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

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***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 (ε_r) 3.5, permeability (μ_r) 1, and loss tangent (tanδ) 0.0027. Polyamide has been chosen because it is flexible, easily conformable to nonplanar 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 Electro-technical 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 sand-witched dielectric substrate [1], [2].

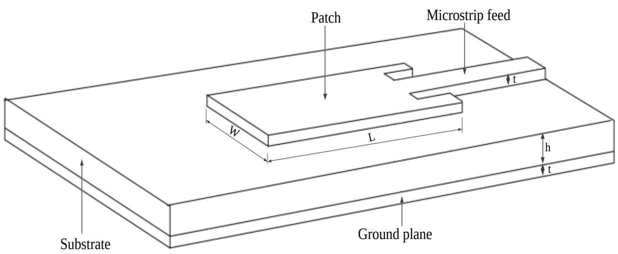

Fig. 1. Geometry of inset feed rectangular planar patch antenna.

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

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permittivity (ε_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 CSPA 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 conformable 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 (θ) 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 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 (ε_r) 3.5, permeability (μ_r) 1, and loss tangent (δ) 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 (ε_r), relative permeability (μ_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_o) of the patch [1], [26]-[28]:

$$L = \frac{\lambda_o}{2\sqrt{\varepsilon_{\text{reff}}}} - 2\Delta L \quad (1)$$

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

$$L_{\text{inset}} = \frac{L}{2\sqrt{\varepsilon_{\text{reff}}}} \quad (3)$$

$$w_f = \frac{7.47h}{e^{(x)}} - 1.25t \quad (4)$$

$$Z_o = \frac{L}{\sqrt{\varepsilon_{\text{reff}} + 1.41}} \ln\left[\frac{5.98h}{0.8w_f + t}\right] \quad (5)$$

where

$$\Delta L = 0.412h \frac{(\varepsilon_{\text{reff}} + 0.3)\left(\frac{W}{h}\right) + 0.262)}{(\varepsilon_{\text{reff}} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$\varepsilon_{\text{reff}} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2}\right)\left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}}$$

$$x = (Z_o\sqrt{\varepsilon_r + 1})/87$$

where λ_o is the free space wavelength and ε_{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 ΔL.

Thus, the effective length (L_{eff}) of the patch is given as $L_{\text{eff}}=L+2\Delta L$. The geometry of the designed planar rectangular patch antenna is shown in the upper section of Fig. 2. Table I depicts dimensions of the optimized planar patch antenna.

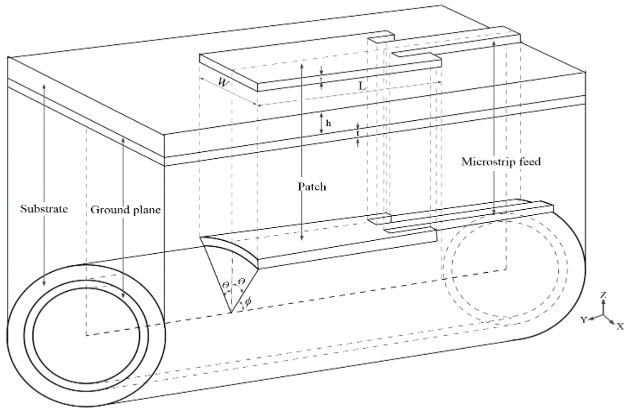

Fig. 2. Geometry of the proposed cylindrical surrounding patch antenna (RPPA transformed to CSPA).

TABLE I. DIMENSION FOR THE DESIGNED RECTANGULAR PLANAR PATCH ANTENNA

Description	Design parameter	Value (mm)
Patch	Length of patch (l_p)	33.380
	Width of patch (w_p)	26.670
	Patch thickness (t)	0.035
Substrate/Ground plane	Length of substrate/ground plane ($l_s = l_g$)	66.670
	Width of substrate/ground plane ($w_s = w_g$)	66.670
Microstrip feed	Inset feed length (l_f)	22.590
	Inset feed length (f_i)	8.346
	Inset feed Width (w_f)	2.352
Substrate	Thickness (h)	1.200
Ground plane	Thickness (t)	0.035
Patch/Microstrip feed	Gap between patch and feed (g_{pf})	1.000

C. Model of the Proposed Cylindrical Surrounding Patch Antenna

The cylindrical surrounding patch antenna (is a 360^o rotated cylindrical version of rectangular planar patch antenna) has been realized from the planar rectangular patch structure by transformation technique in which the width of the planar patch formed an arc in the H-plane of the cylindrical structure [29]-[32] and subtends an angle of 2θ at the center of the cylinder as shown in the lower section of Fig. 2.

