Research article

Wideband miniaturized patch radiator for Sub-6 GHz 5G devices

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ABSTRACT

In this article, the compact wideband elliptically slotted semi-circular patch radiator with the defected ground structure for sub-6 GHz applications is designed and developed. The proposed miniaturized patch radiator offers flexibility in adjusting the band of operation by varying the slot dimensions. The effective size reduction is achieved by comparing different iterations in the process of designing and the size of the regular circular-shaped radiator is reduced into the semi-circular radiating patch. The impact of the variation of effective radius of the semi-circular patch, major-axis radius of the elliptical slot, ground plane length, and feed line width is investigated. The size of the proposed radiator is 23.885 × 23.885 × 1.405 mm3. This compact structure manifests the wide bandwidth of 2140 MHz (3.2 GHz–5.34 GHz) with 50% of fractional bandwidth (FBW). The measured results show good agreement with the simulated results. The various parameters validate the utility of the radiator in the C band of super-high frequency (SHF) spectrum and n77 (3.3 GHz–4.2 GHz), n78 (3.3 GHz–3.8 GHz), and n79 (4.4 GHz–5 GHz) bands of the frequency range 1 (FR1) of the sub-6 GHz 5G spectrum.

1. Introduction

Printed patch radiators were originally presented in the 1950s, but they did not achieve success until the 1970s when they were propelled by the rapid advancement of the integration technology with digitization of wireless information to be transferred. However, even though these antennas are compact, easy to fabricate with low production cost, and are easy to integrate with radio frequency circuits. These antennas also suffer with low fractional bandwidth (FBW = 7%) which proves their incompatibility with the current wireless technologies. To address this limitation, substantial research has been conducted in the last two decades and new novel geometries have been discovered to enhance the bandwidth. This necessitated the discovery of the physical mechanisms regulating the radiative processes occurring in the antennas. 5G technology has opened a way of different research perspectives on its horizon. By the year 2025, the expected number of operational smart devices will be approximately 6.5 billion, which is quite high as compared to the bank accounts (5.5 billion) or many operational landlines (3.0 billion) [1]. To fulfill the demands of the emerging wireless devices and for achieving an ultra-fast transmission rate (peak data rate ≥20 Gbps), low latency (<1 ms), densely populated connections, and higher mobility (≥500 km/h), the 5G wireless communication systems were deployed in the first quarter of 2020 [1]. The estimation of the 5G device connections is expected to reach 577 million by 2023 as compared to just 5 million that was reported in 2019 [2]. The frequency bands for 5G deployment were allocated comprising of three bands which are low-band (up to 1GHz), mid-band (sub-6 GHz), and high-band (mm-Wave) [3, 4, 5]. The focus of the researchers is for the design of miniaturized patch radiators, which can be a feasible choice for integration with the existing 4G technologies and budding sub-6 GHz 5G cellular networks. Numerous studies have been undertaken in recent years for antenna miniaturization. Slot antennas have been used in various applications as they offer a range of advantages. Various slot shapes engraved on the antenna are studied in which they provide an added advantage of providing desired bandwidth adjustments [6, 7, 8, 9, 10]. An ultra-wideband antenna based on a modified ground plane is presented for being operated in the sub-6 GHz 5G bandwidth of 2.32 GHz–5.24 GHz [11]. Also, many other shapes of the slots embedded in the antenna geometry targeting multiband operation [12], T-shape slots [13], L-shaped slots [14], elliptical/circular slots [15], semi-circular slots [16], C-shaped slots [17], hexagonal slots [18, 19] and so forth have been proposed. The modified ground plane of microstrip antennas helps in achieving dual-band [20], wide-bandwidth [21], etc. In [22, 23], a multiband circularly polarized slot antenna is designed and fabricated. The incorporation of the modified ground plane

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structure helps to achieve circularly polarized characteristics and it also improves the axial ratio bandwidth by using a D-shaped radiator. In adding to these advantages a new slot antenna design for dual-band operation is proposed in which two adjunct arc-shaped slots are added to two main semi-circular slots etched on the ground plane to achieve the desired frequency bands [24]. The study of a slotted semi-circular antenna is taken further by engraving a floral shape slot and analyzing it in a detailed manner [25]. The key design advantages of adding these slots are reduced size, simple configuration, adequate gain etc. A wideband antenna for sub-6 GHz applications is proposed in [26], but it is of large size. In [27], the researchers have reported the benefit of engraving an elliptical slot but still its large size offers limited usage. In [28], the circular patch with the defected ground plane is developed for ultra-wideband applications but offers low average gain for the sub-6 GHz 5G applications.

