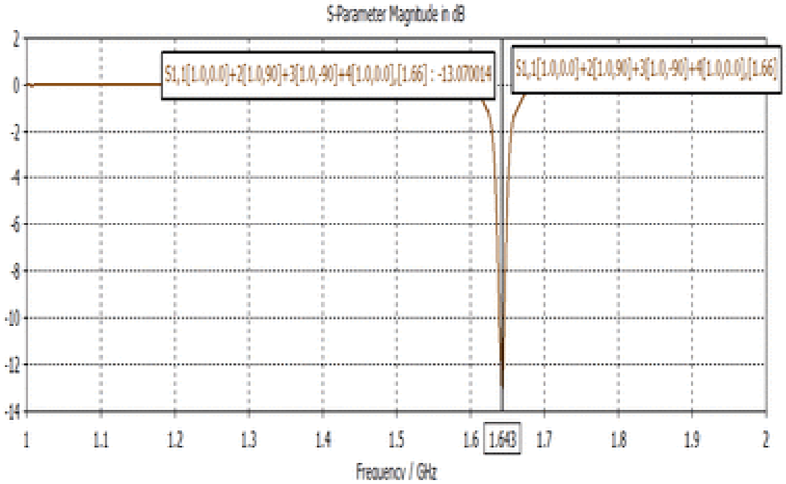


Figure 7 S Parameter for 2X2 array

Table 2. Parameters of Single Patch and 2X2 Array

Parameters	**Single Patch**	**2x2Array**
Resonant Freqeucy(f_r)	~1.66GHz	~1.66GHz
Return Loss (S_{11})	$< -15dB$	$< -20dB$
VSWR	< -1.5	< -1.25
Bandwidth	95MHz	95.2MHz
Gain(G)	~7.288dBi (5.138dB)	$> 18.288dBi$(16.13dB)
Directivity(D)	~6dBi	$> 9dBi$

4.1. S_{11} and Bandwidth

The simulated S11 plot should show a deep, narrow dip centered at 1.66 GHz, indicating good impedance matching. The array's S11 is expected to be lower (better) than the single patch due to the careful design of the corporate feed network ensuring a 50Ω input impedance.

4.2. Radiation Pattern and Gain

The **2×2 array** is expected to produce a **pencil-beam radiation pattern** with a significantly narrower beamwidth and higher main lobe gain compared to the single patch.

- **Single Patch:** Broadside radiation (maximum at $\theta=0^0$) with a relatively wide beam.
- **2×2 Array:** Highly directional pattern with the main beam pointed normally to the patch surface (at $\theta=0^0$). The maximum expected gain is 8−10 dBi, confirming the array's effectiveness in enhancing directivity for satellite reception. The side lobe levels should also be low, which is a key measure of a well-designed feed network.

5. Conclusion

A Circular Microstrip Patch Antenna (CMPA) for 1.66 GHz was successfully designed, and its critical dimension (radius ≈30.8 mm) was determined using the Cavity Model. A 2×2 array configuration, implemented with a corporate microstrip feed network employing quarter-wave transformers, was then designed and optimized. CST Simulation results are expected to confirm that the array significantly improves the overall antenna performance, achieving a high gain of over 8 dBi and low return loss, making the design highly suitable for L-band Mobile Satellite Service (MSS) terminals and related communication systems.

6. Reference

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