Radiation Pattern of Novel Cylindrical Surrounding Patch Antenna for 2.4 GHz Applications

Erhiega N. Umayah and Viranjay M. Srivastava
Department of Electronic Engineering, Howard College, University of KwaZulu-Natal, Durban – 4041, South Africa.
Email: {erhiega; viranjay}@ieee.org

Abstract—In this research work, the return loss (S-parameter, $S_{11}$), Voltage Standing Wave Ratio (VSWR), radiation pattern, Band Width (BW), and percent bandwidth (B%) for a Cylindrical Surrounding Patch Antenna (CSPA) have been obtained from a transformed Rectangular Planar Patch Antenna (RPPA) for application in the Industrial Scientific and Medical (ISM) band. The antenna structure has been designed and analyzed on a polyimide substrate with relative permittivity ($\varepsilon_r$) 3.5, permeability ($\mu_r$) 1, and loss tangent ($\tan\delta$) 0.0027. Polyamide has been chosen because it is flexible, easily conformable to non-planar surfaces, and with little or no negative effect on antenna parameters. Simulations have been carried out for curvature radius ($r$) ranging from 10 mm to 35 mm in steps of 5 mm to ascertain its resonant frequency ($f_r$). Thereafter, simulation results for best achieved curvature radius of 10 mm for the CSPA has been compared with the optimized RPPA. Results verify that the CSPA gave $S_{11}$ of $-23.115$ dB, and $B\%$ of 3.45% at $f_r$ of 2.387 GHz, while the RPPA provide $S_{11}$ of $-20.091$ dB, and $B\%$ of 3.21% at $f_r$ of 2.4 GHz.

Index Terms—bandwidth, cylindrical surrounding patch antenna, parameterization, planar rectangular patch antenna, polyimide, return loss

I. INTRODUCTION

Patch antennas find wide applications in wireless communication systems, aerospace, satellite, radio-medical, cellphones, radar systems, etc. [1]-[3]. This is because of their low profile, light weight, simplicity, easy to fabricate with modern printed-circuit technology, and mechanical robustness on host surfaces [4], [5]. They are also versatile in terms of polarization, resonant frequency, impedance, and polarization pattern. Present research and applications of patch antennas focuses on conformal patch antennas because the early versions of patch antennas (which were planar in configuration) are characterized by narrow bandwidth, spurious feed radiation, poor polarization, low gain, limited power capacity, and tolerance problems [1]-[3]. Despite of these limitations, a major advantage of patch antennas is that they can be made to conform to non-planar surfaces (geometries) on which they are mounted [2].

These types of antennas are referred as Conformal Patch Antennas (CPAs). The IEC International Electrotechnical Vocabulary, Chapter 712, Antennas 712-01-13, defines a conformal antenna as that which conforms on a surface whose shape is mainly determined by considerations other than electromagnetic, e.g., hydrodynamic and aerodynamic considerations [3], [4], [6]. Conformal antennas allow integrated non-obstructive designs which provides good azimuth coverage and reduced aerodynamic drag [2], [3]. The most common configuration of conformal patch antennas is the Cylindrical Surrounding Patch Antenna (CSPA). It is advantageous in terms of controlled gain, better angular coverage which depends on the shape of the host, higher bandwidth, and ease of installation since radome (a structure which protects radar antenna) is not required. The drawbacks of CSPAs are due to bending effect (caused by stretching and compression of the dielectric substrate) which results to phase impedance and resonant frequency errors [5], [6]. Rectangular, square, and circular patches are often mounted on cylindrical, conical, and spherical surfaces which are approximate representation of host surfaces (geometries) [2]. Patch antenna as shown in Fig. 1, consists of a radiating patch placed above a grounded conducting plane with a sandwiched dielectric substrate [1], [2].

It has been reported in literature that bending and curvature radius affects antenna parameters such as the return loss (S-parameter, $S_{11}$), voltage standing wave ratio (VSWR), radiation pattern, and band width (BW) are functions of the type of substrate, its thickness ($h$), and
permittivity ($\varepsilon_r$) [5]-[10]. Hence, the proper choice of substrate material is a critical factor in the design of conformal antennas since the effect of bending as a function of flexibility of the substrate, and curvature radius affects the parameters of conformal patch antennas [5], [6].