To actualize the design of the cylindrical surrounding patch antenna, the following parameters has been considered:

1) Resonant frequency (f_r),
2) Length and width of the patch, substrate, and ground plane,
3) The inner and outer radii of the substrate, ground plane, and the patch were calculated mathematically from the width of the substrate, ground plane, and the patch respectively from

$$r_{\text{out}} = r_{\text{in}} + h \quad (6)$$

where r_{out} is the outer radius, r_{in} is the inner radius, and h is the thickness of the patch/ground plane (t) or the substrate (h).

4) Thickness of the patch/ground plane and that of the substrate,
5) Permittivity and permeability of substrate.

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):

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

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:

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

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 2θ^o at the center of the cylindrical structure. The width of the patch is calculated from (9):

$$w_p = 2\pi\theta^0/360^0 = r/\theta = r\phi \quad (9)$$

where θ^0 is angle in degrees and ϕ 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 (2θ^o) subtended by the width of the patch at the center of the cylinder is varied from 120^0 to 180^0 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.

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

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

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

$$f_r = \frac{c}{2\sqrt{\varepsilon_{\text{reff}}}}\left[\left(\frac{m}{l}\right)^2 + \left(\frac{n\theta}{r}\right)^2\right]^{\frac{1}{2}} \quad (11)$$

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$$f_r = \frac{c}{2\sqrt{\varepsilon_{\text{reff}}}}\left[\left(\frac{m}{l}\right)^2+\left(\frac{n}{r\phi}\right)^2\right]^{\frac{1}{2}} \tag{12}$$

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	Design parameter	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)

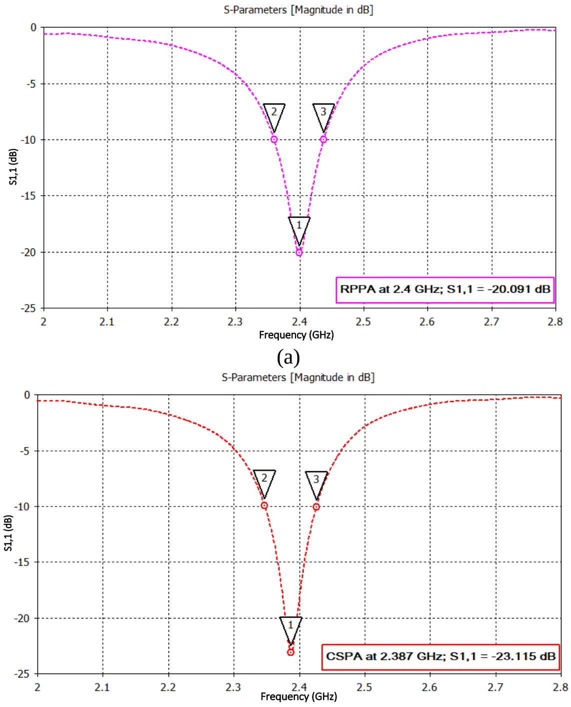
Voltage standing wave ratio is the performance parameter of an antenna that indicates the relationship between lost input energy and mismatch depicted in as [1], [28]:

$$\text{VSWR}=\left(1+|\Gamma|\right)/\left(1-|\Gamma|\right) \tag{13}$$

or

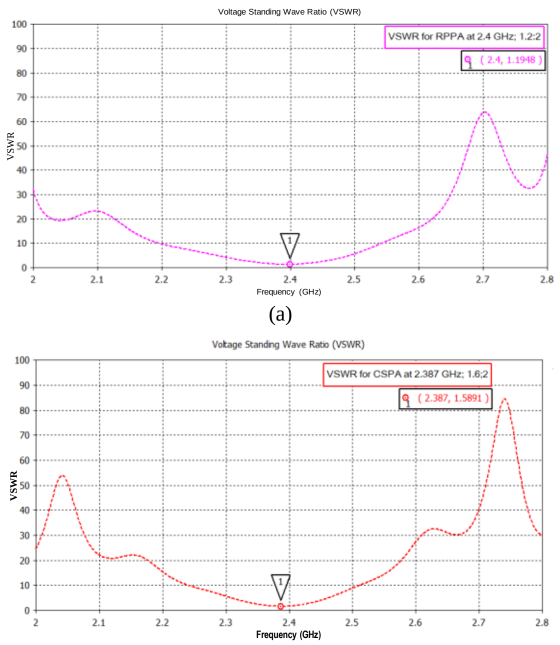
$$\text{VSWR}=\left(10\left(\frac{R_L\text{dB}}{20}\right)+1\right)\Big/\left(10\left(\frac{R_L\text{dB}}{20}\right)-1\right) \tag{14}$$

where Γ 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].



(b)

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



(b)

Fig. 4. Voltage standing wave ratio for (a) rectangular planar patch and (b) cylindrical surrounding patch antenna.

