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Design and Performance Optimization of a Microstrip Antenna

G.C Nwalozie, C.C Okezie, S.U Ufoaroh, S.U Nnebe

Abstract: - Microstrip patch antennas are versatile in terms of their geometrical shapes and implementation. The light weight construction and the suitability for integration with microwave integrated circuits are two more of their numerous advantages. Additionally the simplicity of the structures makes this type of antennas suitable for low-cost manufacturing. And this is also one key feature why microstrip patch antennas are used in mobile communication applications. Inhibiting characteristics of a single microstrip patch, like low gain and smaller bandwidth, make it more necessary for array configuration. In this research the design, performance analysis and optimization of a microstrip patch antenna array was done. The design involved 1- patch, 2 x 1 and 4 x 1 liner arrays, with an element spacing of a half of a free space wavelength. The antenna was designed to operate at 1.8GHz band, which is almost standard for base station applications. The simulation was developed in MATLAB and Transmission line Matrix (TLM) was used for the model.

Keywords: Antenna Array, Patch Antennas, Directivity and Gain.

I. INTRODUCTION

Parallel to the rising importance of wireless communication systems and personnel IT (Information Technologies) services (e.g., Bluetooth), increasing efforts are devoted to the design and implementation of novel microstrip structures from miniaturized electronic circuits to the antenna arrays. One major application is design of microstrip antenna arrays which are attractive candidates for adaptive system in present and future communication systems. Microstrip antennas (MSA) received considerable attention in the 1970's, although the first designs and theoretical models appeared in the 1950's. They are suitable for aircraft, satellite and missile applications. The MSAs are low profile, mechanically robust, inexpensive to manufacture, light weight and ability of integration with electronic or signal processing circuitry [1]. With respect to radiation properties, microstrip antennas are versatile in terms of resonant frequencies, polarization, pattern and impedance. They allow the use of additional tuning elements like pins or varactor diodes between the patch and the ground plane. Some of the disadvantages of MSA are: relatively low efficiency (due to dielectric and conductor losses), low power, spurious feed radiation (surface waves, strips, etc.), narrow frequency bandwidth, and relatively high level of cross polarization radiation [2]. Designing active/passive microwave circuits, on the other hand, requires understanding of both mathematical relations (i.e. theory) and application (i.e. Computer simulations as well as measurements). Mathematical relations exist for only simple, idealized microstrip structures and may help

to understand the fundamentals. Fortunately, powerful numerical simulation methods are available which can be used to design complex microstrip. Among the others are the finite difference time domain (FDTD), the transmission line matrix (TLM), the finite element method (FEM), and method of moments (MoM). Mohammed Islam et al [3] presented "High Gain Microstrip patch Antenna", novel techniques for enhancing gain that improves the performance of a conventional microstrip patch antenna. They showed a novel wideband probe fed inverted multiple slot microstrip patch antenna. The design adopted contemporary techniques, probe feeding, inverted patch structure and stacked multiple slotted patch. The composite effect of integrating these techniques and by introducing the novel multiple shaped patch, offer a low profile, broadband, high gain and compact antenna element. The result showed a satisfactory performance with maximum achievable gain of about 12.35dB and suitable for array applications especially for base station. Adil Hameed and Basin Jarialla [4] reported in "Design and simulation of Broadband Rectangular Microstrip Antenna". In this work, many techniques were suggested and analyses for rectangular microstrip antenna (RMSA) operating in X-band for 10GHz centered frequency. The design of the RMSA was made to several dielectric materials and the selection was based upon which material gives a better antenna performance with reduced surface wave loss. Duroid 5880 and Quartz are the best materials for the design to achieve a broader bandwidth (BW). The overall antenna BW for RMSA was increased by 11.6% with Duroid pin (Reactive loading), while for Quartz 17.4%. Modification of patch shape with similar improving techniques gave an overall increasing VSWR bandwidth of 26.2% for Duroid 5880 and a bandwidth of 30.9% for Quartz. Alexander Kuchar [5] presented a simple microstrip patch antenna array that meets the requirements of a base station antenna in mobile communications system was designed and implemented. The array needed no conventional beam forming network, because it would function as a digital controlled phased array. The array consisted of nine linearly arrayed single antennas with element spacing of half a free space want length. The antenna was designed to operate in ISM band at 2.45GHz, where the required bandwidth is 83.5MHz. Since microstrip patch antennas have a low bandwidth, a special feeding technique-aperture coupling was implemented. The excellent final results for the antenna array- a bandwidth of 160MHz, a front-to-back ration larger than 17dB, and a maximum mutual coupling below



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-14.5dB were achieved. In this work, practical implementation of microstrip patch for all kinds of antenna applications is simplified. It also gives the antenna designer choices for trade-off for one antenna characteristic against the other; such as bandwidth, gain, input impedance, and coupling efficiency etc. This in turn will reduce cost of production because the possible effect or outcome of each design has been studied.