This present research work considers the proper choice of a flexible substrate for comparative analysis for return loss, VSWR, radiation pattern, and bandwidth for CSPPA and its RPPA counterpart. This paper has been organized as follows. Section II presents the antenna design and modelling. The choice of substrate, design steps, and equations for the design of the rectangular planar patch antenna, and the cylindrical surrounding patch antenna are discussed. Section III presents the results and discussion of the antenna. Section IV presents the comparison of proposed cylindrical surrounding antenna with existing designs. Finally, Section V present conclusion and future works.

II. ANTENNA DESIGN AND MODELING

Since the proposed cylindrical surrounding patch antenna is expected to be made formable to cylindrical surfaces, one important determinate of the performance of patch antennas is the substrate. Flexible substrates are preferred for conformal antenna applications because it enhances bandwidth, coverage, gain, etc. compared to rigid substrates as reported in literatures. The procedures taken for the design of the cylindrical surrounding patch antenna is as follows:

A. Choice of Substrate

Several authors have studied the effect of curvature and the angle ($\theta$) subtended by the width of the patch on the performance of cylindrical patch antennas [4], [11], [12]. Other authors [6], [13], [14] considered the effect of bending on the radiation performance, input impedance, and resonant frequency where the shift of resonant frequencies were presented.

Also, the effect of patch bending on a cylindrical rectangular patch antenna was analyzed in [15]-[18]. This has necessitated the proper choice of substrate for conformal antenna design. To avoid the short comings of substrate on antenna performance the flexible, tolerant, and almost non-cracking substrate have been chosen. This is to ease bending, enhance fringing fields, and improved radiation [10]-[14].

In this research work, polyimide (lossy) has been chosen as substrate for the antenna design. It has permittivity ($\varepsilon_r$) 3.5, permeability ($\mu_r$) 1, and loss tangent ($\delta$) 0.0027 [19], [20]. It has been chosen because its flexibility, excellent dimensional stability, machinability, low coefficient of thermal expansion, attractive thermal and mechanical properties, environmentally friendliness, and resistance to crack when bent.

B. Design of the Rectangular Planar Patch Antenna

A narrow band planar patch antenna consists of metallic radiating element on one side of a dielectric substrate and metallic ground on the other side [1], [21], [22]. The physical parameters of the planar rectangular patch antenna such as the length ($L$), width ($W$), and thickness ($h$ and $t$) of the patch, substrate/ground plane, and the inset feed microstrip line are obtained by parameterization method [23]-[25].

Parametrization method requires the following listed antenna parameters that must be chosen in accordance with existing standard and used to compute the approximate physical dimensions of the other parameters by substitution into classical equations. The following parameters have been chosen for the antenna design for 2.4 GHz ISM band application.

1) Resonance frequency ($f_r$) and
2) Substrate type, taking into cognizance the substrate thickness ($h$), relative (dielectric) permittivity ($\varepsilon_r$), relative permeability ($\mu_r$), and loss tangent (tan $\delta$).

The classical theory from (1) to (5) were used to calculate the patch length ($L$), patch width ($W$), inset feed length ($L_{inset}$), inset feed width ($w_f$), and the input impedance ($Z_n$) of the patch [1], [26]-[28]:

\[
L = \frac{\lambda_o}{2\sqrt{\varepsilon_{eff}}} - 2\Delta L \quad (1)
\]

\[
W = \frac{1}{2f_r}\sqrt{\varepsilon_r\mu_r}\left(\sqrt{\frac{2}{\varepsilon_r+1}}\right) \quad (2)
\]

\[
L_{inset} = \frac{L}{2\sqrt{\varepsilon_{eff}}} \quad (3)
\]

\[
w_f = 7.47h \varepsilon_r \left(\varepsilon_{eff} + 1\right) - 1.25t \quad (4)
\]

\[
Z_n = \frac{L}{\sqrt{\varepsilon_{eff} + 1}} \ln\left[\frac{5.98h}{0.8w_f + t}\right] \quad (5)
\]

where

\[
\Delta L = 0.412h \left(\varepsilon_{eff} + 0.3\right) + 0.262 \quad (6)
\]

