Patch Antenna Element and Antenna Array Design and Simulation

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***Abstract* - The objective of this project is to design a circular microstrip patch antenna and antenna array using the electromagnetic simulation tool Advanced Design System (ADS). The patch antenna element was first designed and tested to meet the performance specifications. The antenna array was then constructed using the unit elements to increase the gain and beamwidth of the radiating structure.**

The antenna element achieved a radiation frequency of 4.22 GHz, with a max gain of 5.531dB, a reflection coefficient of -17dB, and an efficiency of 78.1%. The final antenna array design attained a reflection coefficient, gain, and efficiency of -16.96dB, 12.75dB, and 72.9% respectively. A table which summarizes the results obtained from this experiment can be found in Section IV.

I. INTRODUCTION

Microstrip antennas, also referred to as patch antennas, are very popular in the telecommunication industry because they can be manufactured on circuit board using the same etching process as all the other copper traces. On top of their relatively easy integration, they are cheap and have a low profile. Moreover, the micro strip antenna constitutes of four design parts: a very thin metal region known as the patch, a dielectric substrate, a ground plane, and a feed. Constructing these parts is relatively easy compared to other antennas and require less time to analyze.

NASA used micro strip antennas for space exploration in deep space because they were a good choice for transmitting signals on the Saturn/Uranus Atmospheric entry probe. NASA also discussed that micro strip antennas are suitable for space environment because they are very compact and efficient [3]. The main factors that can affect the antenna's performance are temperature and high energy radiation which cause the resonant frequency to increase. However, these factors do not affect the performance considerably and still allow astronauts to transmit information efficiently. All things considered, a micro strip antenna is an adequate choice for antenna design because they are easy to construct and can be used for different purposes.

An antenna array is a design that consists of 2 or more antennas of the same specifications. The primary objective when designing an antenna array is to determine the positions of the array elements to jointly produce a radiation pattern [4]. Antenna arrays are used in a wide variety of applications, such as radio astronomy, radar, and even medical devices. One such application is an antenna array that is placed on different parts of a patient's body. The array can then detect the patient's electrocardiograph signals wirelessly [1]. Antenna arrays are also used in the telecommunications industry. For example, they can be used at a base station to estimate the angle and distance of a mobile phone signal, which is useful for dispatching emergency services as quickly as possible [6].

II. DESIGN APPROACH

A. Antenna Element

The first step in designing the antenna element is to find the radius of the circular patch. In order to do this, the logarithmic function of the radiating element, F was found using

$$F = \frac{8.791 \times 10^9}{f_r \times \sqrt{\varepsilon_r}} \quad (1)$$

where f_r represents the resonating frequency (Hz), ε_r represents the relative dielectric permittivity of the substrate, and F is the logarithmic function of the radiating element [2].

Equation (1) yielded a result of $F = 1.212$. After finding F, the radius of the radiating elements was obtained using

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

where a represents the radius (cm) and h is the thickness of the substrate (m) [2]. Equation (2) yielded an antenna radius of $a = 1.18$cm.

An antenna with radius 1.18cm, as shown in Fig. 1 was then created and simulated in ADS.

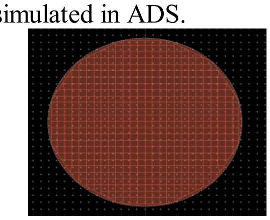


Fig. 1 First iteration of patch antenna

The simulation showed a resonant frequency of 4.34GHz. Through trial and error, the radius was adjusted to 1.21cm to obtain the resonant frequency of 4.22GHz, which was close to the required frequency of 4.2GHz. ADS also found the value of the reflection coefficient, S_{11}, to be -5.857. The input impedance, Z_{in}, can be found using

$$S_{11} = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} \quad (3)$$

where Z_0 represents the characteristic impedance of the port, 50Ω [5]. The result attained from (3) was Z_{in} = 70.59 Ω.

A diagram showing the labelled widths, lengths, and impedances of the antenna element is shown in Fig. 2.

