Characterization of Flexible Patch Antennas on Planar and Curved Surfaces

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Abstract. This paper analyses patch antennas operating at 16 GHz on flexible Kapton polyimide substrate in various shapes, namely rectangular, circular, pentagon, hexagon, heptagon, and octagon. Their applications in medical areas, more particularly in wearable devices for E-health, are targeted. The bending effects of these antennas are studied, more specifically on gain, return loss, radiation characteristics, bandwidth, and beamwidth. A detailed comparison results showed that the rectangular patch had better performance even under the bending when the diameter of the surface is varied from 40mm to 120mm and maintains a gain of 4.8 dB at the given frequency. Under such extreme bending, the antennas operate satisfactorily with an efficiency of 43.424\% to 47.41\%.

1. Introduction

There has been growing interest among researchers in the field of flexible electronics [1,2,3]. Essentially, it has evolved from the printed circuit technology and established itself to satisfy today's modern-day, where tightly configured electronic packages are required while still maintaining stable operation. The antennas used in these applications are developed on flexible substrates, which are critical for integrating sensors in packaging to communicate with wireless communication systems. These antennas utilize various substrates materials, including bandages, and textile fabrics, with their resonant frequency remaining unchanged even after bending, twisting, or stretching [4].

Several techniques are evolved for flexible antenna developments [4,5] due to their lightweight and low cost [6,7]. Such advances are experiencing exponential growth due to various potential requirements for wearable devices, the internet of things (IoT), wireless power transfer (WPT), personalized medicine platform, upcoming 5G technology, emerging wireless sensor networks, and excessive demands for miniaturized communication devices. Some of these potential applications are shown in Figure 1. Furthermore, these antennas allow communication with the existing wireless technology using specified frequency bands. The frequency of operation of the flexible antennas depends on several factors; also, their efficiency depends on materials used in the substrate and the surrounding environment, all influence the choice of adjustable or flexible antennas [7,8,9]. Apart from antennas, capacitors, transistors, and inductors are among other enabling components that must satisfy requirements like lightweight and cheap and compatible with flexible electronic systems, typically developed on substrates like paper, fabrics, and plastics [11,12]. Since the radiation characteristics of the antennas are severely affected by substrate deformation, therefore antenna is the most vulnerable to a performance loss when developed on flexible substrates [13]. As a result, it is crucial to examine how the antenna's performance changes when formed on the flexible substrate.
Since microstrip antennas possess many advantages, including compact structure, they quickly installed even when the surface is curved and provides easy prototyping using planar PCB technology. Therefore, various patch antennas have been designed on Kapton Polyimide Substrate in this work, and their performances like gain, directivity, radiation efficiency, and reflection coefficient are investigated for wireless body area network application. Furthermore, this paper discusses the influence of bending on patch antennas' performances compared to when the antenna is developed on the planar surface. Although multi-band antennas are reported [14,15], their flexibility aspect is not verified, which is discussed in detail in this work.

2. Design methodology

A dielectric separates two thin metallic layers in a microstrip antenna. The top metallic layer works as a radiating patch, while the bottom metallic layer serves as a ground, with a dielectric substrate in between the two layers. Usually, copper and gold are utilized as metallic radiating layers due to their high conductivity [16]. Simple shapes for the patch are preferred, which can be of any type, e.g., square, triangular, and circular, as the theoretical models are easy to develop—a variety of feeding techniques available to feed the patch antennas coaxial or stripline.

There has been limited research on Kapton Polyimide Substrate antennas and their comparison with the planar counterparts. Furthermore, the current study compares different regular forms of the patch antennas on both planar and curved surfaces. However, the antennas are developed on rigid substrates in circular, pentagonal, hexagonal heptagonal, and octagonal shapes [17,18,19]. Among all them, rectangular patch antennas provide improved performance in both planar and curved surfaces, which is further investigated by considering the different amounts of bending by varying the diameters surfaces from 40 to 120 mm. Various parameters like directivity, reflection coefficient, efficiency, and gain are used to characterize the patch antenna's performances.

Furthermore, these parameters are theoretically estimated using conductivity and patch dimension and the feeding mechanism and substrate material used. The proposed antenna is designed on a flexible Kapton Polyimide Substrate, and modeled using the transmission line. A full-wave electromagnetic analysis like the finite element technique (FEM) is carried out to generate different results.