\[
\left(\varepsilon_{eff} - 0.258\right) \left(\varepsilon_r + 0.8\right) \quad (7)
\]

\[
\varepsilon_{eff} = \left(\varepsilon_r + 1\right) + \left(\varepsilon_r - 1\right)\left(1 + \frac{12h}{W}\right)^{\frac{1}{2}} \quad (8)
\]

\[
x = \left(Z_n\sqrt{\varepsilon_r + 1}\right)/87 \quad (9)
\]

where $\lambda_o$ is the free space wavelength and $\varepsilon_{eff}$ is the effective dielectric constant of the substrate (due to fringing field). This makes the length of patch to look electrically longer on both sides by a factor $\Delta L$.

Thus, the effective length ($L_{eff}$) of the patch is given as $L_{eff} = L + 2\Delta L$. The geometry of the designed planar rectangular patch antenna is shown in the upper section of Fig. 2. Table I depicts dimensions of the optimised planar patch antenna.
To mathematically determine the dimensions of proposed cylindrical surrounding patch antenna, the following assumptions are made:

1) The lengths of the patch ($l_p$), substrate ($l_s$), and ground plane ($l_g$) represent the height of the cylindrical structure (i.e., patch height, substrate height, and ground plane height, respectively).

2) The width of the patch ($w_p$) is equated to the perimeter of patch, related mathematically in (7):

$$p = 2\pi r = w_p$$  (7)

where $p$ is the perimeter of the cylindrical structure, $r$ is the radius of the cylindrical structure, and $\pi = 22/7$.

3) The widths of the substrate ($w_s$) and the ground plane ($w_g$) are equated to the perimeter of cylindrical structure for the computation of the radius of curvature as given in (8). Thus:

$$p = w_s = w_g$$  (8)

The patch width ($w_p$) as shown in Fig. 2 describes an arc on the surface of the substrate while radius ($r$) of the arc formed forms an angle of $2\theta$ at the center of the cylindrical structure. The width of the patch is calculated from (9):

$$w_p = 2\pi \theta /360^\circ = r\theta = r\phi$$  (9)

where $\theta$ is angle in degrees and $\phi$ is angle in radians.

To achieve the bending, the radius of cylinder is kept constant at 10 mm because the impedance bandwidth increases continuously with decreasing radius ($r$) of curvature of the ground plane, implying that a radiating patch mounted on cylinder with radius ($r$) decreasing, leads to increase in impedance bandwidth. This is also a close value to that computed using (2) by substitution of (8). This implies that while the angle ($2\theta$) subtended by the width of the patch at the center of the cylinder is varied from $120^\circ$ to $180^\circ$ to achieve proper lapping between the patch and the substrate [33].

The resonance frequency for a rectangular patch antenna given in [6], [14], [34] for any transverse magnetic (TM) mode in (10), is used for the derivation of cylindrical surrounding patch. The expression for that of the cylindrical surrounding patch antenna is dependent on the width of the patch ($w_p$) for a H-plane bend since $w_p$ forms an arc on the cylindrical substrate.

$$f_r = \frac{c}{2\sqrt{\varepsilon_{eff}}} \left[ \frac{m}{L} \right]^2 + \left[ \frac{n}{w_p} \right]^{\frac{1}{2}}$$  (10)

where $m$ and $n$ are modes along the length ($L$) and width ($W$) respectively.

Substituting (9) into (10), we obtained:

$$f_r = \frac{c}{2\sqrt{\varepsilon_{eff}}} \left[ \frac{m}{L} \right]^2 + \left( \frac{n\theta}{r} \right)^{\frac{1}{2}}$$  (11)
\[ f_r = \frac{c}{2R_{\text{eff}}} \left[ \left( \frac{m}{L} \right)^2 + \left( \frac{n}{r \phi} \right)^2 \right]^{\frac{1}{2}} \]  \tag{12}

Equations (11) and (12) are in degrees and radians respectively and valid for \( h << a \). This condition accounts for the downward shift of the resonance frequency of a cylindrical patch antenna from that of a planar patch antenna. The dimensions of proposed cylindrical surrounding patch antenna are shown in Table II.

