ON THE DESIGN OF PATCH ANTENNA ARRAY

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Abstract
In this paper, a coaxial fed patch antenna array for application in the 2.4GHz ISM band was implemented using the Ansoft HFSS software. Standard formulas were used to calculate different parameters of the antenna. These were just used as a basis of design as some parameters varied considerably during simulation. A good extent of the antenna design was hence done through trial and error. The proposed antenna was designed to work at 2.44GHz frequency band. A fractional bandwidth of 2.62%, which was not close to the desired 10% and a reflection coefficient of -18.2131dB were attained. This may have been brought about by poor impedance matching and a high level of spurious feed radiation and surface waves. A way of improving the bandwidth would have been to use proximity coupling feeding method which offers the highest bandwidth (as high as 13%) and is somewhat easy to model and has low spurious radiation. However, its fabrication would have been more difficult. A directivity of 8.53dB was achieved. This was a fairly high though directivity increase could have been studied through use of different substrate material and thickness.

Keywords
Patch antenna array; Ansoft HFSS software

1 INTRODUCTION
An antenna is a transducer between a guided wave and a radiated wave, or vice versa. The structure that "guides" the energy to the antenna is most evident as a coaxial cable attached to the antenna. A patch antenna is a type of radio antenna with a low profile, which can be mounted on a flat surface. It consists of a flat sheet of metal, usually copper, mounted on a larger sheet of metal called a ground plane. A patch array antenna is, in general, some arrangement of multiple patch antennas that are all driven by the same source. Frequently, this arrangement consists of patches arranged in orderly rows and columns (a rectangular array). The reason for these types of arrangements is higher gain. Higher gain commonly implies a narrower beamwidth and that is, indeed, the case with patch arrays. Some papers discuss the problem of patch antenna array design are found in [1,2].

This paper presents the design and analysis of patch network antenna array for the 2.4GHz industrial, scientific and medical(ISM) band[3] which is largely license exempt and can be accessed freely for example Bluetooth. The antenna will be designed with an aim of achieving high directivity and at least a 10% fractional bandwidth. The antenna will have a center frequency of 2.44 which is almost the same as the given ISM band center frequency. It was so chosen so as to have a bandwidth whose range is falls within the 2.4 GHz band.

2 DESIGN METHODOLOGY
A rectangular patch was chosen as the basis of the design because of its ease of fabrication and analysis. The microstrip line was used as the feeding method as it is easy to fabricate, simple to match by controlling the inset feed position and rather simple to model. The antenna was designed to work in the 2.4GHz ISM band which has a frequency range of 2.4-2.5GHz. A center frequency of 2.45GHz, a bandwidth of 100MHz and is freely available worldwide. Some applications in the 2.4GHz ISM band include the home microwave oven, sulphur lamps, communication applications such as wireless LANs, bluetooth and radio control equipment such as low power remote control of toys.

2.1 Design Procedure
The FR4 Glass Epoxy, whose loss tangent is 0.002, was chosen as the dielectric material substrate.

To commence the design procedure assumes, specific information had to be included: dielectric constant of the substrate (\(\varepsilon_r\)), the resonant frequency (\(f_r\)) and the height of the substrate, h.

\[ \varepsilon_r = 4.3, \quad f_r = 2.44GHz, \quad h = 1.6mm \]

For an efficient radiator, the practical width that leads to good radiation efficiencies is

\[ W = \frac{1}{2f_r\sqrt{\varepsilon_r\mu_r}} \left[ \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{W} \right) \right]^{\frac{1}{2}} \]

\[ = 37.58\text{mm} \]

where \(v_o\) is the free-space velocity of light.

The initial values (at low frequencies) of the effective dielectric constant are referred to as the static values, and they were calculated as

\[ \varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12h}{W} \right]^{\frac{1}{2}} = 3.99 \]

A very popular and practical approximate relation was then used to find the normalized extension of the length as

\[ \Delta L = 0.412 \left( \varepsilon_{eff} + 0.3 \right) \left( W + 0.264 \right) \]

\[ = 0.255 \left( W \right) + 0.8 \]

\[ \Delta L = 0.741\text{mm} \]

The actual length of the patch was determined by solving \(L\) as,

\[ L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}\mu_r}} - 2\Delta L \]

\[ = 29.15\text{mm} \]
For efficient transfer of power from a transmission line to the patch antenna, the input impedance of the patch antenna needed to be matched to the characteristic impedance of the transmission line. It was observed that impedance seen by a transmission line attached to the radiating edge was very high, and also the impedance (ratio of voltage to current) decreased as one moved towards the center of the patch. Therefore, depending on the characteristic impedance of the transmission line, an appropriate point on the patch was chosen through calculation as the feed point [4].