Inspired from the above reported research articles, this article presents a novel compact patch radiator achieving wide bandwidth in sub-6 5G wireless applications. A semi-circular patch having elliptical slot, fed at an apex by microstrip feed line, exhibiting radiation in n77 (3.3 GHz – 4.2 GHz), n78 (3.3 GHz – 3.8 GHz) and n79 (4.4 GHz – 5 GHz) bands of frequency range 1 (FR1) in sub-6 GHz spectrum is proposed. The effect of inserting the slot and reducing the size of the ground plane is observed, which indicates that it helps in achieving the wide bandwidth. The design iterations consider the circular patch of radius \( r \), which is evaluated and then modified into a semicircular shape. The effect of inserting different shapes of slot structures is investigated and output performance characteristics of wideband operation with compact size enabled us to insert the elliptical slot in the designed semicircular patch. Thus, an elliptical slotted semicircular patch radiator (ESSPR) is designed and developed for sub-6 GHz 5G communications. Rest of the paper is organized as follows. Section 2 presents the design and geometrical configuration of the proposed ESSPR. The simulated results of the ESSPR are presented in section 3. The fabrication, measured results, validation of measured results with simulated results, and comparison of proposed ESSPR with existing designs are discussed in section 4, whereas section 5 presents the conclusion of the work.

2. Design and geometry of the proposed radiator

It is simpler to design the circular and semi-circular microstrip patch radiators as compared to the other geometries as only one design parameter i.e. patch radius \( r \). Since, the circular geometry provides the minimal footprint area, hence a circular patch radiator is initially constructed and is taken as a reference design. The different iterations of the antenna are targeted to be operated at the center frequency \( f_c \) of 4.27 GHz in the sub-6 GHz frequency range from 3.20 GHz to 5.34 GHz. The Flame retardant 4 (FR4) substrate is chosen with the relative permittivity \( \varepsilon_r \) of 4.4 and an overall thickness \( t \) of 0.02 \( \lambda \). The design steps which are opted to develop the ESSPR are given in Figure 1 and are elaborated as follows:

2.1. Step-1 (Radiator1)

Initially, a reference antenna or Radiator1 consisting of a microstrip line fed circular patch radiator with full ground plane is designed. The actual patch radius \( r \) is evaluated by [23]:

\[
 r = \frac{F}{1 + \frac{2}{m^2} \left[ \ln \left( \frac{w}{2} \right) + 1.7726 \right]}^\frac{1}{2} 
\]

In the above Eq. (1), the constant \( F \) can be evaluated by using Eq. (2):

![Figure 1. Evolution stages of the proposed ESSPR geometry, (a) Radiator1, (b) Radiator2, (c) Radiator3, (d) Radiator4, (e) Radiator5, and (f) Radiator6 (ESSPR).](image-url)
\[ F = \frac{8.791 \times 10^6}{f_c \sqrt{\varepsilon_r}} \]  

(2)

In the above formulae, the unit of operating center frequency \(f_c\) is in Hertz (Hz) and the unit of the overall thickness of the substrate \(t\) is in centimeters (cm). The values substituted in Eq. (1) for the parameters are \(f_c = 4.27 \times 10^9\text{ Hz},\ \varepsilon_r = 4.4\) and \(t = 0.02\lambda\). Using these, the value of \(F\) comes out to be 1.0135 and \(r\) to be 0.97 cm i.e. 0.13\(\lambda\). The dimension of the ground is taken as 0.42\(\lambda\), where \(\lambda\) is the wavelength corresponding to center frequency.