II. THE STRUCTURE OF A MICROSTRIP ANTENNA

In its basic form, microstrip antennas are similar to parallel plate capacitors. Both have parallel plates of metal layer and a sandwiched dielectric substrate between them. But in microstrip antenna, one of these metal plates is infinitely extended than the other, to form the ground plane; whereas the smaller metal plate is described as radiating patch. Since the size of the patch is often proportional to frequency of the propagating signal, this class of antenna is classified as resonant antennas. So far, several shapes of microstrip patches, such as rectangular, circular, triangular, semicircular, sectoral and annular etc, are successfully used as radiating antenna elements employed various communication control devices.



Fig 1 Microstrip Rectangular Patch Antenna

When the patch is excited by a feed line, charge is distributed on the underside of the patch and the ground plane. At a particular instance of time the attractive force between the underside of the patch and the ground plane tend to hold a large amount of charges to the edge of the patch, creating a large density of charge at the edges.



Fig 2 Radiation Mechanism Associated With Microstrip Patch

These are the sources of fringing field. Radiation from the microstrip antenna can occur from the fringing field between the periphery of the patch and the ground plane [1]. Assuming no variations of the electric field along the width (w) and the thickness (t) of the microstrip structures, the electric field excited by the patch is shown in fig 2.Radiation is ascribed mostly to the fringing field at the open circuited edge of the patch length. The fields at the end can be resolved into normal and tangential components with respect to the ground plane. The normal components are 180° out of phase because the patch is $\lambda/2$ long; therefore the four field radiation produced by them cancels in the broadside direction [2], the tangential components (those parallel to the ground plane) are in phase, and the resulting field combine to give minimum radiated field normal to the surface of the structure i.e., broadside direction. Therefore, the patch may be represented by two slots $\lambda/2$ apart as shown in figure below, excited in phase and radiating in the half space above the ground plane.



Fig 3 Increase in Length of the Microstrip Patch

Typically, to excite the fundamental TEM mode, the length L of the rectangular patch remains slightly smaller than $\lambda/2$, where it is the wavelength in the effective dielectric medium [3]. In terms of free space wavelength (λ), is expressed by [3]

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{1}$$

Where $\sqrt{\varepsilon_{eff}}$ is the effective dielectric constant of a microstrip line and is given as

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \frac{h}{w} \right]^{-\frac{1}{2}} \tag{2}$$

The value of \mathcal{E}_{eff} stays between 1 (dielectric constant of air) and the dielectric constant of the substrate \mathcal{E}_r ,



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V. THE TRANSMISSION LINE MODEL (TLM)

because the electromagnetic fields by the microstrip reside partially in the air and partially in the substrate. However, to enhance the electromagnetic (EM) field in the air, which account for radiation, the width (W) of the patch needs to be increased? Radiating EM fields can also be enhanced by decreasing the \mathcal{E}_r or by increasing the substrate thickness (h). It is of note that, since 'W' and 'h' is constrained by the input impedance and unwantedsurface-waves respectively. A compromise is required while selecting antenna dimensions. Since microstrip patches are often fed or integrated with microstrip transmission-lines or circuits, the requirement of these devices are also important. The microstrip antenna can be excited or fed directly either by coaxial probe or by a microstrip line. It can also be indirectly using electromagnetic coupling (proximity) or by aperture coupling method, in which there are no direct metallic contact between the feed line and the patch. Since feeding techniques influences the input impedance, it is often exploited for matching purposes. Also as the antenna efficiency depends on the transfer of power to the radiating element, feeding technique plays a vital role in the design process.