In order to access the appropriate impedance point on the patch, a recess was created in the patch. The recess or inset feed was used to improve the impedance matching between the patch and the feed line. The inset feed position, where the input impedance was 50 ohms and the lengths and widths for the microstrip feeds were calculated using the Matlab code. A FDTD-Finite Difference Time Domain analysis shows that the inset disturbs the transmission line or cavity model and increases the impedance variation with distance compared to a coaxial probe feed given a patch resonant length L and feed position y0 from the center. Transmission line analysis method was applied as it gives a good insight. However, it is more difficult to model coupling as well as less accurate [5].

2.2 Ground Plane

As part of the antenna, the ground plane should be infinite in size as for a monopole antenna but in reality this is not easy to apply besides a small size of ground plane is desired. In practice, it has been found that the microstrip impedance with finite ground plane width (Zg) is practically equal to the impedance value with infinite width ground plane (Zg∞). If the ground width Wg is at least greater than 3×W. The radiation of a microstrip antenna is generated by the fringing field between the patch and the ground plane, the minimum size of the ground plane is therefore related to the thickness of the dielectric substrate [6].

The size of the ground plane was chosen as 114 mm length by 148 mm width.

2.3 Microstrip Discontinuities

Surface waves are electromagnetic waves that propagate on the dielectric interface layer of the microstrip. The propagation modes of surface waves are practically transverse electric (TE) and transverse magnetic (TM). Surface waves are generally at any discontinuity of the microstrip. Once generated, they travel and radiate, coupling with other microstrip of the circuit, decreasing isolation between different networks and signal attenuation. Surface waves are a cause of crosstalk, coupling, and attenuation in a multi-microstrip circuit. For this reason surface waves are always an undesired phenomenon.

A discontinuity in a microstrip is caused by an abrupt change in geometry of the strip conductor, and electric and magnetic field distributions are modified near the discontinuity. The altered electric field distribution gives rise to a change in capacitance, and the changed magnetic field distribution to a change in inductance.

a) Bends

Four 90° bends were encountered in the design. This brought about excess capacitance at the square corners making the characteristic impedance value to be lower than that of the uniform connecting lines. A bend of this angle doesn’t work well above a few GHz due to a high voltage standing wave ratio (VSWR). The same holds true for bends with angles greater than 90°.

Compensation for the microstrip corner bend was made by the use of decreased capacitance technique. Since experiments on various bends have proven that a decrease in the input reflection coefficients can be achieved if the corner is chamfered (mitered), the configuration in Fig.1 was applied

![Figure 1. Configuration for compensated right-angled bends](image)

where W in Fig.1 is the width of the line

Therefore, \[ W = 2.62 \times 1.3 = 4.716 \text{mm} \]

b) Step Width Junction

This discontinuity was found at the \( \frac{\lambda}{4} \) Transformers The effect of the fringing capacitance associated with the wider line of the step discontinuity is similar to an increase in the length of that line. The characteristics of step width junction discontinuity is shown in Fig.2

![Figure 2. Characteristics of the step width junction discontinuity](image)

In terms of distributed elements, the discontinuity capacitance C has the effect of an increase in length of the wide line w1, and an equal decrease in length of the narrow line w2. To compensate for the excess capacitance, the wider line w1 was made to be electrically longer by a length of 9.26 mm.

c) T-Junction

These discontinuities(Fig.3) were found in the patch antenna array as branch lines. The T-Junctions were easily compensated for by simply adjusting the lengths of the different lines. The offset in the main line is usually very small, and the main effect is on the length of the stub

![Figure 3. T-junction discontinuity compensation and minimization of the effect](image)

\[ w1 = 12 = 2.62 \text{mm} \quad ; \quad 0.7w1 = 0.7 \times 2.62 = 1.84 \text{mm} \]
2.4 Main Beam Direction

For the 4-element array of Fig.4, the main beam was directed broadside to the array by ensuring there was no input phase difference from element to element. To implement an even number of in-phase patch elements, the feed network needed to be carefully designed. The distance from the 50-ohm Sub-Miniature version A (SMA) source to each patch element needed to be identical or multiples of \( \lambda \). Unequal line lengths would have produced phase shifts, which would yield fixed beams that would be scanned away from the broadside. A quarter-wave transformer was used to match the 100-ohm line to a 50-ohm line. The 100-ohm microstrip line was fed using a 50-ohm SMA. In the design of an effective in-phase radiator, the distance between the patch elements needed to be optimized to yield a peak gain. The antenna-array chapter in Antenna Theory by Balanis provided insight on the optimum antenna separation distance. The author identified a separation distance of \( \lambda/2 \) as providing the optimal gain. In the design, this separation was used as 31.33mm [7].

