Comparative View of Return Loss, VSWR, Gain, and Efficiency of Cylindrical Surrounding Patch Antenna with Frequency Shift

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***Abstract*—In this research work, the return loss (*S*-parameter, S_{11}), Voltage Standing Wave Ratio (VSWR), gain, and efficiency of a compact and flexible Cylindrical Surrounding Patch Antenna (CSPA) have been derived from Rectangular Planar Patch Antenna (RPPA) for applications in the Industrial, Scientific and Medical (ISM) frequency band. For ease of bending, the radiating patch was stablished on surface of the cylindrical substrate (ploymide) of thickness 1.2 mm. It is flexible and has permittivity (ε_r) 3.5, permeability (μ_r) 1, and loss tangent (tanz_1) 0.0027. The RPPA was made conformal into cylindrical shapes at an angle of 90° and radius of curvature (*r*) ranging from 10 mm to 35 mm in steps of 5 mm to achieve the best return loss and gain. Results for the optimal performance parameters have been presented for CSPA and RPPA at 2.371 GHz and 2.4 GHz, respectively. Results show that for the CSPA S_{11}, VSWR, and gain are −17.734 dB, 1.2984, and 4.52 dBi, respectively (with better angular coverage) compared to RPPA which has −11.969 dB, 1.6741, and 5.74 dBi, respectively.**

***Index Terms*—conformal patch antennas, cylindrical surrounding patch antenna, ISM application, radiation pattern, return loss**

I. Introduction

In recent years, patch antennas have witnessed tremendous interest from researchers and the industry for flexible antennas and electronics. It has been estimated from market analysis that revenue from flexible electronics is 30 Billion USD in 2017 and will be more than 300 Billion USD in 2028 [1]. For over three decades, planar patch antennas have been applied extensively in various communication systems because of their lightweight, low profile, compactness, economic efficiency, and conformability to any structure. Their applications are however limited because of their rigid planar geometries, low gain, narrow impedance bandwidth, and poor angular coverage [2]-[4]. However, these limitations have driven the need for conformal (flexible) antennas [5], [6].

Conformal (non-planar) patch antennas (CPAs) are transformed versions of planar patch antennas (PPAs) that are applicable to surfaces (geometries) which may be cylindrical, conical, or spherical [3]. Though planar and conformal patch antennas share some common advantages (low profile, light weight, mechanically robust on host surfaces, versatile in terms of polarization, cheap to fabricate with modern printed circuit technology) conformal patch antennas are the focus of recent research and applications [2], [3], [7]-[9]. Conformal patch antennas are preferred to their planar patch counterparts because they exhibit versatile performance parameters such as better bandwidth, gain, directivity, omini-directionality, enhanced integrated non-obstructive designs, reduced aerodynamic drag, and good azimuth coverage [1], [3], [8], [10]-[12].

The conformal patch antennas suitable for 2.4 GHz industrial, scientific and medical (ISM) applications (in wireless applications). Different designs of varied configurations and feed type have been proposed. Lee *et al*. [13] have presented an omnidirectional multiband antenna system on a substrate size $200\times200\times6$ mm^3. Although this antenna has a good return loss between −17 dB to −30 dB, it has poor directivity of 2.3 dB, and bulky in size. Rao [14] has proposed a $51\times35\times1.57$ mm^3 penta-band antenna for vehicular communication. The problem with this antenna is its poor directivity of 1.88 dB. Similarly, Mulla and Deshpande [15] have proposed a $65\times38.5\times0.8$ mm^3 multi-band antenna for improvement of impedance matching. Though the antenna is very compact in size, it has a poor directivity of 1.3 dB.

Finally, Xu *et al*. [16] have presented a multiband fractal antenna of $58\times40\times1.6$ mm^3 size. This antenna has maximum directivity of 4.8 dB, and S_{11} −12 dB to −27 dB. However, this antenna is not very compact and flexible. From this review, it has been observed that, some antennas have attractive return loss and good directivity with drawbacks in terms of poor size or combination of poor return loss/directivity/size, which makes them unsuitable for conformal applications. The cylindrical surrounding patch antenna proposed in this research work is very compact and has been designed by using polyimide substrate of $40.33\times48.90\times1.2$ mm^3 ($33.10\times41.70\times0.035$ mm^3 patch size) for 2.4 GHz frequency band applications.