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≤VSWR≤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]:

$$\mathrm{BW} = f_h - f_l \tag{15}$$

$$B\% = (\Delta f 100\%)/f_r \tag{16}$$

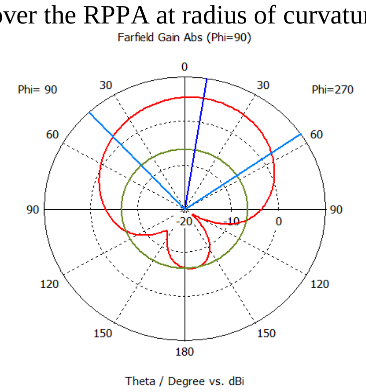
where f_h and f_L are upper resonant frequency and lower resonant frequency, respectively. The Δf and f_r are the width range of the acceptable frequencies, and the resonant frequency, respectively. The BW and B% for the antennas are shown in Fig. 3 which are 3.2% and 77 MHz for the RPPA and 3.5% and 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 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

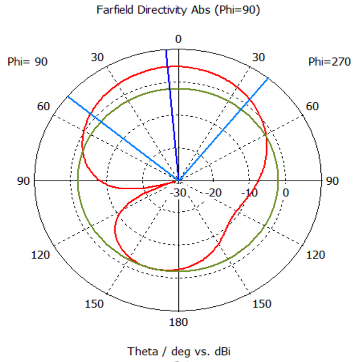
This is the plot of the far-field properties as a function of spatial co-ordinates specified by elevation angle (θ) and azimuth angle (ϕ). It is the plot of the power radiated per unit solid angle. It could be in polar, Cartesian, 2-dimensional or 3-dimensional graph.

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 (ϕ, θ) = (0–2π, π/2) for E-plane and (π/2, 0–2π) for H-plane [35]-[39].

Fig. 5 and Fig. 6 show the polar radiation patterns for the proposed RPPA and the CSPA for ϕ =0 and θ= π/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 0^0. 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 0^0, it indicates the stability and proper directivity of the radiation patterns of the CSPA over the RPPA at radius of curvature 10 mm.

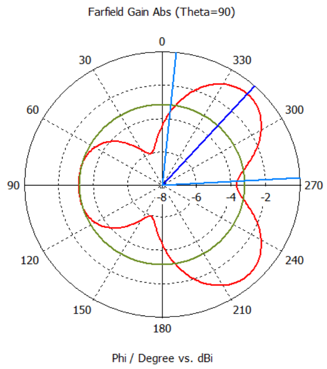


(a)

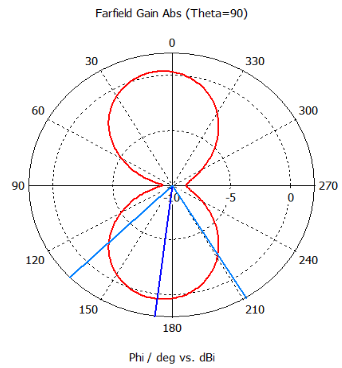


(b)

Fig. 5. Polar radiation pattern, E Plane: (a) rectangular planar patch and (b) cylindrical surrounding patch antenna.



(a)



(b)

Fig. 6. Polar radiation pattern, H Plane: (a) rectangular planar patch and (b) cylindrical surrounding patch antenna.

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 literatures. 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

Ref.	Substrate	Conformal/ flexible (C/F)	Antenna size (mm^3)	Resonant frequency (GHz)	Return loss (dB)	Gain (dBi)
[40]	Leather	Yes	80×80×2	2.4/3.51/4.69	–26 to –38	2.1
[41]	FR4	Yes	32×50.3×1.8	0.4/2.4 – 2.5	–18 to –22	–0.63
[42]	Roger's RT Duriod 5880	Yes	200×200×6	1.8/2.4/3.5/5.8	–17 to –30	2.6/2.3/3/2
[43]	Plexiglass	NA	56×44×0.8	1.575/2.45/3.5/5.2	–22 to –28	3.55/3.93/5.02/4.86
[44]	Felt		46×25×2	2.45	–15 to –31	4.48
[45]	Nutrile Butadiene Rubber	No	58×40×3.5	2.36 – 2.5	–12 to –22	No
[46]	FR4	No	30×40×1.6	2.4 – 2.7	–17 to –32	No
[47]	Roger's RT Duriod 5880	Yes	51×35×1.57	1.2/1.5/2.4/3.3/5.8	NA	1.07/1.75/1.88/1.52/5.48
[48]	FR4	No	65×38.5×0.8	0.95/1.5/2.4	–22 to –34	1.2/1.2/1.3
[49]	Liquid Crystal Polymer (LCP)	Yes	40×22×0.1	2.5 – 11	–22 to –24	4.2
[50]	FR4	No	58×40×1.6	2.4/5/5.87	–12 to –27	5.2/4.8/5
This work	Polyimide	Yes	33.38×26.67× 0.035	2.387	–23.115	4.67

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.

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