Design and Simulation of a Patch Antenna for Microwave Imaging

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Abstract - This paper outlines the design and simulation of an inset fed rectangular patch antenna at 2.4 GHz mainly for the detection of breast cancer. The microstrip antenna is used in number of applications viz., biomedical, GPS, aircraft, cell phones and WLAN devices because of its conformability to curved surfaces, low profile, inherent narrow bandwidth, easy to modify and fabricate features and relatively low cost. Breast cancer affects many women and has fatal conclusions if it is not diagnosed correctly. Early diagnosis is the most important parameter to detect and interfere with cancer tissue. Some of methods for breast cancer detection are X-ray mammography, MRI and ultrasound. However, they have some limitations. For example; between 4 and 34% of all breast cancers are missed because of poor malignant or benign cancer tissue contrast. Microwave imaging to detect breast cancer is a promising method and there are many works in this area. All the materials used for trans-receiving microwave signals have different permittivity and conductivity. In this work, a microstrip patch antenna operating at 2.4 GHz (ISM band of radio waves) is designed and simulated over Rogers RT Duroid (εᵣ=2.2) substrate. Important results such as electric field, magnetic field distribution, reflection coefficient and current density on the antenna are evaluated.

Key words: Inset fed, patch antenna, microwave imaging, FEM

I. INTRODUCTION

The microstrip antenna was initially proposed by G.A. Deschamps in 1953, but it did not become practical until the 1970s. Subsequently, it was developed further by Robert E. Munson and other researchers using low-loss dielectric materials that were just becoming available [1]. A microstrip antenna can take any size and regular geometrical shape and can be fed in a number of different ways. In this paper, the critical design parameter that affects the radiation and also the modeling of an 'inset-fed' MSA (microstrip antenna) has been presented. Results of simulation achieved in COMSOL Multiphysics, a finite element method (FEM) based CAD simulation software, are discussed. MSA are often used where thickness and conformability to the host surfaces are the key requirements [2]. Since patch antennas can be directly printed onto a circuit board these are becoming increasingly popular within the mobile phone market. By slotting on microstrip patch and modifying ground plane, imaging quality can be increased. The design of a simple patch antenna operating at 2.4 GHz is simulated and results are demonstrated. A band of radio spectrum has been reserved internationally for the use of exclusively industrial, scientific and medical purposes other than telecommunications. This radio band is known as ISM band used worldwide for the purpose. From this band, 2.4 GHz frequency is being used as commonplace for microwaves recommended by the regulatory authorities. So, the patch antenna is designed to operate at 2.4 GHz frequency. The following are the advantages of MSAs in general [3]:

1) Low profile,
2) Compact in size,
3) Easy to customize and fabrication techniques,
4) Low manufacturing cost, and
5) Simple structure.

However, the disadvantages of MSA are its low-power handling capability and narrow bandwidth (1 to 5%). But the bandwidth can be increased further by using stacked substrates and with increased complexity [1][2].

II. MODEL DESCRIPTION AND DESIGN

In this design example, we have chosen an inset feed for the reason that it does not need any additional matching network. Figure 1 shows an inset fed rectangular patch antenna.

Fig. 1. An inset fed rectangular MSA

The L and W shown in the figure are the length and width of the patch respectively, and R represents the stub length. A microstrip transmission line can also be
The width \( W \) of the microstrip antenna given in equation (1) controls the input impedance. Larger values of widths can increase the bandwidth. For decreasing the input impedance to 50\( \Omega \), often requires a very wide patch antenna [4].

\[
\text{Length, } L = \frac{c}{2 \sqrt{\varepsilon_r}} - 2\Delta L
\]  

From equation (2) it is clear that the frequency of operation of the MSA is determined or controlled by its length, \( L \). It means that at higher frequencies such as the one in our current design a very small length of patch antenna is typically required. Also equation (2) says that the patch antenna should have a length equal to one half of a wavelength within the substrate.

A. Patch Antenna-Description: The microstrip antenna is constructed on a dielectric substrate usually employing the same type of lithographic patterning as used to fabricate PCBs. In its most basic form, it consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side. Typical relative permittivity values used for MSA lies between 2.2 and 12, i.e. 2.2 \( \leq \varepsilon_r \leq 12 \) [3]. The length of the simplest electrical patch is \( \lambda/2 \) or it is \( \lambda/2 \) long. It needs the larger ground plane for better performance at the cost of large antenna size. Figure 2 describes the structure of a typical patch antenna.