### 2.2. Step-2 (Radiator 2)

In this step, the concept of a defected ground substrate (DGS) is being used and the dimension of the ground plane is optimized to a value at which we get considerable performance in the desired sub-6 GHz frequency range. The concept of DGS is already known by many researchers to provide wider bandwidth and many DGS shapes have already been suggested in the literature. The advantage of reducing the dimension of the ground plane is that it reduces inductive coupling of the ground plane with the radiator and hence it helps to increase the bandwidth as the energy stored in the substrates gets reduced and thus it decreases the quality factor (Q factor) and increases the bandwidth [29].

### 2.3. Step-3 (Radiator 3)

In the next step, the circular patch is converted into the semi-circular patch radiator. The radius \(r\) as calculated from Eqs. (1) and (2) is maintained at the same value and the effective dimensions of the substrate are optimized and reduced to attain miniaturization while maintaining and even improving the output characteristics of the designed structure. The length of the substrate is 0.34\(\lambda\). The dimension of the ground plane is optimized as 0.17\(\lambda\). The dimensions of the Radiator 3, shown in Table 1, are used for attaining the desirable characteristics as given in Table 2. The antenna radiates with an adequate bandwidth. The value of gain and directivity motivates us to modify this design for getting the better performance.

### 2.4. Step-4 (Radiator 4)

The design geometry is modified by inserting slots in the patch radiator for achieving miniaturization with improved performance characteristics. The slot in the patch helps to get the smaller microstrip antenna with improved bandwidth and efficiency. A circular slot with the slot radius of 0.04\(\lambda\) is inserted at the center of the patch radiator. The effect of the slot is visible with the data reported in Table 2. Here, the values of gain and directivity are enhanced along with the adequate bandwidth. However, the bandwidth of Radiator 4 is not as good as retrieved in Step-3.

### 2.5. Step-5 (Radiator 5)

The optimized design, which is achieved by the Radiator 3, is utilized and a rectangular slot is inserted into the semicircular patch for achieving the miniaturization. The dimensions of the inserted rectangular slot are kept such that the length of the slot is 0.14\(\lambda\) and the width of the slot as 0.05\(\lambda\). The radius \(r\) of the patch radiator, calculated using Eqs. (1) and (2), is used in the design of Radiator 3. The performance characteristics are reported in Table 2, which indicate that although the gain and directivity are better than Radiator 3, however, Radiator 4 gives better gain and directivity as compared to Radiator 3.

### 2.6. Step-6 (Radiator 6)

In this step, the elliptical slot is inserted into the semicircular patch. The advantage of elliptical slot for achieving the miniaturization is that it
helps in reducing the radiating area with adequate characteristics and is also insensitive to the polarization. The dimensions of the elliptical slot are directly related to the lowest transmission zero frequency of the impedance bandwidth. An empirical formula to extract the lowest transmission zero frequency of the elliptical disc monopoles is given by [30]:

$$f_l = \frac{30 \times 0.24}{H + r}$$

(3)

where \(f_l\) (in GHz) denotes the lower transmission zero frequency, \(H\) is the effective height of the elliptical disc to be engraved and \(r\) denotes the equivalent radius of the elliptical cylinder. Further in [31], Eq. (3) has been modified and is formulated as:

$$f_l = \frac{30 \times X}{H + r}$$

(4)

In equation (4), \(H\) and \(r\) are in centimeters and \(f_l\) is in GHz. The term \(X\) denotes the element factor which is equal to 0.32 for the elliptical slot and 0.35 for the circular slot. The semi-major axis and semi-minor axis of the elliptical slot are 0.04\(\lambda\) and 0.02\(\lambda\), respectively. The performance characteristics are reported in Table 2. From Table 2, it is noticeable that an elliptical slot-based semicircular patch radiator proves to be the best candidate for achieving wideband radiation characteristics with reasonable gain and directivity. Thus, the elliptical slotted semicircular patch radiator (ESSPR) is fabricated and its detailed analysis is presented.