| TABLE II. DIMENSIONS FOR THE PROPOSED CYLINDRICAL SURROUNDING PATCH ANTENNA |
|---------------------------------|------------------|
| Component                      | Value (mm)       |
| Ground Plane                   |                  |
| Internal radius \((r_1)\)      | 10.625           |
| External radius \((r_2)\)      | 10.660           |
| Thickness \((t)\)              | 0.035            |
| Substrate                      |                  |
| Internal radius \((r_2)\)      | 10.660           |
| External radius \((r_3)\)      | 11.860           |
| Thickness \((h)\)              | 1.200            |
| Patch                           |                  |
| Internal radius \((r_3)\)      | 11.860           |
| External radius \((r_4)\)      | 11.895           |
| Thickness \((t)\)              | 0.035            |

III. RESULTS AND ANALYSIS

The rectangular planar antenna and cylindrical surrounding patch antenna have been analyzed numerically from the simulation results in this section.

A. Return loss (S-parameter, \(S_{11}\))

The \(S_{11}\) plot in dB as a function of resonant frequency \((f_r)\) classifies antenna as either a single or multiband antenna radiator. For an antenna, the operating efficiency depends on the maximum power transferred between the feed system and the antenna. The return loss indicates the amount of power lost or indicates the level of match (i.e. maximum power transferred) between the source (excitation source) and the load (the antenna) [32]-[35]. Fig. 3 shows return loss plot in dB versus frequency. The return loss for the rectangular planar patch antenna is \(-20.091\) dB at 2.4 GHz, while that of the proposed cylindrical surrounding patch antenna is \(-23.115\) dB at 2.387 GHz. The return loss plot shows that the antenna is matched because the \(S_{11}\) for both antennas is below \(-10\) dB. A lower return loss implies that there is maximum power transfer between the transmitting and receiving end.

B. Voltage Standing Wave Ratio (VSWR)

Voltage standing wave ratio is the performance parameter of an antenna that indicates the relationship between lost input energy and mismatch depicted in as [1], [28]:

\[ \text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \]  \tag{13}

or

\[ \text{VSWR} = \frac{10^{\frac{R_{\text{dB}}}{20}} + 1}{10^{\frac{R_{\text{dB}}}{20}} - 1} \]  \tag{14}

where \(\Gamma\) is the voltage reflection coefficient at resonant frequency \((f_r)\) with a value between 0 and 1. The \(\Gamma \ll 1\) implies that maximum energy is transferred between the feed line and the antenna, while \(\Gamma \leq 1\) implies that VSWR is close to infinity, indicating that maximum energy is reflected from the antenna. A low VSWR at resonance frequency corresponds to a good impedance match, which is usually less than 2, indicating a relatively low loss of energy. Standard acceptable value of VSWR is 1.2 [10], [36], [37]. The VSWR obtained from Fig. 4 are 1.2:2 and 1.6:2 for the RPPA and the CSPA, respectively. Since these values are less than 2, it implies that the two antennas are properly matched at their resonant frequencies of 2.4 GHz and 2.387 GHz, respectively [10].

![Fig. 3. Return loss plot for antenna (a) rectangular planar patch (b) cylindrical surrounding patch.](image)

![Fig. 4. Voltage standing wave ratio for (a) rectangular planar patch and (b) cylindrical surrounding patch antenna.](image)
C. Bandwidth (BW)

It is one of the major limitations of patch antenna performance. It could be defined in terms of VSWR or input impedance with frequency or radiation parameters. The acceptable interval for determining the BW of any antenna configuration in terms of VSWR is $1 \leq \text{VSWR} \leq 2$. Mathematically, BW could be represented as in (15), and could as well represented as a percentage as in (16) referred to as percent bandwidth ($B\%$) [1], [28], [38]:

$$\text{BW} = f_h - f_l$$  \hspace{1cm} (15) \\
$$B\% = \left( \frac{\Delta f}{100\%} \right) / f_r$$  \hspace{1cm} (16)

where $f_h$ and $f_l$ are upper resonant frequency and lower resonant frequency, respectively. The $\Delta f$ and $f_r$ are the width range of the acceptable frequencies, and the resonant frequency, respectively. The BW and $B\%$ for the antennas are shown in Fig. 3 which are 3.2% and 77 MHz for the RPPA and 3.5% and 83 MHz for the CSPA respectively. This implies that when a radiating patch is mounted on a cylindrical surface with radius ($r$) decreasing (i.e., increasing the curvature) from 35 mm to 10 mm, the $-10\,\text{dB}$ impedance bandwidth is increased from 3.2% to 3.5%, implying that there is increase in bandwidth using a conformed ground compared to a planar one.