2.1. Rectangular microstrip patch antenna (RMSPA) design

The length (L) and width (W) of the proposed RMSPA are described in detail in [16]. An RMSPA is usually of size $\lambda/2$ at the operating wavelength, as shown in Figure 2 [16,20]. The length of inset patch ($y_0$) in Figure 2 is computed using Eq. (1) so that the patch's input impedance is equal to the feed line's characteristic impedance which is 50 $\Omega$.

$$R_{\text{Input}}(y = y_0) = R_{\text{Input}}(y = 0) \cos^2 \left( \frac{\pi}{L} y_0 \right)$$

where, $R_{\text{Input}}(y = 0)$ is the input impedance at the leading radiating edge of the Patch and $R_{\text{Input}}(y = y_0)$ is the characteristic input impedance of 50 $\Omega$.

![Figure 1. Various application areas of Flexible](image-url)
2.2. Circular microstrip antenna (CMSA) design

A circular microstrip antenna (CMSA) is another widely used configuration [20]. It’s designed and developed using the cavity model, which provides a reasonable circular-size microstrip antenna. The procedure involves assuming that the dielectric constant of the substrate $\varepsilon_{\text{sub}}$, resonant frequency $f_0$, and substrate height $h$. Knowing these parameters allows calculating of the radius of CMSA using the Eq. (2) and (3), which eventually determines the effective radius ‘$a_e$’ for efficient radiation. The CMSA with an effective radius has achieved good gain, radiation pattern, bandwidth, return loss, and radiation parameters [17,21].

$$a = \frac{F}{1 + \frac{2h}{\pi \varepsilon_{\text{sub}} F \left[ \ln \left( \frac{\pi F}{2h} \right) + 1.7726 \right]^{1/2}}$$ (2)

$$F = \frac{8.791 \times 10^9}{f_0 \sqrt{\varepsilon_{\text{sub}}}}$$ (3)

Where ‘$a$’ is the radius of the circular patch. Further, the fringing phenomenon makes the patch appear electrically larger, which is accounted for by taking a correction in length in the case of the rectangular patch [20]. Similarly, a correction is made for the circular patch by using an effective radius ‘$a_e$’ to replace the actual radius ‘$a$’, and expressed as follows

$$a_e = \frac{1.8412 c}{2 \pi f_0 \sqrt{\varepsilon_{\text{sub}}}}$$ (4)

Where, $f_0$ = resonant frequency, $c$ = velocity of the light in free space and $\varepsilon_{\text{sub}}$ = relative permittivity of the substrate.

The value of the effective dielectric constant ($\varepsilon_{\text{eff}}$) is calculated as

$$\varepsilon_{\text{eff}} = \frac{1}{2} (\varepsilon_{\text{sub}} + 1) + \frac{1}{4} \frac{(-1)}{\sqrt{(1+2h/a)}}$$ (5)
2.3. Other regular geometries for the patch design

In other geometries patches, like pentagonal, hexagonal, heptagonal, and octagonal, the side length 'S' is determined using Eqs. (6) - (7).

\[
\text{Area} = \frac{S^2 N}{4 \tan\left(\frac{\pi}{N}\right)}
\]  

(6)

For example, to calculate the arm side of the hexagonal patch, the relationship between the equivalent areas of the circular and hexagonal patches are equated as given below [18].

\[
\pi a_e^2 = \frac{3\sqrt{3}}{2} S^2
\]

(7)

where \( S \) = sides of a regular hexagonal patch antenna and \( a_e \) = Effective radius of the circular patch antenna.

Optimization of antenna parameters is carried out to improve the performance of the patch antennas. For example, suppose the return loss is achieved at a slightly higher frequency using the design parameters. In that case, these are further optimized to ensure the antenna resonates at the operating frequency. Similarly, if the return loss is more than -10 dB, a slight change in the inset feed point to get input impedance matched 50 \( \Omega \) for better flow of power into the antenna.

3. Comparisons of designed and optimized parameters for simulation

Summary of various calculated parameters for the patch antennas in each case using the formulae described in sections 2.1 and 2.2 are given in Tables 1 to 6. The computed values are further optimized using HFSS (High-Frequency Structure Simulator) [22] to achieve the best reflection coefficient at the operating frequency of 16 GHz in different categories of the patch antennas. The corresponding patch antennas structure in each case, both on planar and curved surfaces, are provided in Figures (4) to (9).