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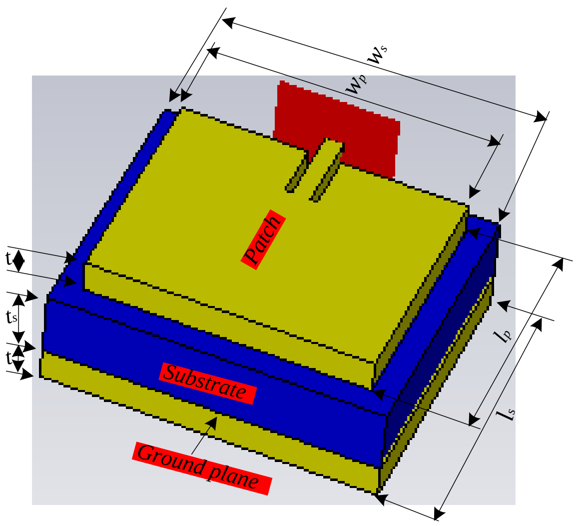
In general, the antenna performance is adversely affected by the mechanical bending of the structure. It changes the resonant frequency (f_r), return loss (S_{11}), radiation pattern, bandwidth (BW), and voltage standing wave ratio (VSWR) of the antenna. The conformal antenna designs are capable to circumvent the performance degradation, if the bendability parameters such as the curvature radius (r), bending angle (θ), and substrate thickness (t_s) are critically considered [8]-[10]. Various physical parameters and dimensions of the antennas have been presented in Fig. 1. The polyimide material, which features smoother machining, excellent dimensional stability, low coefficient of thermal expansion, and high resistance to the crack [17]-[20], has been used as the flexible substrate for the antenna design in this work.

Cylindrical Surrounding Patch Antennas (CSPA) find applications in radars, vehicles, mobile equipment, space/satellite ships and modern flexible electronic devices [21]-[24]. In this research work, authors proposed a conformal antenna, i.e. cylindrical surrounding patch antenna on polyimide substrate for 2.4 GHz ISM frequency band. The results of simulations for the Rectangular Planar Patch Antenna (RPPA) and the CSPA have been analyzed in terms of return loss (S_{11}), Voltage Standing Wave Ratio (VSWR), and total efficiencies.



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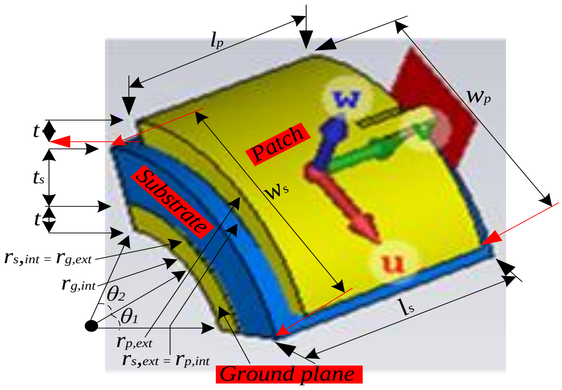


(b)

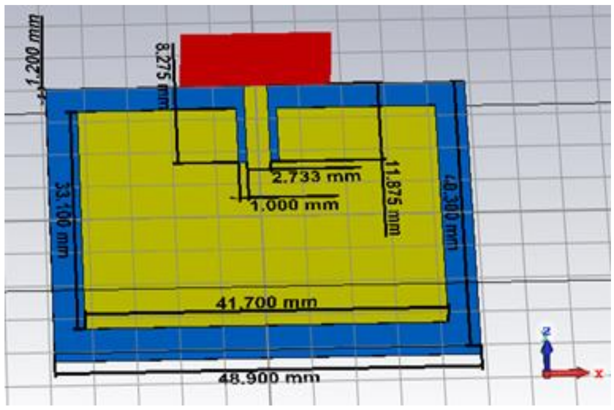
Fig. 1. Parametrs observation for (a) planar patch and (b) designed circular patch.

This research work is organized as follows. Section II presents the designed and optimized CSPA for 2.4 GHz. In Section III, the analysis of various parameters is presented. Finally, Section IV concludes the work and recommends the future aspects.