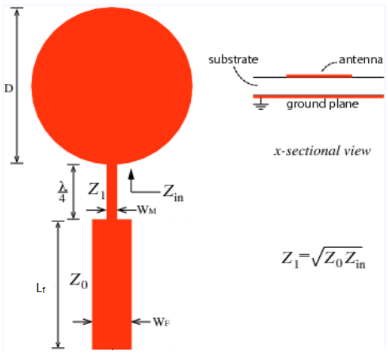


Fig. 2 Circular patch antenna specifications

To calculate the width of the microstrip, w_m, (4) and (5) were used,

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \left[\frac{\varepsilon_r - 1}{2\sqrt{1 + 12(\frac{h}{w_m})}}\right] \quad (4)$$

$$Z_{in} = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{w_m}{h} + 1.393 + \ln(\frac{w_m}{h} + 1.444)\right]} \quad (5)$$

$$\varepsilon_{eff} = 2.356$$
$$w_m = 1\,mm$$

where ε_{eff} represents the effective relative dielectric constant [5]. Using (5) again, but replacing Z_{in} with Z_0 (50Ω) the width of the feed, w_f, was calculated to be 1.44mm. The wavelength of a wave moving in the dielectric, λ, was then calculated using (6) [5].

$$\lambda = \frac{c}{f_r\sqrt{\varepsilon_{eff}}} \quad (6)$$

$$\because \lambda = 46.11\,mm$$
$$\therefore \frac{\lambda}{4} = 11.5\,mm$$

After creating and simulating the antenna with the specifications λ/4 = 11.5mm, w_m = 1mm, a = 12.1mm, w_f = 1.44mm, the gain and reflection coefficient did not meet the required parameters. After several iterations, the final parameters which met the required specifications are shown in Table I.

TABLE I
ANTENNA ELEMENT DIMENSIONS

Parameter	Dimension (mm)
a	12.1
w_f	1.44
w_m	0.15
λ/4	11.5
L_f	12.5

B. *Antenna Array*

To achieve the desired antenna array configuration shown in Fig. 3, the antenna element generated in the previous section was duplicated seven times.

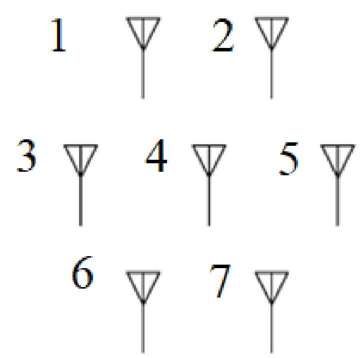


Fig. 3 The desired 2-3-2 antenna array geometry with numbered antenna elements

However, instead of attempting to design the full seven-antenna array from the outset, the design approach taken was to simulate the three leftmost antennas first as shown in Fig. 4.

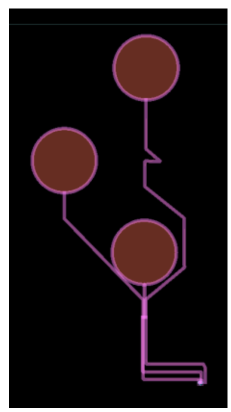


Fig. 4 Initial 3-element antenna array

To achieve the required radiation specifications, the feeding method of each antenna element was altered. The 50Ω matched microstrip line was removed and increments of one wavelength (46.1mm) were added to each antenna feed to achieve the desired antenna configuration. The lengths of each feed are shown in Table 2.

TABLE 2
ANTENNA ELEMENT FEED LINE LENGTHS

Antenna Feed	Length (mm)
1	150.3
2	150.3
3	105.2
4	107.5
5	105.2
6	58.9
7	58.9

The 50Ω feed was then reintroduced and attached to all three feeds and a port was placed at its edge. The simulation results were acceptable, so this array became the new unit antenna element and was duplicated and mirrored to achieve the 6-element array shown in Fig. 5.

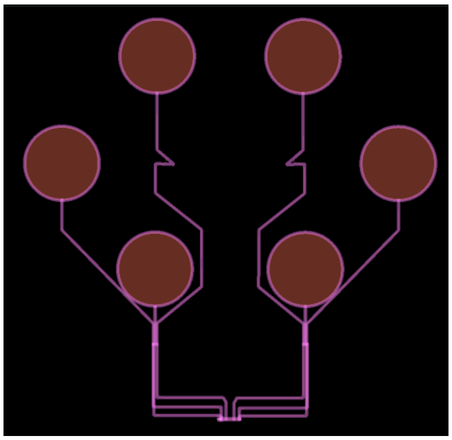


Fig. 5 6-element antenna array created from two 3-element array units

However, there were now 6 feed lines that needed to be interfaced with the 50Ω microstrip line. As discussed in the antenna element section, the width of the 50Ω was 1.4mm, so there was not enough room to connect 6 individual .15 mm feed lines with 0.1mm spaces in between them. Therefore, the 50Ω microstrip line was rotated 90°, the port was connected to its side, the new array was simulated. Again, the results of the simulation showed a gain of 11.2 and a reflection coefficient of -8.25, so the final antenna element was added.