The procedure followed to develop the geometry of the proposed elliptical slot semicircular patch radiator is depicted in Figure 1. A SMA connector is connected to the transmission line and the ground plane. Table 1 gives a detailed explanation of the proposed antenna’s design specifications. A semicircular disc patch is analysed by treating it as equivalent to the rectangular patch radiator with the dimensions \(L_e \times W_e\) [32], where \(L_e = 2a\) and \(W_e = a/2\). The resonance frequency of a semicircular disc patch antenna may be computed using Eq. (5) [33, 34]:

$$f_r = \frac{k_{np} C}{2na_e \sqrt{\varepsilon_e}}$$

(5)

Table 2: Antenna parameters of various configurations.

| Output characteristics | Value            |
|------------------------|------------------|
| Highest frequency (f_H) | NR               |
| Lowest frequency (f_L)  | 5.67 GHz         |
| Bandwidth (f_H – f_L)   | 3.62 GHz         |
| Gain (dB)               | 1.81             |
| Directivity (dB)        | 2.11             |
| NR- Not Radiating.      |                  |
where \( k_{pq} \) is the \( p^{th} \) zero root of the derivative of Bessel function of the order \( q \), \( c \) is the velocity of light, \( \varepsilon_e \) is the effective dielectric constant of the substrate and the effective radius of the semicircular disk patch is given by Eq. (6) [34]:

\[
a_e = \sqrt{\frac{L_e W_e}{\pi}}
\]

The effective radius \( (a_e) \) of the semicircular disk patch radiator is derived by equating the area of the semicircular patch to the equivalent rectangular patch of dimension \( (L_e \times W_e) \), where \( L_e \) and \( W_e \) are the rectangular patch's effective length and width, respectively [33]. The equivalent circuit of the final proposed elliptical slotted semicircular patch radiator is shown in Figure 2 with circuit parameters i.e. patch resistance \( (R_p) \), patch inductance \( (L_p) \), patch capacitance \( (C_p) \), slot capacitance \( (C_{slot}) \), partial ground resistance \( (R_{pg}) \), partial ground inductance \( (L_{pg}) \), partial ground capacitance \( (C_{pg}) \) and lumped elements due to coupling. These parameters are calculated by using mathematical formulations as given in Eqs. (7), (8), and (9) below [34, 35]:

\[
C_p = \frac{\varepsilon_0 \varepsilon_{ref} L_e W_e}{h}
\]

\[
L_p = \frac{1}{\omega_p^2 C_p}
\]

\[
R_p = \frac{Q_r}{\omega_p C_p}
\]

where \( L_e, W_e, \varepsilon_{ref} \) and \( \omega_p \) denote the length of the rectangular patch, the width of the rectangular patch, the effective permittivity of the medium and the angular frequency, respectively.

The value of \( Q_r \) can be evaluated using Eq. (10) [34, 35]:

\[
Q_r = c \sqrt{\frac{\varepsilon_{eff}}{\lambda_p h}}
\]
where $c$, $h$ and $f_p$ denote the velocity of light in free space, the height of the substrate and the resonant frequency of operation, respectively. The impedance of the patch is given in Eq. (11):

$$Z_p = \frac{1}{\frac{j}{c} + \frac{1}{R_p} + j\omega L_p} \quad (11)$$

The equivalent impedance ($Z_{pg}$) of partial ground plane is considered to be a parallel combination of the inductance ($L_{pg}$), capacitance ($C_{pg}$), and resistance ($R_{pg}$) and is computed by using Eq. (12) [36]:

$$Z_{pg} = \frac{1}{R_{pg} + \frac{1}{j\omega L_{pg}} + j\omega C_{pg}} \quad (12)$$

It’s worth noting that the two resonant circuits, one of which is the lumped equivalent circuit of the rectangular patch radiator and the other is the partial ground plane as illustrated in Figure 2, are linked together by a mutual inductance ($L_{C}$) and mutual capacitance ($C_{C}$). The capacitance due to engraving of a slot is added in series with the overall capacitance of the patch. In the proposed design, an elliptical slot is added to the semicircular patch radiator. The different iterations, comprising of a circular, rectangular and an elliptical slot, are given in Figure 1. The output characteristics retrieved from the different iterations are mentioned in Table 2, which clearly indicates that an elliptical slot is best to achieve wide bandwidth among all slotted designs as illustrated with adequate values of gain and the directivity.