II. Modelling of the Proposed Cylindrical Surrounding Patch Antenna

The proposed CSPA (Fig. 2 (b)) is a rotatory version of RPPA (Fig. 2 (a)), which was initially designed and thereafter conformed on the cylindrical substrate. To achieve the proposed conformal antenna, polyimide substrate is chosen for the design of the antenna because it is flexible, mechanically robust, and thermally stable [2], [12], [13]. The antenna is designed on 1.2 mm thick polyimide substrate with permittivity (ε_r) 3.5, permeability (μ_r) 1, and loss tangent (tan z) 0.0027. The dimensions of the length and width of the antenna are obtained from transmission line method [2], [9], [22]. The patch width (w_p) is expressed as

$$\begin{aligned} w_p &= \frac{c}{2 f_r \sqrt{\dfrac{\varepsilon_r + 1}{2}}} \\ &= \frac{3\times10^8}{\left(2\times2.4\times10^9\right)\sqrt{\left(\dfrac{3.5+1}{2}\right)}} \\ &= 41.7 \text{ mm} \end{aligned} \tag{1}$$



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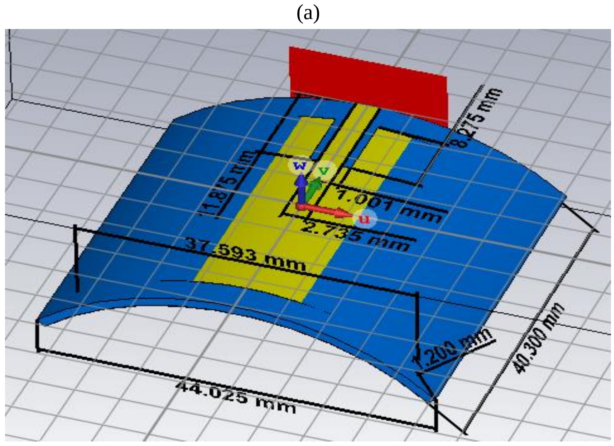


(b)

Fig. 2. Geometry of (a) rectangular planar patch antenna (RPPA) and (b) cylindrical surrounding patch antenna (CSPA).

where f_r and ε_r are the resonant frequency and permittivity of the substrate (3.5), respectively and c is the velocity of light in free space (3×10^8 m/s). Patch antennas radiate due to fringing fields between the edges of the patch and the ground plane [25]. Fringing field depends on the dimensions of the patch and the thickness of the substrate. The greater the fringing field, the higher the substrate. As shown in Fig. 3, fringing field makes the length of the patch to look electrically longer on both sides by a factor of $2\Delta l$. Thus, fringing field affects the performance of a patch antenna [25]. The waves that travel both in the air and in the substrate due to fringing field introduces an effective permittivity (ε_{reff}) as:

$$\begin{aligned}\varepsilon_{reff} &= \left(\frac{\varepsilon_r+1}{2}\right)+\left(\frac{\varepsilon_r-1}{2}\right)\left(1+\frac{12t_s}{w_p}\right)^{-\frac{1}{2}}\\ &= \frac{(3.5+1)}{2}+\frac{\left(\frac{3.5-1}{2}\right)}{\sqrt{\left(1+\frac{12\times1.2}{41.7}\right)}}\\ &= 3.33\end{aligned} \tag{2}$$

where t_s and w_p are the thickness of substrate and width of path, respectively. The length extension of the patch (Δl) depends on the effective permittivity and thickness of the substrate. Thus, the effective length (l_{eff}) of the patch is given as $l_{eff} = l_p + 2\Delta l$. Using substrate of 1.2 mm, the effective length of the patch (l_{eff}) and length extension (Δl) are

$$\begin{aligned}l_{eff} &= c/2f_r\sqrt{\varepsilon_{reff}}\\ &= \frac{3\times10^8}{\left(2\times2.4\times10^9\right)\sqrt{3.33}}\\ &= 34.3 \text{ mm}\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta l &= 0.412t_s\frac{\left(\varepsilon_{reff}+0.3\right)\left(\frac{w_p}{t_s}\right)+0.262)}{\left(\varepsilon_{reff}-0.258\right)\left(\frac{w_p}{t_s}+0.8\right)}\\ &= 0.412\times1.2\left[\frac{(3.33+0.3)\left(\frac{41.7}{1.2}+0.264\right)}{(3.33-0.258)\left(\frac{41.7}{1.2}-0.8\right)}\right]\\ &= 0.603 \text{ mm}\end{aligned} \tag{4}$$

Also, the inset feed length is given as

$$l_{inset} = \frac{l_p}{2\sqrt{\varepsilon_{reff}}} = \frac{33.1}{5.47} = 6.05 \text{ mm} \tag{5}$$

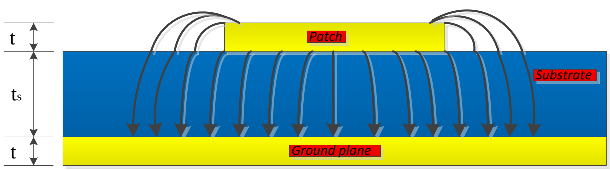


Fig. 3. Electric field lines.