2.5 Matching Microstrip Lines to Source

The characteristic impedance of a transmission line of the microstrip feed patch was designed with respect to the source impedance. The characteristic impedance \( Z_o \) of the transmission line from the source with respect to the source impedance \( Z_s \) was

\[
\frac{Z_s}{Z_o} = n^2
\]

\[
Z_o = 2 \times 50 = 100 \text{ ohms}
\]

Where the factor \( n \) was the number of twigs emanating from the node connected to the source. The inner conductor of the coax was soldered to the 100-ohm microstrip line, and the outer conductor connected to the ground plane. Since the coax fed two 100-ohm microstrip lines in parallel, no mismatch occurred at this input as the parallel combination of the two microstrip lines was equal to 50-ohm [8].

2.6 Quarter-Wave Transformer

For the input impedance of a transmission line of length \( L \) with a characteristic impedance \( Z_2 \) and connected to a load with impedance \( Z_A \):

\[
Z_{in}(-L) = Z_2 \left[ \frac{Z_A + jZ_2 \tan(\beta L)}{Z_A + jZ_2 \tan(\beta L)} \right]
\]

When the length of the transformer is a quarter wavelength;

\[
Z_{in}(\frac{L}{4}) = \frac{Z_A}{Z_2}
\]

The above states that by using a quarter-wavelength of a transmission line, the impedance of the load \( Z_A \) can be transformed by the above equation. Hence by using a transmission line with a characteristic impedance of 50-ohms, the 50 ohm inset feed line was matched to

\[
Z_o = \sqrt{50 \times 50} = 50 \text{ ohms}
\]

Where \( Z_o \) = Characteristic impedance of the quarter-wavelength transformer

This ensured that no power would be reflected back to the SMA feed point as it tried to deliver power to the antenna.

The length of the quarter wavelength transformer was calculated as

\[
L = \frac{\lambda}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{reff}}} = 15.39 \text{mm}
\]

Where \( \lambda = \text{Effective wavelength} \)

\( \lambda_0 = \text{Free space wavelength} \)

2.7 Simulation

The antenna array was designed using the Ansoft HFSS 13.0 software. HFSS is a 3D full wave electromagnetic field simulator. It uses the finite element method together with adaptive meshing to solve the wave equations. If a 3D model has been made, HFSS sets up the mesh automatically. HFSS computes S-parameters, can calculate and plot both the near and far field radiation and compute important antenna parameters such as gain and radiation efficiency. This software was used to vary the sizes of the patches, microstrip feed lines and ground plane in order to come up with the desired results. Fig.4 illustrates the HFSS antenna model, and its printed circuit board (PCB) layout is shown in Fig.5.

![Figure 4. 4 element patch antenna HFSS model](image1)

![Figure 5. 4-element patch antenna PCB layout with dimensions](image2)

3 HFSS SIMULATION RESULTS AND ANALYSIS

3.1 Variation of Patch Length and Width

Dimensions calculated in the design procedure were used to create the 4 element array patch antenna. The antenna, however, did not produce acceptable results. In order to shift the reflection coefficient \( S_{11} \) minima towards the desired center frequency of 2.4GHz, the length and width of the patch were shortened as follows...
Table 1

| Length (mm) | Width (mm) | Resonance Frequency (GHz) | Peak Directivity (dB) |
|-------------|------------|---------------------------|-----------------------|
| 38.47       | 29.85      | 2.27                      | 7.34                  |
| 34.47       | 29.85      | 2.33                      | 7.78                  |
| 30.47       | 28.66      | 2.45                      | 8.30                  |
| 30.47       | 26.85      | 2.56                      | 7.84                  |
| 30.47       | 23.85      | 2.87                      | 7.34                  |

A length of 30.47mm and width of 28.66 mm were selected as the $S_{11}$ minima operated at the center frequency. It was observed that a decrease in width increased the resonance frequency. This is due to the increase in $\Delta L$ and $\varepsilon_{eff}$. The input impedance at resonance also increased because the radiation from the radiating edges decreases, which increases the radiation resistance. The bandwidth of the antenna decreases. There is a decrease in the directivity, efficiency, and hence gain, resulting from a decrease in the effective aperture of the antenna. Effective aperture (also known as effective area) is the area over which the antenna collects energy from the incident wave and delivers it to the receiver load [4].