The same method of adding one wavelength to the 12.5mm feed line was used to connect the central antenna to the 50Ω microstrip line. The line was then condensed by adding curves. The final antenna array configuration is shown in Fig. 14.

Upon the completion of the antenna array, the gain met specifications, but the reflection coefficient did not meet the design requirement of -12 and below as it was -8.12. An iterative process of adjusting the width and length of the port feed and re-simulating was then conducted until the reflection coefficient was under -12 and the gain was 11.20. Further changes to the length or width greatly affected the reflection coefficient, so another method needed to be used to increase the gain.

The radiation pattern of the antenna array was analyzed and what appeared to be destructive interference was seen at its center. Thus, the position of the center antenna's feed line on the 50Ω port feed was adjusted with the intention of shifting its phase relationship to the other antennas. This method of gain control was successful, and the final feed network is shown in Fig. 6.

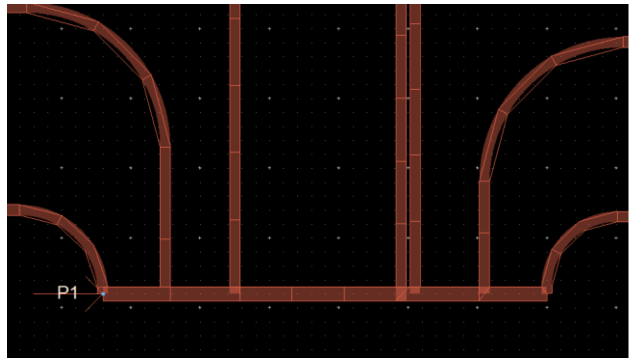


Fig. 6 Antenna array feed network depicting the central feed shifted to the right to affect its phase

III. RESULTS AND DISCUSSION

A. *Antenna Element*

The patch antenna element was designed in ADS using (1), (2), (3), (4), (5), and (6). A maximum gain of 5.59 was achieved at a resonant frequency of 4.22GHz. The efficiency of the element was 78.2%.

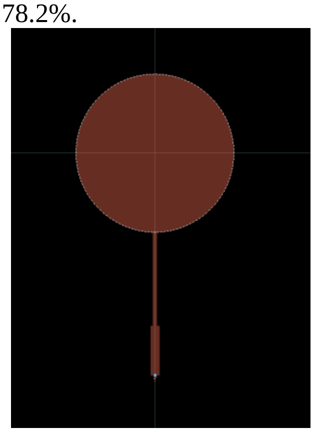


Fig. 7 Final design of circular patch antenna

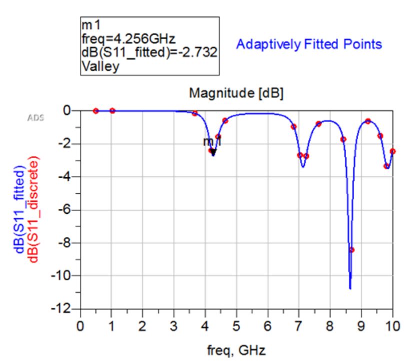


Fig. 8 S_{11} from 0.5GHz to 10GHz

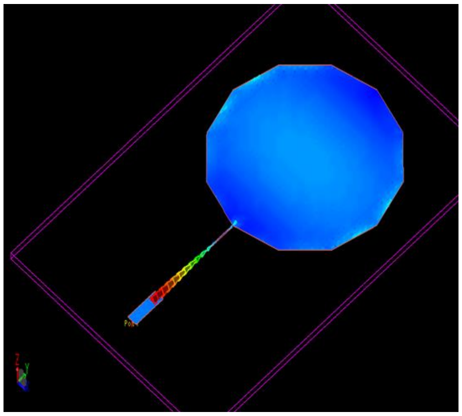


Fig. 9 Current distribution through the antenna element

The radiation pattern of the antenna element is circularly symmetrical and has only one main lobe with no side lobes.