Finally, the actual length of patch (l_p), length of substrate (l_s) and width of substrate (w_s) are

$$\begin{aligned}l_p &= l_{eff}-2\Delta l = 34.3-2\times0.603 = 33.1 \text{ mm}\\ l_s &= 6t_s+l_p = 6\times1.2+33.1 = 40.3 \text{ mm}\\ w_s &= 6t_s+w_p = 6\times1.2+41.7 = 48.9 \text{ mm}\end{aligned} \tag{6}$$

All the physical dimensions of the RPPA are shown in Table I. The microstrip feed is matched to 50 Ω excitation source and is placed at an offset optimized position from the centre of the rectangle to generate improved performance characteristics such as return loss of less than −10 dB, better gain/coverage, radiation pattern, efficiency, and directivity.

TABLE I. PHYSICAL DIMENSIONS OF THE RECTANGULAR PLANAR PATCH ANTENNA

Parameter	Value (mm)
Length of Patch (l_p)	33.100
Width of Patch (w_p)	41.700
Length of Substrate (l_s)	40.330
Width of Substrate (w_s)	48.900
Length of microstrip feed line (l_f)	11.875
Thickness of Substrate (t_s)	1.200
Width of microstrip feed line (w_f)	2.733
Patch thickness (t)	0.035
Inset feed length (f_i)	8.275
Gap between Patch and microstrip feed line (g_{pf})	1.000

To bend the RPPA into a cylindrical shape (CSPA), the radius of curvature (r) and the bending angle (θ) were considered. As has been reported in literature, these parameters, affects antenna performance parameters such as: return loss, gain, voltage standing wave ratio, efficiency, radiation pattern and angular coverage [3], [26]. In this research work, the antenna structure has been bent along the H-plane (width direction). It has been assumed that the widths of substrate and the patch formed arcs as shown in Fig. 2. This implies that the widths of the substrate is equal to the length of an arc (p) given as

$$p = 2\pi r\frac{\theta_1+\theta_2}{360} \tag{7}$$

where r is the radius of the arc formed by the widths of the substrate and the patch at the center of the cylindrical structure. The arc formed subtends an angle $\pi/2$ radian at the centre of the cylinder. Substituting w_s=48.9 mm, authors obtained a radius of curvature (r) of 31.15 mm at a bend angle of 90°. It has been reported in literature that impedance bandwidth decreases with increase in radius of curvature (r) of the substrate. Similarly, decreasing radius (r) of the cylindrical surface results to improved impedance bandwidth [3], [26]. The internal and external radii of the substrate and the patch are obtained mathematically as

$$\begin{aligned}&r_{s,ext} = r_{s,\text{int}}+t_s,\ r_{p,ext} = r_{p,\text{int}}+t\\ &r_{g,ext} = r_{g,\text{int}}+t,\ r_{s,\text{int}} = w_s/2\pi\\ &r_{p,\text{int}} = w_p/2\pi,\ r_{g,\text{int}} = w_g/2\pi\end{aligned} \tag{8}$$

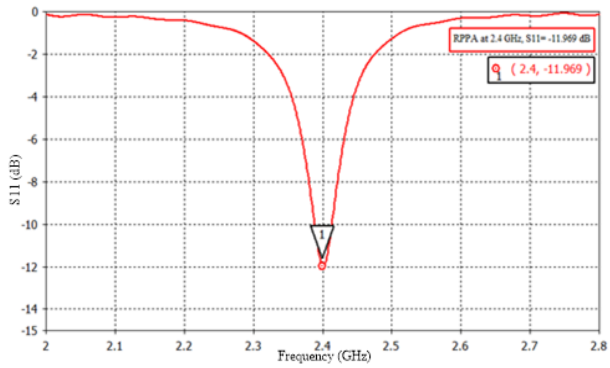
where r_{ext} and r_{int} are the external radius and internal radius, respectively. Table II depicts the physical dimensions of the CSPA. The radius of curvature was optimized (varied) from 10 mm to 35 mm in steps of 5 mm to obtain best performance parameters of the antenna. The best performance parameters were obtained at an angle of $\pi/2$ radian and curvature radius of 10 mm.