III. ADVANTAGES OF MICROSTRIP ANTENNAS

- They are light in weight and low profile
- They can be made conformal to the host surface
- Their ease of mass production using printed circuit technology leads to a low fabrication cost
- They are easier to integrate with other micro strip circuits.
- They support both linear polarization and circular polarization
- They can be realized in a very compact form, desirable for personal and mobile communication hand held devices.
- They allow for dual and triple band operations

IV. DISADVANTAGES OF MICROSTRIP ANTENNAS

- Narrow bandwidth
- Lower power gain
- Lower power handling capability
- Polarization impurity
- Surface wave

There are many methods of analysis of microstrip antennas. The most popular methods are based on the transmission line model, cavity model and full wave analysis. In this work, transmission line model is used to calculate the dimensions and input impedance associated with the radiating patches.

Although the transmission line model yields less accurate results, it is a very simple model and provides a good physical insight of the basic antenna performance. In this model, the microstrip patch element is viewed as a transmission line resonator with field only varying along the length (no transverse field variations), and the radiation occurs mainly from the fringing fields at the open circuited ends. The patch is represented by two slots that are spaced by length of resonator. This model was originally developed for rectangular patches but has been extended for generalized patch shapes. Many variations of this model have to been used to analyze the microstrip antenna [7], since the normal analysis was derived for rectangular patch, some authors [8] have modified it to suite other patch shapes like rectangular, and others have modified it to suit to triangular patch shapes[9].



Fig 4 Rectangular Patch Antenna



Fig 5 Transmission Line Model Equivalent of a Rectangular Micro Strip Patch

The given parameters for the antenna design are as follows:

 F_0 = Operating frequency = 1.8GHz

 ε_r = relative primitively (i.e. dielectric constant) of the substrate

(here $\varepsilon_r = 2.2$ for duroid 5880 substrate)

h = substrate height = 1.6mm

at low frequencies, ε_{eff} remains constant and can be expressed in terms of patch dimensions and substrate dielectric constant (ε_r , according to equation (2)



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Also, due to the fringing effect, the electrical length of the patch increases by a distance of 2 ΔL , as illustrated in figures 4

In transmission line model, ΔL , is expressed as

$$\Delta L = h * 0.412 \frac{(\varepsilon_{eff} + 0.3) \binom{W}{h} + 0.264}{(\varepsilon_{eff} - 0.258) \binom{W}{h} + 0.8}$$
(3)

 ΔL = fringe factor

The width can be calculated thus

$$w = \frac{c}{2F_0\sqrt{\left(\frac{\varepsilon_r+1}{2}\right)}} \tag{4}$$

C is the velocity of Electromagnetic wave ($C=3*10^8$ m/s).

Equally Le which is the effective length of the patch is given as

$$L_{\varepsilon} = \frac{C}{2F_0 \sqrt{\varepsilon_{\varepsilon ff}}}$$
(5)

Therefore patch length L is given as,

 $L = Le - 2\Delta L$ (6)

The input impedance should be accurately known so that a good match between the element and the feed can be designed.

For a rectangular patch, typical input impedances at the edge of a patch range from 100Ω to 400Ω , and can be approximated as follows [1],

$$Z_{in} = 90 \frac{\varepsilon_r^2}{\varepsilon_r^{-1}} \left[\frac{L}{W}\right]^2 \tag{7}$$

Now, as operating frequency increases, effective dielectric constant (ε_{eff}) increases and eventually approaches the value of substrate dielectric constant (ε_r).

A microstrip antenna is basically a broadside radiator, which has a relatively large beam width and low gain characteristics. The formula for the E and H - Plane radiation pattern are given by [10],

E – plane

$$F(\varphi) = \frac{\left| \sin\left(\frac{\kappa_0 n}{2}\right) \cos\varphi \right| \cos\left(\frac{\kappa_0 L}{2}\right) \cos\varphi}{\left[\frac{\kappa_0 n}{2}\right] \cos\varphi} \tag{8}$$

H - plane

$$F(\theta) = \frac{\left[\frac{\sin\left(\frac{K_0W}{2}\right)\cos\theta\right]\sin\theta}{\left[\frac{K_0W}{2}\right]\cos\theta} \tag{9}$$

f Engineering and Innovative Volume 2, Issue 7, January 2013 gth of the Where $K_0 = \frac{2\pi}{\lambda_0}$ is the free space waver number and λ_0

is the operating wavelength.