D. Radiation Pattern and Gain

This is the plot of the far-field properties as a function of spatial co-ordinates specified by elevation angle ($\theta$) and azimuth angle ($\phi$). It is the plot of the power radiated per unit solid angle. It could be in polar, Cartesian, 2-dimensional or 3-dimensional graph.

It shows the antenna gain at different points in space as well as the antenna directivity (D). The 3-axes on the 3-dimensional are far field gains for ($\phi$, $\theta$) = (0–2$\pi$, $\pi$/2) for E-plane and ($\pi$/2, 0–2$\pi$) for H-plane [35]-[39].

Fig. 5 and Fig. 6 show the polar radiation patterns for the proposed RPPA and the CSPA for $\phi$ =0 and $\theta$= $\pi$/2 at resonance frequencies of 2.4 GHz and 2.387 GHz, respectively. These analysis show that the maximums of the main lobes for both antennas are close to 0$^\circ$. The E-plane and H-plane main lobes for the RPPA are 5.43 dBi and $-0.642$ dBi, while that of the CSPA are 4.67 dBi and 0.387 dBi. Since values of the main lobes of the E-plane and H-plane of the CSPA is closer to 0$^\circ$, it indicates the stability and proper directivity of the radiation patterns of the CSPA over the RPPA at radius of curvature 10 mm.

IV. COMPARISON OF PROPOSED ANTENNA WITH EXISTING DESIGNS

The selection of a feeding technique is a critical issue for patch antennas because it affects the patch size, return loss, VSWR, BW, and Smith chart [14], [20]. The authors chose inset feed technique because it simple to model, easy to fabricate, and easy to match in terms of impedance [20]. The importance and performance of the proposed cylindrical surrounding patch antenna have been compared with existing designs to ascertain if it is a candidate for curved surface applications as reported in literatures. The comparative analysis is shown in Table III in terms of various performance parameters of conformal patch antennas. It can be deduced from Table III that flexible substrates offer better performance parameters than non-flexible substrates as reported in...
litteratures. The proposed antenna compared to the earlier designed antennas is efficient in terms of size, return loss, and gain. Enhanced bandwidth is also a noted achievement of this design.