TABLE II. DIMENSIONS FOR THE PROPOSED CYLINDRICAL SURROUNDING PATCH ANTENNA

Component	Design parameter	Value (mm)
Ground plane	Internal radius (r_1)	7.790
	External radius (r_2)	7.820
	Thickness (t)	0.035
Substrate	Internal radius (r_2)	7.820
	External radius (r_3)	9.020
	Thickness (t_s)	1.200
Patch	Internal radius (r_3)	9.020
	External radius (r_4)	9.060
	Thickness (t_p)	0.035

III. PARAMETRIC ANALYSIS

This section presents the results for the rectangular planar patch antenna and the cylindrical surrounding patch antenna. The results validate that radius of curvature has effect on the performance parameters as evident in the resonant frequency and gain of cylindrical surrounding patch antenna [23], [26]-[29]. In Fig. 2 (b), the width of the cylindrical surface changed from 48.900 mm to 44.025 mm, which indicates 9.96% change (reduction) in the width of the CSPA at 90° angle of curve (bend) and 10 mm curvature radius.



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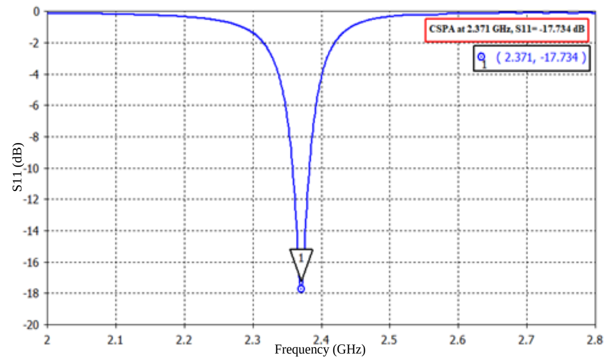
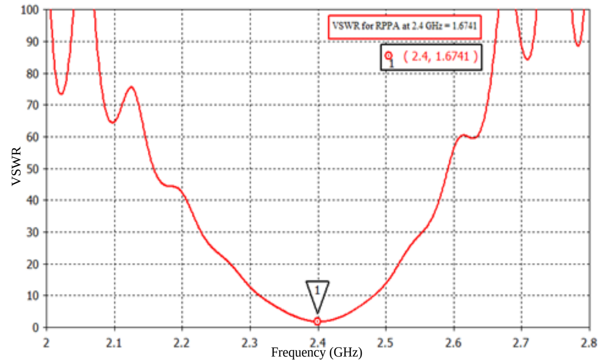


(b)

Fig. 4. Return loss of (a) rectangular planar patch antenna and (b) cylindrical surrounding patch antenna.

Fig. 4 (a) and Fig. 4 (b) show return loss (S_{11}) for the rectangular planar patch antenna (–11.969 dB at 2.4 GHz) and for the cylindrical surrounding patch antennas (–17.734 dB at 2.371 GHz), respectively. This indicates that there is maximum power transfer from the excitation source to the antenna (load) and thus maximum transmission of signals.

Fig. 5 (a) and Fig. 5 (b) show that the voltage standing wave ratio for the rectangular planar patch antenna (1.6741:2 at 2.4 GHz) and for cylindrical surrounding patch antenna (1.2984:2 at 2.371 GHz), respectively. These values indicate a good match of the feed line and the antennas since the values are less than 2. However, standing wave is much more reduced in the case of the cylindrical surrounding patch antenna compared to the rectangular planar patch antenna.



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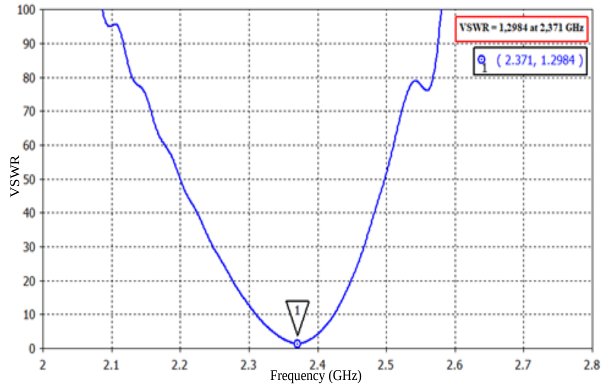
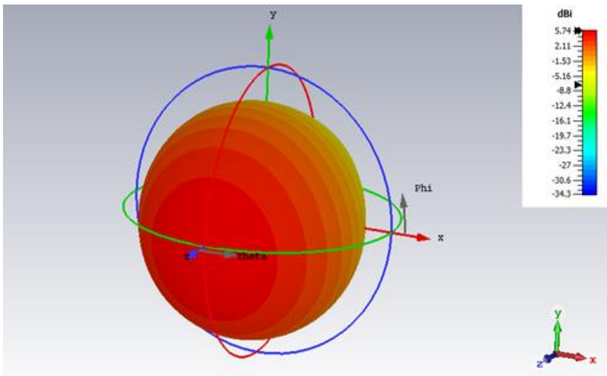