3.2 Reflection Coefficient and Bandwidth

Fig.6 shows the reflection coefficient $S_{11}$ of the proposed antenna in dB. $S_{11}$ gives the reflection coefficient at the inset feed position where the input to the microstrip patch antenna was applied. It should be less than -10dB for an acceptable operation. It shows that the proposed antenna had a frequency of resonance of 2.44GHz [9].

![Figure 6. Return loss $S_{11}$ obtained for the patch array](image)

The simulated impedance bandwidth of about 63.3MHz (2.4721-2.4088 GHz) was achieved at -10dB reflection coefficient (VSWR ≤2). The reflection coefficient value that was achieved at this resonant frequency was equal to -18.2131 dB. This reflection coefficient value suggested that there was good matching at the frequency point below the -10dB region [9].

The fractional bandwidth achieved for the antenna was

$$BW = \frac{f_L - f_c}{f_c} \times 100\% = \frac{2.4721 - 2.4088}{2.4405} = 2.62\%$$ (8)

Where $f_c$, $f_U$ and $f_L$ are the center, upper and lower cutoff frequencies respectively.

3.3 Radiation Pattern

The radiation patterns in the E-plane and H-plane of the patch antenna array at 2.44GHz for $\gamma = 10.545$ mm are shown in Fig.7 and Fig.8 above. They are also referred to as the azimuth plane and elevation plane pattern respectively. The coplanar components in the E and H planes are $E_\phi$ in $\Phi = 0^\circ$ and $E_\theta$ in $\Phi = 90^\circ$ planes.

The strongest energy was radiated outward, in the $yz$-plane, at the widths of the patch elements and at an angle of $36^\circ$. It was observed that the antenna had an azimuth plane beamwidth of about $57^\circ$ and an elevation plane beamwidth of $41^\circ$ as indicated on patterns in Fig.7 and Fig.8 by the blue lines. These lines were drawn where the gain was down from the peak by -3dB. The beamwidths were the total angular width between the two 3dB points on the curves.

The azimuth and elevation patterns were derived by simply slicing through the 3D radiation pattern. For the azimuth plane pattern, slicing was done through the $xz$ plane at $y = 0$, while for the elevation plane the slicing was done through the $yz$ plane at $x = 0$.
The Fig.10 shows that the antenna had two main lobes which were 180° out of phase with each other. It was used to determine the half-power beamwidths for the radiation patterns as the peaks and 3 dB points below them could easily be picked.

3.4 Inset Feed Position

Initially, the length of the inset feed position was calculated as \( y_0 = 14.15 \text{mm} \) from the edge of the antenna. The slot width was chosen as 3.62mm which was 1mm greater than that of the microstrip feed. An increase in the width of the slot brought about an increase in the resonance frequency. The microstrip feed going into the patch element was 15.67mm in length which is equal to \( \lambda / 4 \) wavelength. The resulting resonance frequency was below the desired value hence the length had to be increased as given in table 2

| Length of Feed (mm) | Resonance Frequency (GHz) |
|---------------------|---------------------------|
| 15.67               | 1.77                      |
| 18.67               | 2.26                      |
| 20.67               | 2.29                      |
| 25.67               | 3.29                      |

The feed length of 18.67mm was chosen for analysis as it was closer to the center frequency and also not too long.

Changing of the inset feed position \( y_0 \) affected the resonance frequency of the patch antenna. The longer the length, the lesser the resonance frequency became and vice versa. Lesser directivity, gain as well as magnitude of the \( S_{11} \) parameter were realized when a longer length was used.

3.5 VSWR Plot

Fig.11 shows the VSWR plot for the designed antenna. The value of the VSWR should lie between 1 and 2. SWR is used as an efficiency measure for transmission lines, electrical cables that conduct radio frequency signals, used for purposes such as connecting radio transmitters and receivers with their antennas, and distributing cable television signals[9].

Here the value for the proposed microstrip patch antenna was 1.2801 at the resonating frequency of 2.44GHz.