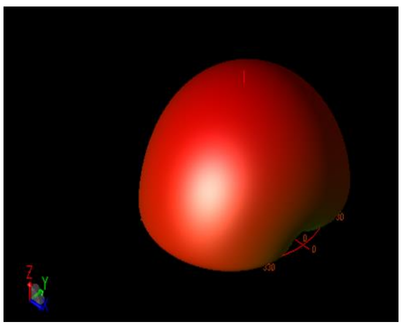


Fig. 10 Far-field 3D radiation pattern for antenna element at a frequency of 4.2 GHz

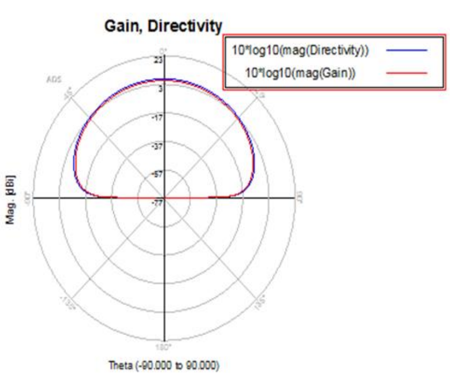


Fig. 11 Gain and Directivity of the antenna element

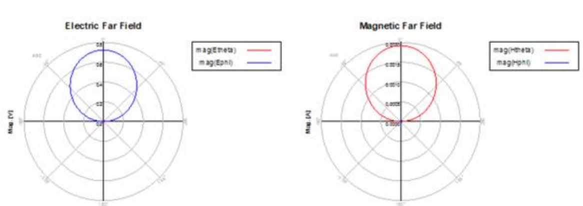


Fig. 12 Antenna element electric and magnetic far-field polar plots

Frequency (GHz)		4.22
Input power (Watts)		0.00239271
Radiated power (Watts)		0.00187127
Directivity(dBi)		6.66255
Gain (dBi)		5.59503
Radiation efficiency (%)		78.2074
Maximum intensity (Watts/Steradian)		0.00069053
Effective angle (Steradians)		2.70991
Angle of U Max (theta, phi)	1	90
E(theta) max (mag,phase)	0.721292	-28.7777
E(phi) max (mag,phase)	0.00507644	86.6433
E(x) max (mag,phase)	0.00507644	-93.3567
E(y) max (mag,phase)	0.721182	-28.7777
E(z) max (mag,phase)	0.0125883	151.222

Fig. 13 Antenna element parameters

B. *Antenna Array*

The antenna array was created using seven patch antennas as unit elements. A maximum gain of 12.75 was achieved at a resonant frequency of 4.22GHz. The efficiency of the array was 72.9%.

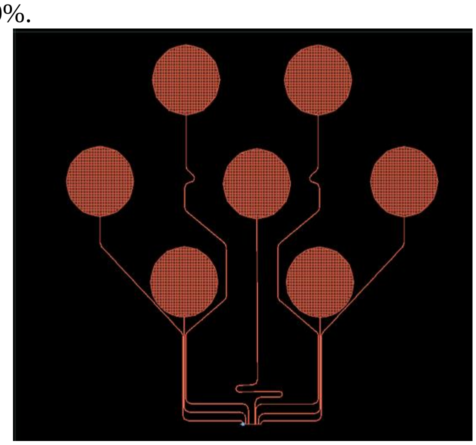


Fig. 14 Final configuration of 2-3-2 antenna array

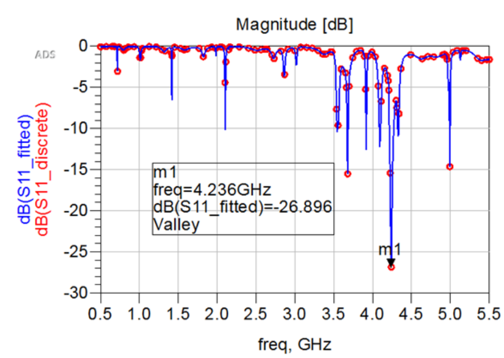


Fig. 15 S_{11} from 0.5GHz to 5.5GHz

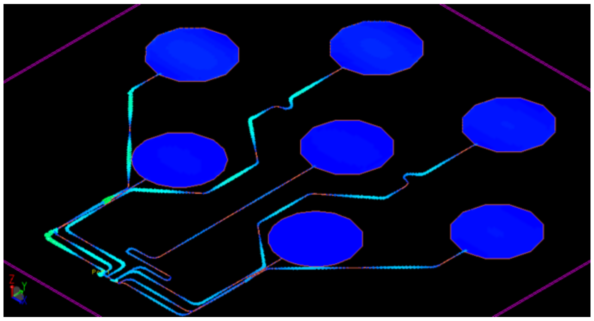


Fig. 16 Current distribution through the antenna array

The radiation pattern of the antenna array is no longer as circularly symmetric as an individual unit element. There is a decrease in gain at about θ = -20°, indicating that the antenna elements may be causing destructive interference. However, the radiation pattern retains the main lobe structure of the unit element.