The input impedance, \( Z_{in} \), the effective dielectric constant, \( \varepsilon_{eff} \), and the extension length, \( L \), of a patch antenna can be calculated from the following three equations.

\[
\text{Input impedance, } Z_{in} = 90 \frac{\varepsilon_r^2}{\varepsilon_r - 1} \left( \frac{w}{L} \right)^2 \Omega
\]

The effective dielectric constant can then be found by:

\[
\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{w}{L} \right]^{1/2}
\]

where ‘\( h \)’ is the substrate thickness and ‘\( w \)’ is the width of the line. The extension length has been adapted into the form:

\[
\Delta L = 0.412 h \left( \frac{\varepsilon_{eff} + 0.31}{\varepsilon_{eff} - 0.31} \right) \left( \frac{w}{L} \right)^{-0.258}
\]

B. Radiation Mechanism: The patch antenna is fed at a point where voltage, \( V \), is maximum and current, \( I \), is minimum (ideally zero). The characteristic impedance, \( Z_c \) and width of microstrip transmission line ’\( w \)’ are interdependent, that means ’\( w \)’ increases with an increase in \( Z_c \). For a patch antenna to radiate, \( V \) and \( I \) must be 90° out of phase with each other. We consider MSA as an open circuit transmission line. For an open circuited transmission line, \( |Z| = 1 \). If \( |Z| = 1 \), \( V \) and \( I \) are 90° out of phase.

The vertical E-field components beneath the patch antenna as shown in the figure below, do not contribute to the radiation. At the ends of length (\( L \)), fringing fields are present that have horizontal components going along the same direction (not shown in figure). Hence they add up in phase and results in radiation. MSA is not a current radiator which means that the current is not responsible for the radiation but the voltage is sole responsible for radiation. Conclusively we can say that the radiation is produced as a result of current flowing on the patch and the ground plane.

C. Characteristics of a Patch Antenna: A patch antenna is a narrow-band, wide beam antenna fabricated by etching the antenna element pattern in metal trace bonded to an insulating dielectric substrate with a continuous metal layer bonded to the opposite side of the substrate which forms a ground conductor [2]. A microstrip antenna can be constructed in various sizes and shapes. An MSA can be of square, rectangular, circular, triangular or elliptical shape. Theoretically it can be of any continuous shape but the most popular shapes are rectangular and circular. Square patches are
used to generate a pencil beam and rectangular patch for a fan beam radiation patterns.

Due to straightforward fabrication, circular patches can also be used but the calculation of current distribution in circular patches is relatively more involved [2].

Some of the major applications where the microstrip antenna is used are listed below:

- Implantable antennas used for medical applications such as telemetry and wearable medical devices [6][7].
- Microwave Imaging for diagnosis and therapeutic uses, particularly in breast imaging [8].
- Aircraft and Spacecraft [9].
- Mobile radio communication devices [10],
- GPS, Bluetooth, WLAN devices [11], and
- Global Navigation Satellite System (GNSS) [12]

D. Design Trade Offs: A 3D model of the antenna under context has been built in COMSOL Multiphysics software. It is designed and simulated at a frequency of 10 GHz. The critical design parameters used in this design has been tabulated below. All of the parameters in a rectangular patch antenna design (L of patch, W of patch, D (height) of substrate, permittivity) control the properties of the antenna. First, the length, L of the patch controls the resonant frequency as discussed above. The relation between the length of the patch L and resonant frequency f₀ is given in equation (1). Second, the width of the patch W controls the input impedance and the radiation pattern. The wider the patch becomes the lower the input impedance is. The permittivity εr of the substrate controls the fringing fields-lower permittivities have wider fringes and therefore better radiation. Decreasing the value of εr increases the bandwidth and hence the efficiency whereas the input impedance increases with higher permittivity values. In this design, the height of the patch and that of the substrate are chosen to be same so that the patch is embedded within the substrate material. Typically the height h is much smaller than the wavelength of operation, but not much smaller than 0.05 of a wavelength. The thickness of the patch itself and that of the ground plane are not critically important [4]. The bottom layer of the substrate and that of the patch constitute the ground plane i.e. a perfect electric conductor (PEC) in our case that stops radiation toward the bottom side.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Substrate thickness</td>
<td>0.2</td>
</tr>
<tr>
<td>W_patch</td>
<td>Patch width</td>
<td>11.9</td>
</tr>
<tr>
<td>L_patch</td>
<td>Patch length</td>
<td>9.1</td>
</tr>
</tbody>
</table>

The Bandwidth of the patch antenna can be controlled by the height, h, of the substrate. It increases or widens with the height or thickness of the dielectric material. But due to thicker substrate losses due to surface wave modes increases in the antenna. That is, the substrate height is inversely related to the loss [2].