The half power beam widths in the H and E planes are given by,

$$OB_{H} = 2\cos^{-1} \left[\frac{1}{\sqrt{2 + K_{0} W}} \right]$$
(10)

$$OB_E = 2\cos^{-1} \left[\frac{1}{\sqrt{(2+K_0^2 + L_g^2 + K_0^2 + h^2 W)}} \right]$$
(11)

Thus beam width can be increased by choosing a smaller element, thus reducing W and L. For a given resonant frequency, these dimensions may be changed by selecting a substrate having a higher relative permittivity. As beam width increases, elements gain and directivity decrease, however, efficiency is unaffected. The expression for approximately calculating the directivity D of the rectangular microstrip antenna is given by,

$$D \cong 0.2W + 6.6 + 10 \log_{10}\left(\frac{1.6}{\sqrt{\varepsilon_{T}}}\right) dB \quad (12)$$

The antenna gain which is a product of directivity and efficiency can be approximated thus,

$$Gain=D\varepsilon$$
 (13)

 ε is the efficiency is given as

$$\varepsilon = \frac{P_{sp}}{\left(P_{sp} + P_{sur}\right)} \tag{14}$$

 P_{sp} is the space wave power and P_{sur} is the surface wave power

$$Gain (dB) = \frac{4\pi A}{\lambda^2 H}$$
(15)

$$A = L \times W$$

 $\lambda_{H=\frac{\lambda_0}{\sqrt{\varepsilon_r}}}$

The most serious limitation of the microstrip antenna is its narrow bandwidth (BW). The BW could be defined in terms of its VSWR or input impedance various with frequency or in terms of radiation parameters. For the circularly polarized antenna, BW is defined in terms of the Axial Ratio. VSWR is a very popular parameter for determining the BW of a particular antenna configuration $(1 \le VSWR \ge 2)$ is an acceptable interval for determining the BW of the antenna. BW is represented more concisely as a percentage where:

$$BW\% = \frac{\Delta F}{F_0} * 100\%$$
 (16)



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Where Δf is the width of the range of acceptable frequencies, and f_0 is the resonant frequency of the antenna [12].

V. ARRAY DESIGN

Any antenna array can be factored into two components. One component, $E_{element}$, contains the field pattern of a single radiating element and the second component, array factor AF, that contains geometric information concerning how the antennas are arranged. $E_{total} = \sum_{n=1}^{N} E_{element} = E_{element AF}$ (17)

The importance of this separation of terms is the fact that the array pass band and stop band can be designed by controlling both the amplitude and phases of the array factor. The element field pattern then only affects the angle at which the pass band can be placed and the directivity of the overall array pattern. The relative spacing between elements are essential in shaping the radiation pattern of the array antenna. The array factor for any N-element array is given by

$$AF = \sum_{n=1}^{N} a_n e^i (n-1)^{\psi}$$
 (18)

Where $\psi = kd\cos\theta + \beta = 2\pi d/\lambda \cos\theta + \beta$

From this equation it is evident that the excitation.

Phase ($\approx\beta$), and the excitation amplitude ($\approx a_n$) are importance factors (among others) to influence the radiation characteristic of the designed array antenna. For uniform linear array the amplitude a_n is 1 for all elements. This study concentrates on broadside linear array that does not require phase shift; therefore β can be eliminated from the equation. The gain of a single patch (in dB) is a factor element:

Gain of antilog₁₀Gain=Gain (not in dB)

The array gain for equally weighted and phased elements is equal to the number of elements, for N^- element.

G array = N x (antilog of single patch gain) (19)

The effective area can be approximated as:

$$Gain = \frac{4\pi A}{\lambda_{H}^{2}}$$

Where A is the effective area.

Mutual coupling is primarily attributed to the fields that exist along the air-dielectric interface. So by selecting the correct distance, these fields can be decomposed to constructive space waves or destructive surface waves. The spacing at which one plane coupling overtakes the other one also depends on the electrical properties and the geometrical dimensions of the microstrip antenna. The spacing of elements is usually $0.5\lambda > d \ge \lambda$.