| Table 1. Antenna design dimensions for rectangular microstrip patch antenna (RMSPA). |
|---------------------------------|-----------------|-----------------|
| Antenna dimensions             | Calculated       | Optimized       |
| Patch length \( L \)           | 5.209 mm         | 5.151 mm        |
| Patch Width \( W \)            | 6.469 mm         | 6.7 mm          |
| Feed Length \( LF \)           | 2.935 mm         | 2.9 mm          |
| Feed Width \( Wo \)            | 0.305 mm         | 0.305 mm        |

| Table 2. Antenna design dimensions for circular microstrip patch antenna (CMSPA). |
|---------------------------------|-----------------|-----------------|
| Antenna dimensions             | Calculated       | Optimized       |
| Effective patch radius \( a_e \)| 3.0714 mm        | 3.07 mm         |
| Feed Length \( LF \)           | 2.9 mm           | 2.9 mm          |
| Feed Width \( Wo \)            | 0.305 mm         | 0.305 mm        |

| Table 3. Antenna design dimensions for a pentagonal patch. |
|---------------------------------|-----------------|-----------------|
| Antenna dimensions             | Calculated       | Optimized       |
| Arm side \( S \)               | 4.14 mm          | 4.07 mm         |
| Feed Length \( LF \)           | 2.9 mm           | 2.9 mm          |
| Feed Width \( Wo \)            | 0.305 mm         | 0.304 mm        |

| Table 4. Antenna design dimensions for a hexagonal patch. |
|---------------------------------|-----------------|-----------------|
| Antenna dimensions             | Calculated       | Optimized       |
| Arm side \( S \)               | 3.37 mm          | 3.39 mm         |
| Feed Length \( LF \)           | 2.935 mm         | 2.9 mm          |
| Feed Width \( Wo \)            | 0.305 mm         | 0.304 mm        |
Table 5. Antenna design dimensions for a heptagonal patch.

| Antenna dimensions          | Calculated dimensions(mm) | Optimized dimensions(mm) |
|-----------------------------|---------------------------|--------------------------|
| Arm side S                  | 2.854                     | 2.846                    |
| Feed Length LF              | 2.935                     | 2.9                      |
| Feed Width W0               | 0.305                     | 0.304                    |

Table 6. Antenna design dimensions for an octagonal patch.

| Antenna dimensions          | Calculated dimensions(mm) | Optimized dimensions(mm) |
|-----------------------------|---------------------------|--------------------------|
| Arm side S                  | 2.47                      | 2.84                     |
| Feed Length LF              | 2.935                     | 2.9                      |
| Feed Width W0               | 0.305                     | 0.304                    |

Figure 4. (a) Planar rectangular Patch, (b) Bent rectangular Patch on a cylinder of Diameter 60 mm.

Figure 5. (a) Planar circular patch, (b) Bent Circular patch on a cylinder of Diameter 60 mm.

Figure 6. (a) Planar pentagonal Patch, (b) Bent pentagonal Patch on a cylinder of Diameter 60 mm.
4. Performance investigations under plane surface

Various performances in each case of the patch antenna are generated using the HFSS [22], and results are discussed in the following sections.

4.1. Reflection coefficient

The patch antennas in various configurations observe to provide resonance at 16 GHz, which can be noticed from the reflection coefficient S11 plotted in Fig. 10. The reflection coefficient in each case was found well below -24 dB. However, the heptagonal patch shows poor S11 (See Fig. 10), and the corresponding bandwidth is inferior compared to other shapes of the patch antennas. Furthermore, analysing the voltage standing wave ratio (VSWR) (See Fig. 11) in each case indicates its value lies between 1.0 to 2.0, confirming the excellent performance of the antennas developed in this work.

4.2. Gain

The gains in X-Z, i.e., \( \phi = 0^\circ \) and Y-Z planes, i.e., \( \phi = 90^\circ \) are plotted in Figures 12 and 13, and their corresponding value in rectangular plots are shown in Figures 14 and 15, respectively. The highest gain achieved is 4.8dB for the rectangular Patch (See red colour), which is better than the gain in [23]
which was 4.8dB, whereas the least gain of 4.4 dB for the circular patch (See cyan colour). The difference in gains for different patches other than the rectangular patch is minimal because all other patches occupied roughly the same area, whereas the rectangular patch possesses more effective area and thus more gain and high efficiency [24-26].

![Figure 10. Return loss comparison of different planar patch.](image1)

![Figure 11. VSWR plot for different planar patch](image2)

![Figure 12. Gain plot for X-Z Plane with $\phi = 0^\circ$.](image3)
Figure 13. Gain plot for Y-Z Plane with $\phi = 90^\circ$.

Figure 14. Rectangular Gain plot for X-Z Plane.