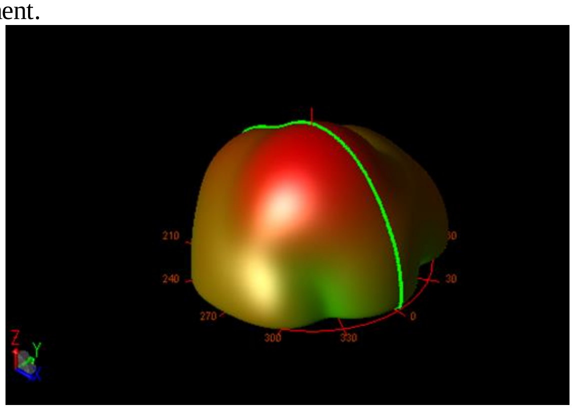


Fig. 17 Far-field 3D radiation pattern for antenna array at a frequency of 4.2 GHz.

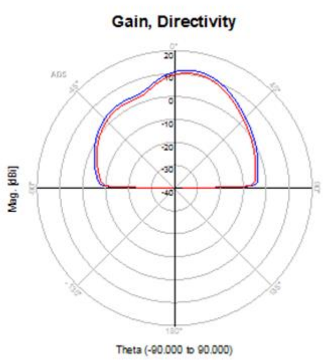


Fig. 18 Gain and Directivity of the antenna array

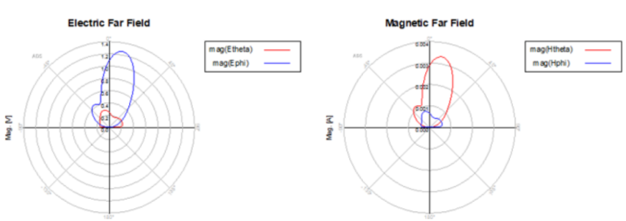
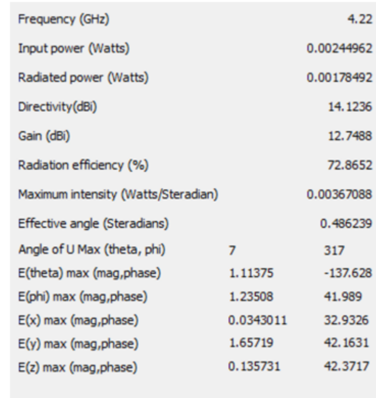


Fig. 19 Antenna array electric and magnetic far-field polar plots



Frequency (GHz)		4.22
Input power (Watts)		0.00244962
Radiated power (Watts)		0.00178492
Directivity(dBi)		14.1236
Gain (dBi)		12.7488
Radiation efficiency (%)		72.8652
Maximum intensity (Watts/Steradian)		0.00367088
Effective angle (Steradians)		0.486239
Angle of U Max (theta, phi)	7	317
E(theta) max (mag,phase)	1.11375	-137.628
E(phi) max (mag,phase)	1.23508	41.989
E(x) max (mag,phase)	0.0343011	32.9326
E(y) max (mag,phase)	1.65719	42.1631
E(z) max (mag,phase)	0.135731	42.3717

Fig. 20 Antenna array parameters

IV. Performance Summary

TABLE II
SUMMARY OF ANTENNA ELEMENT AND ANTENNA ARRAY PARAMETERS

	units	Required	Achieved
Substrate		RO4730G3	RO4730G3
relative dielectric constant		2.98	2.98
tan D		0.0023	0.0023
thickness 1	mm	0.526	0.526
thickness 2	mm	0.526	0.526
Antenna element			
Type		2	2
radiation frequency, fo	GHz	4.20	4.22
input reflection coefficient	dB	< -15	-17.00
minimum gain	dB	5.00	5.59
minimum efficiency	%	70.00	78.20
Antenna array			
configuration		2 - 3 - 2	2 - 3 - 2
minimum gain	dB	12	12.75
reflection coefficient	dB	< -12	-16.96
efficiency	%	n/a	72.9

V. Distribution of Labor

TABLE IV
DISTRIBUTION OF LABOR

Student	Antenna Element	Antenna Array	Report Writing
Sanit Sharma		x	25%
Eduardo Gasca		x	25%
Hassan Aljohani	x		25%
Alexander Wassef	x		25%

References

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