VI. SIMULATION ANALYSIS AND OPTIMIZATION RESULT

The analysis and optimization is done by using a simulation package (MATLAB), and the results obtained are presented below. This involved the analysis of a single patch, 2×1 and 4×1 rectangular microstrip antennas with the various ways of improving the performance of microstrip antenna. The transmission line method was used for calculation of patch dimensions, and other antenna parameter such as gain, bandwidth, efficiency, impedance, etc. were calculated The table below gives the summary of the designed rectangular microstrip patch antenna.

Table 1 Rectangular Microstrip Patch Specification

Features	Required Value
Frequency (GHz)	1.80
Dielectric constant	2.20
Width (mm)	65.88
Length (mm)	56.14
Height (mm)	1.60
Rad resistance (Ohm)	2000
Input Impedance (Ohm)	283
Efficiency	0.99
Gain (dB)	5.6
Directivity (dB)	6.94



Fig6. Radiation Pattern Of A Microstrip Patch

From the figure above, it can be seen that the designed antenna has a large beamwidth with sidelobes. The gain is 5.6 dB.



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2-Patch Microstrip Antenna

The figure below shown the radiation pattern of 2-patch microstrip antenna with element spacing of 0.5 λ



Fig 7 Radiation Pattern Of 2-Patch Antenna With Element Spacing Of 0.5λ

From the figure above, it can be seen that the 2-patch antenna has a lager beamwidth, with approximated gain of 7.6dB, with no side lobes.

4- Patch Microstrip Antenna



Fig 8 Radiation Pattern of a 4 Patch Antenna with Element Spacing Of 0.5λ

From the figure above, it can be seen that the array has a reduced beam width, with improved gain of 11.6dB, with side lobes.

Bandwidth and Efficiency

As stated earlier the most serious limitation of the microstrip antenna is its narrow bandwidth (BW). In the table below approximated values of bandwidth with dielectric constant and substrate height are given:

Table 2 Dielectric Constant, and Calculated Bandwidth

Dielectric Constant	Bandwidth(BW)
(ε _r)	%
1.0	1.8

2.0	1.3
2.0	1.1
3.0	1.1
4.0	0.9
6.0	0.9
8.0	0.6
10.0	0.5
16.0	0.4

Table 3 Substrate Height and Calculated bandwidth

Substrate Height	Bandwidth(BW)
(mm)	%
1.0	1.9
2.0	1.5
3.0	2.3
4.0	3.1
5.0	3.9
6.0	4.6
8.0	6.2
10.0	7.7
12.0	9.3
14.0	10.8

From the tables above, it can be seen that increasing the dielectric constant reduces the bandwidth (BW), again increasing the substrate height increases bandwidth (BW). Also by increasing the width w the bandwidth can be increased but this is limited in order not to excite the higher order modes. The relationship between BW & dielectric constant is plotted below:



Fig 9 Plot of BW Vs Dielectric Constant



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There are various techniques for increasing the bandwidth BW of (MSA)'s. The main techniques used to increase the bandwidth are:

a. Low Quality Factor

The principle of producing low quality factor of the cavity below the patch can be achieved by either using low dielectric constant or larger thickness of the substrate but it is restricted by surface wave generation leading to low gain and low efficiency of the antenna.

b. *Modified Shape Patches*

The regular (MSA) configurations, such as rectangular and circular patches can be modified to rectangular ring and circular ring respectively to enhance the BW. The larger BW is because of a reduction in the quality factor of the patch resonator, which is due to less energy stored beneath the patch and higher radiation.

c. Multilayer Configurations

In multilayer configuration, two or more patches on different layers of the dielectric substrate are stacked on each other. Based on the coupling mechanism, these configurations are categorized as electromagnetically coupled or operative-coupled microstrip antennas [23]. The design process of broadband MSA is based mainly on the measurements acquired from the narrowband rectangular antenna using single layer configuration. The antenna is assumed passive, linearly polarized, fed by a coaxial probe with input impedance nearly of 50ohms. The patch antenna element is designed to radiate or operate with narrow impedance bandwidth. The narrow bandwidth of the microstrip antenna can be widened using combination between lowering Q-factor, modified shaped patches, and reactive loading approaches. To achieve the broad banding of the microstrip antenna, it is important to determine the requirement with such design. The requirements needed to start the design process of a broadband microstrip antenna are:

- a. Type of substrate material to be chosen
- b. The centre frequency and
- c. The operating bandwidth.