E. Important Terms Of Antenna: To understand the working concept of antenna and the radiation of electromagnetic waves, few related terms need to be known clearly. Very important of them are explained in brief in the following [13][14].

i). Radiation Pattern: The radiation pattern of an antenna is a plot of the magnitude of the far-zone field strength versus position around the antenna at a fixed distance from the antenna. Thus the pattern can be plotted from the pattern functions $F_\theta(\theta, \phi)$ and $F_\phi(\theta, \phi)$ versus either the angle $\theta$ (for an elevation plane pattern) or the angle $\phi$ (for an azimuthal plane pattern). The choice of plotting either $F_\theta$ or $F_\phi$ is dependent on the polarization of the antenna.

ii). Near-field and Far-field: The fields around an antenna may be divided into two principal regions, one near the antenna called the near field or Fresnel zone and one at a large distance called the far field or Fraunhofer zone. The boundary between the two may be arbitrarily taken to be at a radius [2]:

$$R_{ff} = \frac{2\pi^2}{\lambda} \text{m.}$$ (6)

- Near-field: The near-field is the E-field radiated in the vicinity of the antenna. The near-field diminishes with the radial distance and hence become negligible at large distances. Shape of the wave in this region is spherical.

- Far-field: Consider an antenna located at the origin of a spherical coordinate system. At larger distances where the localized near-fields are negligible the radiated E-field also called as Far-field of an arbitrary antenna which is expressed as:

$$E(r, \theta, \phi) = [\theta F_\theta(\theta, \phi) + \phi F_\phi(\theta, \phi)] \frac{v}{m}$$ (7)
Where E is the electric field vector, \( \theta \) and \( \phi \) are unit vectors in the spherical coordinate system, and r is the radial distance from the origin. The amplitude of the far-field varies inversely with respect to the radial distance ‘r’. Also the far-field distance is the distance where the spherical wave front radiated by an antenna becomes a close approximation to the ideal phase front of a plane wave. It depends on the maximum dimension of the antenna. If we call this dimension as ‘P’, then the far-field distance is defined as [15]:

\[
\frac{2\pi^2}{\lambda} m
\]  

(8)

**iii). Antenna Bandwidth:** The bandwidth of an MSA is directly proportional to its width, W and height of the substrate, h. With an increase in W, bandwidth increases. However, W should be taken for lower values to avoid excitation of higher order modes. Small BW makes MSA really useful, for example in GPS application and other narrow BW application. The BW of the MSA is inversely related to the quality factor Q and is given by:

\[
Bandwidth, BW = \frac{(VSWR-1)}{4\cdot VSWR} \]  

(9)

**iv). Impedance Bandwidth:** It is defined as the range of frequencies over which the input return loss (RL) is not smaller than a designated value, usually 10 dB [16].

The term impedance bandwidth is used for a linearly polarized patch antenna in which E-field vector has either horizontal or vertical component but not both. Hence the E-field is linearly polarized. If the E-field has horizontal component then the polarization sense is horizontal whereas if the E-field has vertical component then the polarization sense is vertical.

**v). Reflection coefficient, Return Loss, and VSWR:** The antenna input impedance \( Z_o \) needs to be matched with the characteristic impedance denoted by \( Z_c \) of the transmission line connected to the feed point of the antenna. Usually a 50Ω cable is used to feed the antenna. Thus the input impedance of the antenna needs to be equal to 50Ω otherwise there will be an impedance mismatch at the antenna feed point. In the case of impedance mismatch there will be reflections, that is, some of the signals fed to the antenna will be reflected back to the signal sources [16].

Reflection coefficient (\( \Gamma \)): It is defined as the ratio of reflected wave voltage to the incident wave voltage. The reflection coefficient at the feed point of the antenna can be related to the antenna input impedance by the following equation:

\[
Reflection \ coefficient, \Gamma = \frac{Z_{in}-Z_0}{Z_{in}+Z_0} \]  

(10)

Return loss (RL): It is defined as:

\[
Return \ loss, RL(dB) = -20\log |\Gamma| \]  

(11)

For a well-designed antenna, the required return loss (RL) should usually be at least 10 dB though some antennas on small mobile terminals can only achieve about 6 dB [16].

Voltage standing wave ration (VSWR): It is defined as the ratio of maximum voltage \( V_{max} \) to the minimum voltage \( V_{min} \). It is given as:

\[
VSWR = \frac{|V_{max}|}{|V_{min}|} = \frac{1+|\Gamma|}{1-|\Gamma|} \]  

(12)

Where, \( \Gamma \) is the reflection coefficient.