Figure 15. Rectangular Gain plot for Y-Z with $\phi = 0^\circ$, Plane with $\phi = 90^\circ$

A summary of various antenna performances is given in Table 7 for easy comparisons for different types of patch antennas. As observed from Table 7, the rectangular patch antenna provides relatively high performance compared to other shaped antennas. However, a circular patch, which provides the highest bandwidth, is suitable for applications where requirement bandwidth is high. Similarly, the pentagonal patch has a very narrow HPBW and its suitability for more directive applications.
5. Performance investigations under curved surface

The details of the antennas discussed in Section 3 in the unit configuration on the bent cylindrical surface having a radius of 30mm, and various performances are investigated.

5.1. Reflection coefficient

As shown in Fig 16, the resonant frequency is shifted significantly, particularly in the circular and hexagonal patches. However, for all other patch shapes, the resonating frequency remains at 16 GHz. Furthermore, the bending has lowered the reflection coefficient for all the patches, indicating less power flowing into the antennas. The remaining powers are returned in most of the cases except the rectangular patch, where the reflection coefficient remains well below -10dB, as shown in Figure 16.

![Figure 16. Return loss comparison of different planar patch.](image1)

![Figure 17. Gain plot for X-Z Plane with $\phi = 0^\circ$.](image2)

| Antenna Parameters   | Rectangular | Pentagon | Hexagon | Heptagon | Octagon | Circular |
|----------------------|-------------|----------|---------|----------|---------|----------|
| Reflection Coefficient | -45.0734    | -26.2303 | -27.1739 | -20.5605 | -36.8201 | -24.9383 |
| Bandwidth (MHz)       | 220         | 220      | 210     | 190      | 230     | 230      |
| Gain ($\theta = 0^\circ$) | 4.8007     | 4.4920   | 4.433   | 4.4078   | 4.3382  | 4.4025   |
| Directivity           | 6.5397      | 6.4869   | 6.2954  | 6.3251   | 6.1972  | 6.3125   |
| 3-dB Beamwidth        | 74.88°      | 73.45°   | 76.08°  | 74.98°   | 77°     | 75.89°   |
| Radiation Eff. (%)    | 46.187      | 43.3736  | 44.094  | 43.635   | 43.824  | 43.689   |

Table 7. Antenna parameters for different planar patch shapes
5.2. Gain
The gains plot with $\phi = 0^\circ$ (X-Z plane) and $\phi = 90^\circ$ (Y-Z plane) are shown in Fig. 17 and Fig. 18, respectively. The corresponding rectangular plots are shown in Fig. 19 and Fig. 20, suggesting the highest gain for the rectangular and the lowest for the circular patch when bending is incorporated. For other patches, e.g., pentagonal, hexagonal, heptagonal, and octagonal, the difference in gains is minimal. Because all other patches have approximately the same area, while rectangular patch has the highest effective radiating surface area and hence high gain is achieved. Furthermore, the peak gain in the case of the circular patch is shifted from $\phi = 0^\circ$ to $\phi = 210^\circ$ in the X-Z plane and $\phi = 0^\circ$ to $\phi = 130^\circ$ in the Y-Z plane.

Figure 18. Gain plot for Y-Z Plane with $\phi = 90^\circ$.

Figure 19. Rectangular Gain plot for X-Z plane with $\phi = 90^\circ$. 
Table 8 summarises antenna performance for different patch configurations after bending has been introduced. As observed from Table 8, the rectangular patch antenna has a minor deviation in antenna performance. The rectangular patch has the largest effective surface area and delivers the highest gain; nevertheless, the Heptagonal patch has the highest gain’s directivity. As observed from Table 8, the bending has a significant effect on the circular patch as its performance is seriously degraded from the nominal value. Because the rectangular patch performs well even after bending, various changes in the diameter of the cylinder will be carried out, and the impact of bending on the rectangular antenna characteristics will be examined in detail.

| Antenna parameters | Rectangular | Pentagon | Hexagon | Heptagon | Octagon | Circular |
|--------------------|-------------|----------|---------|----------|---------|----------|
| Reflection Coefficient | -33.93 | -6.25 | -7.19 | -7.34 | -7.37 | -7.7297 |
| 10-dB Bandwidth (MHz) | 240 | - | - | - | - | - |
| Gain ($\theta = 0^\circ$) | 4.4 | 3.8676 | 3.4869 | 3.7668 | 3.2202 | -0.0210 |
| Directivity | 5.2074 | 5.9058 | 5.9276 | 6.0059 | 5.0292 | 6.3681 |
| 3-dB beamwidth | 89.46° | 90.7265 | 90.98° | 90.08° | 91.125° | 83.54° |
| Radiation efficiency | 45.45% | 40.67% | 38.73% | 40.62% | 44.39% | 24.57% |