The substrate material is important in the successful design, where low quality factor of the cavity below the patch can be achieved by proper choice of the substrate material. The substrate height is limited by the excitation of surface wave, and then choice is based on woods criterion which depends on the operated frequency and substrate material [26].

h< 0.076
$$^{\Lambda_0}$$
 for $\epsilon_r \approx 2.3$, and h< 0.023 $^{\Lambda_0}$ for $\epsilon_r \approx 10$.



Fig 10 Plot of Antenna Gain Vs Dielectric Constant

Here, plot shows that antenna gain is proportional dielectric constant of the material.

VII. CONCLUSION

In this work, a single patch, 2-patch and 4 – patch microstrip linear array is designed and simulated. The achieved characteristics of designed antenna array are: the antenna operates at a centre frequency of 1.8GHz with impedance bandwidth of about 5%. The bandwidth can be improved by one of the methods described. The array antenna gain was estimated at 11.6dB for 4- element array. It was also observed in simulation that the antenna gain increases with increase in dielectric constant, as against the theory.

REFERENCES

- [1] Balanis, Constantine, "Antenna theory-Analysis and Design", John Wiley & Sons Ltd, Reprinted 1997.
- [2] Saunders, Simon R., "Antennas and Propagation for Wireless Communication Systems", John Wiley & Sons Ltd., October 2003.
- [3] Mailloux, R.J., et al, "micro strip antenna technology", IEEE Trans. Antennas and Propagation, Vol. AP-29, January 1981, pp.2-24.
- [4] James, R.J., et al, "Some recent developments in micro strip antenna design", IEEE Trans. Antennas and Propagation, Vol.AP-29, January 1981, pp.124-128.
- [5] Johan Lagerquist "Design and Analysis of an Electrically Steerable Microstrip Antenna for Ground to Air Use", Master's Thesis, May 2002.
- [6] Alexander Kuchar "Aperture Coupled Microstrip Patch Antenna Array". March 1996.
- [7] Adil Hameed and Basim Jar'alla "Design and Simulation of Broadband Rectangular Microstrip Antenna", Eng. Tech. Vol. 26, No 1, 2008.
- [8] Mohammad Islam et al "High Gain Microstrip Patch Antenna", European Journal of Scientific Research, ISSN 1450- 216X, Vol. 32 No.2 (2009), pp. 187-193.
- [9] Garg, R, Bhartia, P., Bahl, I., Ittipioon, A., "Microstrip antenna design handbook", Artech House Inc., MA, England, 2001.
- [10] Pozar, D.M., "A Review of Aperture Coupled micro strip Antennas: History, operation, Development, and Applications", IEEE Letters, May, 1996.



ISO 9001:2008 Certified International Journal of Engineering and Innovative Technology (IJEIT)

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- [11] Carver, K. R., Mink, J. W., "Microstrip Antenna Technology", IEEE Trans. Antennas propagation, Vol.AP-29, January 1981, pp.2-24.
- [12] Gao, S, C., Li, L, W., Yeo, T, S., Leong, M, S., "A dual frequency Compact Microstrip patch Antenna", Radio Science, Volume 36, Number 6, pp 1669-1682, Nov-Dec, 2001.
- [13] James, J.R., and P.S. Hall, Handbook of Microstrip Antennas, Vol. 1, London: Peter Peregrines Ltd., 1989.
- [14] Dubost, G., and G. Beauquet, "Linear Transmission line Model Analysis of Circular Patch Antennas," Electronics Letter, Vol. 22, October 1986, pp. 1174-1176.
- [15] Lo, Y.T., Solomon, D., and Richards, W.F., "Theory and Experiment on Microstrip Antennas," IEEE Trans. Antennas propagation, Vol.AP-27, March 1979, pp 137-145.
- [16] Costantine A. Balanis, "Antenna Theory Analysis and Design", Wiley, 2nd edition, Chapter 14, 1997.
- [17] James I.J & Hall P.s.," Handbook of Microstrip Antennas", Vol. 1, Peter Peregrinus Ltd., 1989
- [18] C.A. Balanis, "Antenna Theory, Analysis and Design", John Wiley and Sons, 3rd Ed., New York, 2005.
- [19] Pozar, D.M., "Microstrip Antenna Aperture Coupled to a Microstrip Line," Electronic Letters, Vol. 21, No.2, 1985, p.49-50.