**vi). Feeding Techniques:** There are various ways that can be used to feed microstrip antennas. The four most popular feeding techniques are the microstrip line, coax feed, aperture coupling and proximity coupling. The feeding technique used here is microstrip based inset feeding technique to improve matching between the feed and the antenna. The input impedance could be lowered if the patch was fed closer to the center. One method of achieving this is by using an inset feed as shown in figure 1. An inset feed extends into the patch antenna. Since the current distribution is sinusoidal, moving in a distance ‘d’ from the end will increase the current by \( \frac{\pi d}{L} \). The voltage also decreases in magnitude by the same amount that the current increases. Hence, the input impedance scales as:

\[
Z_{in}(d) = \cos^2 \left( \frac{\pi d}{L} \right) Z_{in}(0) \]  

(13)

In the above equation, \( Z_{in}(0) \) is the input impedance if the patch was fed at the end. The inset feeding method can be used to fine tune the input impedance to the desired value [4]. The width of the cutout region is chosen to be large enough so that there is minimal coupling between the antenna and the microstrip, but not so large as to significantly affect the antenna characteristics. The length of the microstrip line, L_feed, is chosen to minimize the reflection coefficient.

### III. SIMULATION OF MICROSTRIP PATCH ANTENNA

With the advent of fast digital computers numerical methods have become more popular and attractive than ever. The RF Module of COMSOL is used by designers of RF and microwave devices to design antennas, waveguides, filters, circuits, cavities, and special category of materials called meta-materials. It is now
possible to quickly and accurately compute electromagnetic field distributions, transmission, reflection, impedance, Q-factors, S-parameters, and power dissipation. This simulation tool offers the benefits of lower cost combined with the ability to evaluate and predict physical effects that are not directly measurable in experiments. Most EM problems involve either partial differential equations or integral equations to be solved. The modeling of the rectangular patch antenna discussed above has been performed in COMSOL Multiphysics software which is a finite element method (FEM) based simulation tool. Finite Element Method is a numerical technique used to solve the partial differential equations (PDEs) such as Maxwell’s equations [17]. The reason for choosing finite element based simulation over other methods is that it can handle any complex structures of antennas with relative ease compared to other methods [18].

In COMSOL multiphysics both single and multiple physics problems can be solved by adding different physics interfaces. To solve any RF problems such as antenna or radiation problems, electromagnetic waves frequency domain interface must be added. The electromagnetic waves, frequency domain interface is a part of RF branch and is added whilst adding physics interface. It is used to solve time harmonic EM field (such as E and H) distributions. Since infinite space cannot be modeled in real time therefore the antenna has been surrounded by sphere of finite radius. The eight domains of the spheres are described as perfectly matched layers (PMLs) meaning the energy radiated by the antenna is perfectly absorbed by each of the layers. For source driven simulations as is the case in the present design, the Frequency Domain study type at a single frequency is used. This physics interface of the COMSOL, numerically approximate the solution of the wave equation i.e., it solves the time-harmonic wave equation given below for the electric field.

$$\nabla \times \mu_{r}^{-1} (\nabla \times \mathbf{E}) - k^2 \left( \varepsilon_{r} - \frac{j\omega}{\omega_{c}} \right) \mathbf{E} = 0$$  \hspace{1cm} (14)

The wave number, $k$, is defined as

$$k = \omega \sqrt{\varepsilon_{r} \mu_{r}} = \frac{\omega}{c_{0}}$$  \hspace{1cm} (15)

where $c_{0}$ is the speed of light in vacuum.

The step-by-step method of model creation or the design flow in COMSOL is described below: First, the appropriate space dimension is selected from the model wizard and then from select physics under the RF interface, the electromagnetic waves frequency domain physics interface is added. In the next step which is the selection of study type, frequency domain is added to be studied. Then the important design parameters which are tabulated in table 1 are defined under global definitions node. From the definitions toolbar, ‘perfectly matched layers’ (PMLs) is selected. The spherical coordinate system is chosen from the PML settings window for radiation problems. The perfectly matched layers are very critical for the simulation of EM waves that propagate into an unbounded domain and due to the fact that infinite space cannot be modeled. PMLs are layers that absorb the radiated waves from the antenna with small reflections [19].

In the next step under the component 1 node the device is constructed using geometrical objects such as blocks. Different blocks are assembled using Boolean and sub partition option to create the antenna as a whole as shown below:

![3D Geometrical shape of antenna](image)

Once the antenna is created it is enclosed in a sphere (for 3D) which acts as a PML. Then the whole geometry is assembled by forming a union.

Next the materials for patch and the substrate are added by selecting the “Add Material” from the material tool bar. A relative permittivity of $\varepsilon_{r} = 2.2$ is chosen for the required Rogers RT Duroid as substrate patch and air enclosed that surrounds the patch.