6. Bending analysis of rectangular patch using different diameter of cylindrical surface

The unit patch antenna designed in section 2 is used for bending analysis. In Figure 21, a cylinder with a diameter (D) varying from 40 to 120mm is used to carry out bending analysis investigation using HFSS [22]. When the antenna is curved along the Y-axis, as shown in Figure 22, it twists both sides’ surfaces. Furthermore, the antenna is then put through various cylinder diameters to observe bends in various situations. As the diameter of the cylinder decreases, more bending occurred. The simulated results for different changes in the diameter and their effect on various antenna performances are discussed in the next section.

6.1. Reflection coefficient

The simulated reflection coefficient under different Y-axis bending is shown in Figure 23. As observed from the results, more than 90% of power is supplied to the antenna, and $S_{11}$ always remains very low (<-31 dB). However, the bending marginally shifts the resonant frequency to a higher frequency for bending when diameter D is more than 80mm.
Figure 21. Rectangular patch antenna bending different at diameters.

Figure 22. Unit patch antenna bending on cylinder object.

Figure 23. Simulated Return Loss of the antenna at different bending diameters.

6.2. Gain

Figure 24 shows a rectangular gain plot of rectangular patch antenna bent on varying diameters, whereas the gain plots in the elevation plane are shown in Figures 25 and 26. From these Figures, bending causes an increase in the side lobes and decreases the antenna gain. Furthermore, source currents distribute fields away from boresight in the far-field, resulting in higher side lobes. The planar surface has optimum performance due to the large effective surface area compared to a curved surface. Moreover, when the radius of the curved surface is increased, the gain of the antenna increases, which matches with planar antenna gain when D=120 mm.
Figure 24. Rectangular Gain plot for X-Z Plane with $\phi = 0^\circ$.

Figure 25. Gain plot for X-Z Plane with $\phi = 0^\circ$.

Figure 26. Gain plot for X-Z Plane with $\phi = 90^\circ$.

Table 9 summarizes the antenna performances under different bending conditions. As observed from Table 9, that when the bending is decreased, bandwidth also decreases. Moreover, the
peak gain for \( D = 100 \) mm shifts from \( \phi = 0^\circ \) to \( \phi = 13^\circ \). However, for all other bending conditions, the peak gain remains at \( \phi = 0^\circ \). Moreover, in the planar surface antenna, the best performance in terms of directivity, gain, and Beamwidth is achieved; however, bandwidth drops.

| Diameter (mm) | Return loss (GHz) | Bandwidth (MHz) | Peak Gain (dB) | Radiation efficiency | 3-dB beamwidth | Directivity |
|---------------|-------------------|-----------------|---------------|----------------------|----------------|-------------|
| 40            | -33.8391          | 250             | 3.6795        | 47.41%               | 89.75°         | 6.5397      |
| 60            | -31.9286          | 240             | 4.3798        | 45.45%               | 89.46°         | 6.5397      |
| 80            | -42.8833          | 240             | 4.5963        | 44.712%              | 81.18°         | 6.5397      |
| 100           | -38.1495          | 240             | 4.6230        | 43.424%              | 76.41°         | 6.5397      |
| 120           | -38.5664          | 230             | 4.7601        | 42.225%              | 82.9°          | 6.5397      |
| No bend       | -45.0732          | 220             | 4.8007        | 46.19%               | 74.88°         | 6.5397      |

### 7. Conclusion and future scope
In this work unit patch antenna with a different configuration has been analyzed. Various shapes of the patch antennas are fed using the microstrip feed technique. Each of the patches considered provides unique advantages in some of the application scenarios. In planar condition all the configurations have approximately same performance. However, in folding/bending condition rectangular patch antenna provides a definite edge as compared to other shapes patch antennas. therefore, it is further investigated for different bending diameter (D) in the range from 40 mm to 120mm.

The Beamwidth of the rectangular patch antennas decreases as the bending is reduced. The narrowest Beamwidth occurs with no bending in the structure. Gain decreases with an increase in bending due to increased side lobes. However, the antenna still operates satisfactorily with 43.424% to 47.41% of efficiency even after bending. Moreover, the chosen substrate doesn't change antenna parameters significantly even after bending, making it suitable for wearable medical application. The study carried out in this report provides a foundation for further research in the future for design of large smart phased array antennas on both planar and bent surfaces which can be used in various medical monitoring applications.

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