3.6 Smith Chart

The smith chart is a graphical representation of the normalized characteristic impedance. It provides the information about the impedance match of the radiating patch. The smith chart for the designed patch antenna array(Fig.12) showed an input impedance of 51.73+12.47i ohms at resonant frequency 2.44GHz. The magnitude of the input impedance was 53.21 which showed that accurate machine was not achieved. This was due to shifting of the inset feed position away from the center of the patch element which was done in order to improve the directivity, gain and return coefficient of the antenna.

3.7 Ground Plane

For a finite ground plane, the resonance frequency of the antenna was almost the same but the input impedance was slightly higher than that of the infinite ground. It was observed that an increase in the dimensions of the ground plane increased the resonance frequency and magnitude of the \( S_{11} \) parameter. There was an increase in the directivity and hence gain.

3.8 H Plane Inter-element Separation

From the variation of the spacing between the patch elements in the H-plane, it was observed that as the spacing was increased, the magnitude of the return loss \( S_{11} \) as well as the directivity of the antenna decreased. This meant that the gain decreased. The resonance frequency, radiated power and efficiency however increased. A separation of \( \lambda / 2 \) was chosen for the simulation as it gave the optimal gain.

3.9 E Plane Inter-element Separation

An increase in the E-plane separation gave similar results to that of the H-plane. However, a separation of \( \lambda / 2 \) could not be achieved because of the orientation of...
the patch elements as well as the different lengths of the microstrip feeds.

Table 3

| Antenna Parameters in HFSS |
|---------------------------|
| **Input:**                |
| Setup Name: InFinite Sphere | OK |
| Solution: LeastAdaptive |   |
| Array Setup: Name | Export |
| Infinite Variation | Free-2.4GHz |
| Design Variation |   |

The table 3 shows a summary of the antenna parameters from the HFSS software. The software did not give the antenna parameters summary in decibels as shown. The directivity (D) and efficiency (η) were 7.1273 and 46.7%, which gave a gain G (ηD) of the antenna as 3.32. The front to back ratio was 242.9, implying that there was a difference of about 23.85 dB between the peak gain in the forward direction and the gain 180-degrees behind the peak. This is evidence of presence of back lobes from the radiation.

4 CONCLUSION

A 4 element, microstrip fed patch antenna array of rectangular shaped radiating elements was successfully designed using the FR4 Epoxy Glass substrate. Through analysis with the Ansoft HFSS simulation software, it was observed that the antenna worked in the 2.4GHz ISM band by having a resonance frequency of 2.44GHz, and had a fractional bandwidth of 2.26% and a directivity of 8.53dB. The patch antenna array was coaxially fed through a 50 ohm cable with a 50 ohm sma-connector. Impedance matching was done well though not accurately. The maximum achievable gain by the antenna was 5.2235 dB.

References

[1] Kaur, P., Aggarwal, S.K. & De, A. "Performance Enhancement Of Rectangular Microstrip Patch Antenna Using Double H Shaped Metamaterial" Radioelectronics And Communications Systems, Vol.59, NO.11, 2016.

[2] Singh, A., Aneesh, M., Kamakshi, K. Et Al. "Circuit Theory Analysis Of Aperture Coupled Patch Antenna For Wireless Communication" Radioelectronics And Communications Systems, Vol.61, No.4, 2018.

[3] Waihenya, N. "Patch antenna for the 2.4 GHz ISM band" Graduate Project, University of Nairobi, Kenya, 2015.

[4] Harish, A.R., and Sachidananda, M. "Antennas and wave propagation" 4th Edition, Oxford University Press, 2007.

[5] Balanis, C. A. "Antenna theory, analysis and design" 3rd Edition, John Wiley & Sons, Inc., 2005.

[6] Huang, Y., Kevin, B., "Antennas from theory to practice" John Wiley and Sons, Ltd, Publication, 2008.

[7] Hermann, J., Zach, D., and Angel, A. "Analysis and design of ISM-band patch antenna array", ECE 4370 Project: 5.8GHz High-Directivity Antenna, Georgia Institute of Technology, USA, 2012.

[8] John, R. and Marc, P., "Patch antennas and microstrip lines, Microwave and millimeter wave technologies modern UWB antennas and equipment", Edited by Igor Mini, 2010, In-Tech DOI: 10.5772/9016.

[9] Jaswinder, K., and Rajesh, K., "Co-axial fed rectangular microstrip patch antenna for 5.2 Ghz WLAN application", Universal Journal of Electrical and Electronic Engineering, Vol. 1, Issue 3, 2013.