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When this (emw) physics interface is added the default nodes viz., Wave Equation, Electric, Perfect Electric Conductor (PEC), and Initial Values are also added to the Model Builder. Then, from the Physics toolbar, other critical nodes that implement, for example, boundary conditions are also added.
For voltage or current excitation lumped port node is selected in the model. The lumped port is a simplification of the port boundary condition which is being on boundaries that extend between two metallic boundaries i.e. between the top layer of the patch, bottom layer of the patch and the bottom layer of the substrate. The type of port is selected from the lumped port settings such as uniform port, user defined port or coaxial cable. At this port, the excitation of the wave must be turned on [19].

The most important design step is that of meshing. Figure 5 below shows that the designer has the choice of selecting the mesh sequence type which is either physics controlled or user controlled.

The element size is an important parameter that determines the accuracy of results especially that of input return loss. It gets better as the simulation is run from extremely coarse to extremely fine. Extremely fine element size can be chosen on powerful computers to verify the accuracy of results.

![Mesh settings](image1)

**Fig. 5. Mesh settings**

Once the meshing is done the structure is divided into number of finite elements such as triangular elements as can be seen from the figure 6 below: The software by itself applies different meshing sequence depending up on the geometry.

![Finite element subdivision](image2)

**Fig. 6. Finite element subdivision of a patch antenna**

The solution is found for each element separately by solving the governing matrices and equations and lastly all the elements are assembled in the solution region. Finally, computation is executed for the model builder and the results are obtained.

### IV. RESULTS AND DISCUSSION

The inset fed rectangular microstrip patch antenna has been designed and simulated on COMSOL Multiphysics software platform. The dielectric material chosen for the substrate for the sake of achieving optimal results is Rogers RT Duroid that has relative permittivity, \( \varepsilon_r \), of 2.2. Figure 7 shows the radiation pattern in the E-plane; the E-plane is defined by the direction of the antenna polarization and includes the direction of maximum radiation also. Similar pattern in H-plane is shown in figure 8. The current density distribution pattern of the patch antenna is shown in figure 9. The directional radiation pattern due to the PEC ground plane that blocks the radiation toward the bottom end can be seen in figure 10. It is observed that when antenna is used, the simulated reflection coefficient, \( S_{11} \), is below 20 dB at about 2.45 GHz. The far-field is obtained by selecting a domain for far-field calculation from the physics toolbar.

![Far-field radiation pattern](image3)

**Fig. 7 & 8. Far-field radiation pattern at E-plane and H-plane respectively.**

![Current density](image4)

**Fig. 9. Current density on the patch antenna.**

This will add the far-field domain under electromagnetic waves with frequency domain interface. The far-field radiation pattern is obtained by evaluating the squared norm of the far-field on a sphere centered at origin. It should be noted that each coordinate at the surface of the sphere represents the angular direction and then select the boundaries where the algorithm integrates the near field [19].

![Far-field radiation pattern](image5)

**Fig. 10. Far-field radiation pattern at E-plane.**
The Far Field distributions are obtained from this module. It is a map of the values of global variables such as far field norm, normEfar and normdBEfar, or components of the far field variable Efar mentioned in the module. The variables are plotted for a selected number of angles on a unit three dimensional sphere. The angle interval and the number of angles can be manually specified. Also the radius of the 3D sphere can be specified. It can be seen that the radiation pattern obtained is reasonable and is directive towards the top (Figure 10, Figure 11). The radiation in the opposite direction is greatly minimized by the use of perfect electric conductor (PEC) at the bottom which acts like a ground plane. The main advantage with the Far Field plot, as compared to making a Line Graph is that the sphere that is used for defining the plot directions is not part of design geometry for the solution. Thus, the number of plotting directions is decoupled from the discretization of the solution domain [19].

![Image](http://example.com/fig11.jpg)

Fig. 11. Three dimensional directive Far-field radiation pattern

V. CONCLUSION

A microstrip antenna intended to use for microwave imaging has been designed and simulated in this work. The proposed antenna design is useful for diagnosing breast cancer at an early stage. The proposed antenna is designed at 2.4 GHz and is simulated in COMSOL Multiphysics software which is a FEM based 3D EM simulation tool. The results obtained after the simulation yielded the values of electric and magnetic fields and also for current density. To increase the accuracy of the obtained results, user controlled meshing strategy from the sequence type under the size settings could be implemented where the user has the choice of setting element size parameters such as resolution of narrow regions, maximum and minimum element size etc. Therefore, in this work the simulation has been optimized to obtain best possible results in minimum computational time.

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