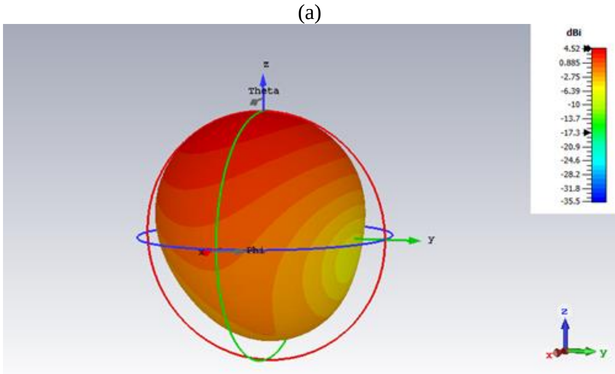
(b)

Fig. 5. Voltage standing wave ratio of (a) rectangular planar patch antenna and (b) cylindrical surrounding patch antenna.

Fig. 6 (a) and Fig. 6 (b) shows that the gain for the rectangular planar patch antenna and the cylindrical surrounding patch antenna are 5.74 dBi and 4.52 dBi, respectively. Though the rectangular planar patch has a higher gain because it is directional, the low gain from the cylindrical surrounding patch antenna is due to bending effect. The gain of the cylindrical surrounding patch antenna is still within acceptable limits that guarantees reliable signal transfer. In Fig. 7, the CSPA exhibits total efficiency of –4.635 dB at 2.371 GHz while the RPPA displays –1.724 dB at 2.4 GHz. Though the RPPA has a better total efficiency, the efficiency of the cylindrical surrounding patch antenna is optimal (stable at the resonant frequency of 2.371 GHz).



(a)



(b)

Fig. 6. Gain of (a) rectangular planar patch antenna and (b) cylindrical surrounding patch antenna.

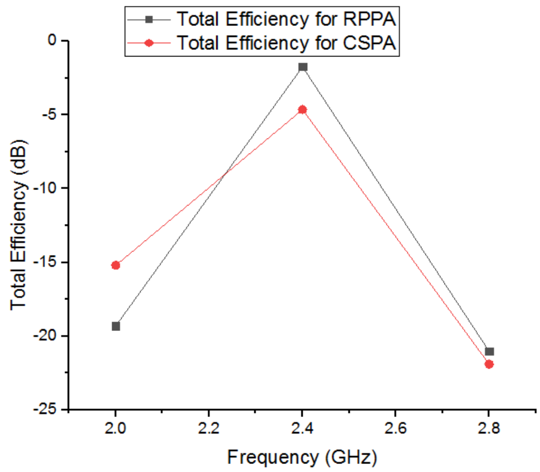


Fig. 7. Total efficiency comparison of RPPA and CSPA.

The design shows that the proposed cylindrical surrounding patch antenna is very compact in size and exhibits good return loss, higher bandwidth, and angular coverage in the ISM 2.4 GHz frequency band. The higher bandwidth of the cylindrical surrounding patch antenna is also evident from the graphs shown in Fig. 4 (a) and Fig. 4 (b).

IV. Conclusions and Future Aspects

The designed and simulated rectangular planar patch antenna has been conformed on a cylindrical surface at a radius of curvature of 10 mm with bending angle of 90° for best return loss and directivity. The shift in frequency of the CSPA from the designed 2.4 GHz to 2.371 GHz is due to bending of the substrate. Improved return loss and angular coverage have been observed for the cylindrical surrounding patch antenna compared to the rectangular planar patch antenna. The CSPA offers improved bandwidth and omnidirectional patterns compared to its planar counterpart.

The proposed CSPA is very compact and flexible with attractive return loss and directivity, and is thus suitable for LTE1 band applications. The antenna is also a preferred structure for vehicular communication systems with minimum risk of RF exposure. Future aspects will involve the use of arrays (more radiating) elements to enhance antenna parameters such as directivity, bandwidth, angular coverage, and gain.

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