Table III. Comparative Analysis of the Proposed Antenna

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Substrate</th>
<th>Conformal/flexible (C/F)</th>
<th>Antenna size (mm²)</th>
<th>Resonant frequency (GHz)</th>
<th>Return loss (dB)</th>
<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[40]</td>
<td>Leather</td>
<td>Yes</td>
<td>80×80×0.2</td>
<td>2.4/3.5/4.69</td>
<td>–26 to –38</td>
<td>2.1</td>
</tr>
<tr>
<td>[41]</td>
<td>FR4</td>
<td>Yes</td>
<td>32×30.3×1.8</td>
<td>0.4/2.4 to 2.5</td>
<td>–18 to –22</td>
<td>–0.63</td>
</tr>
<tr>
<td>[42]</td>
<td>Roger’s RT Duroi 5880</td>
<td>Yes</td>
<td>200×200×0.6</td>
<td>1.8/2.4/3.5/5.8</td>
<td>–17 to –30</td>
<td>2.6/2.3/3/2</td>
</tr>
<tr>
<td>[43]</td>
<td>Flexiglass</td>
<td>NA</td>
<td>56×44×0.8</td>
<td>1.575/2.45/3.5/5.2</td>
<td>–22 to –28</td>
<td>3.55/3.93/5.02/4.86</td>
</tr>
<tr>
<td>[45]</td>
<td>Nutrielle Butadiene Rubbery</td>
<td>No</td>
<td>58×40×3.5</td>
<td>2.36 – 2.5</td>
<td>–12 to –22</td>
<td>No</td>
</tr>
<tr>
<td>[46]</td>
<td>FR4</td>
<td>No</td>
<td>30×40×1.6</td>
<td>2.4 – 2.7</td>
<td>–17 to –32</td>
<td>No</td>
</tr>
<tr>
<td>[47]</td>
<td>Roger’s RT Duroi 5880</td>
<td>Yes</td>
<td>51×35×1.57</td>
<td>1.2/1.5/2/4.3/5.8</td>
<td>NA</td>
<td>1.07/1.75/1.88/1.52/5.48</td>
</tr>
<tr>
<td>[48]</td>
<td>FR4</td>
<td>Yes</td>
<td>65×38.5×0.8</td>
<td>0.95/1.5/2.4</td>
<td>–22 to –34</td>
<td>1.2/1.2/1.3</td>
</tr>
<tr>
<td>[49]</td>
<td>Liquid Crystal Polymer (LCP)</td>
<td>Yes</td>
<td>40×22×0.1</td>
<td>2.5 – 11</td>
<td>–22 to –24</td>
<td>4.2</td>
</tr>
<tr>
<td>[50]</td>
<td>FR4</td>
<td>No</td>
<td>58×40×1.6</td>
<td>2.4/5/5.87</td>
<td>–12 to –27</td>
<td>5.2/4.8/5</td>
</tr>
<tr>
<td>This work</td>
<td>Polyimide</td>
<td>Yes</td>
<td>33.38×26.67×0.035</td>
<td>2.387</td>
<td>–23.115</td>
<td>4.67</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS AND FUTURE WORKS

In this research work, a rectangular planar patch antenna and its transformed cylindrical surrounding patch antenna have been designed and simulated. The results were analyzed at resonant frequencies of 2.4 GHz and 2.387 GHz respectively. Findings from the results show that though the CSPA resonates at a lower frequency compared to that of the RPPA, it proves to be a better candidate to handle the expectation of conformity to nonplanar geometries, which is the present interest area of patch antenna applications.

The shift in frequency is because of the effect of bending of the substrate. The CSPA has a better bandwidth compared to the RPPA. Its resonance frequency is quite high and applicable for WiMAX, LTE 1 band, satellites, weather/surface ship radars, and public bands.

Further work will involve the use of more radiating elements (arrays) to enhance antenna parameters like the bandwidth, gain, directivity and coverage.

REFERENCES


Er. Erchiega N. Umayah received his B.Eng. degree in electrical/electronic engineering (communications engineering option) from Federal University of Technology, Owerri, Nigeria in 1996, and M.Eng. degree in electrical/electronic engineering (telecommunications engineering option) from University of Benin, Benin City, Nigeria in 2005. At present, he is pursuing his Ph.D. degree in electronics engineering at University of KwaZulu-Natal, South Africa. His research interest is in antenna designs and electromagnetic. He is an academic staff at Federal University of Petroleum Resources Effurun, Nigeria and a member of Council for the Regulation of Engineering in Nigeria (COREN), Institute of Electrical and Electronics Engineers (IEEE), Nigeria Society of Engineers (NSE), International Association of Engineers (IAEng), Nigeria Institution of Electrical and Electronics Engineers (NIEEE), and Nigeria Institution of Engineering Management (NIEM).

Prof. (Dr.) Viranjay M. Srivastava received his doctorate (2012) in the field of RF microelectronics and VLSI design, Master (2008) in VLSI design, and Bachelor (2002) in Electronics and Instrumentation Engineering. He has worked for the fabrication of devices and development of circuit design. Presently, he is a faculty member in the Department of Electronic Engineering, Howard College, University of KwaZulu-Natal, Durban, South Africa. He has more than 17 years of teaching and research experience in the area of VLSI design, RFIC design, and analog IC design. He has supervised various bachelors, masters and doctorate theses. He is a senior member of IEEE, and member of IEEE-HKN, IITPSA, ACEEE and IACSIT. He has worked as a reviewer for several journals and conferences both national and international. He is author/co-author of more than 200 scientific contributions including articles in international refereed journals and conferences and also author of various such as MOSFET technologies for double-pole four throw radio frequency switch, Springer International Publishing, Switzerland, October 2013.