The resonant frequency ($f_R$) of any tuned circuit is given in Eq. (13) [32, 33, 34]:

$$f_R = \frac{1}{2\pi \sqrt{L_C C_C}} \quad (13)$$

where $L'$ = $L_p$ and $C' = C_{pg} + C_{slot}$.

It may be noted that by engraving a slot within the patch antenna radiator, the value of overall capacitance reduces, which in turn helps to increase the resonant frequency of operation as per Eq. (13). It may be noted that the capacitance offered by a rectangular slot is minimum and that to offered by an elliptical slot is maximum. Hence, the overall capacitance of the final design consisting of an elliptical slot is least among the other circular and rectangular slotted designs. It results in the largest bandwidth offered by an elliptical slotted semicircular patch antenna radiator as compared with other slotted structures. The effect in the output characteristics is visualized in Table 2 which validate the theoretical interpretations. The equivalent impedance as a result of coupling between the ground plane and the patch antenna radiator is determined by using Eq. (14) [36]:

$$Z_{pg} = \frac{1}{R_{pg} + \frac{1}{j\omega L_{pg}} + j\omega C_{pg}}$$

### Table 3. Various simulated parameters of various antenna configurations.

| Parameter          | Radiator3 | Radiator4 | Radiator5 | Radiator6 (ESSPR) |
|--------------------|-----------|-----------|-----------|-------------------|
| $W \times L \times h$ | 0.34\%\times0.34\%\times0.02\% | 0.34\%\times0.34\%\times0.02\% | 0.34\%\times0.34\%\times0.02\% | 0.34\%\times0.34\%\times0.02\% |
| Area of slot (mm$^2$) | -- | 28.27 | 40 | 18.85 |
| Bandwidth (MHz) | 2410 | 1160 | 910 | 2140 |
| FBW | 53\% | 27.61\% | 22.66\% | 50.11\% |
| Gain (dB) | 1.81 | 2.98 | 2.78 | 2.76 |
| Directivity (dB) | 2.11 | 3.17 | 2.97 | 2.98 |
| Radiation Efficiency (%) | 94.5 | 96 | 95 | 96 |

### Table 4. Simulated gain, directivity and radiation efficiency of the ESSPR.

| Frequency (GHz) | Gain (dB) | Directivity (dB) | Radiation efficiency (%) |
|----------------|-----------|------------------|--------------------------|
| 3.6            | -0.07     | 0.11             | 95.98                    |
| 3.8            | 0.37      | 0.56             | 96                       |
| 4.0            | 0.79      | 0.98             | 95.78                    |
| 4.2            | 1.18      | 1.38             | 95.58                    |
| 4.4            | 1.54      | 1.74             | 95.48                    |
| 4.6            | 1.88      | 2.09             | 95.38                    |
| 4.8            | 2.20      | 2.41             | 95.29                    |
| 5.0            | 2.49      | 2.70             | 95.21                    |
| 5.2            | 2.76      | 2.98             | 95.13                    |
\[ Z_c = \left( j\omega L_c + \frac{1}{j\omega C_c} \right) \]  
where \( C_c \) and \( L_c \) depict the mutual capacitance and the inductance of the two resonant circuits, respectively, as illustrated in Figure 2 and are given in Eqs. (15) and (16) [34]:

\[ L_c = \frac{X(L' + L_{pg})}{1 - X^2} + \frac{4C^2(1 - X^2)L'L_{pg}}{2(1 - X^2)^2} \]  
(15)

\[ C_c = \frac{-(C + X) + \sqrt{(C + X)^2 - 4C^2X(1 - X^2)}}{2} \]  
(16)

where \( X = \frac{1}{\sqrt{Q_1 Q_2}} \), and \( Q_1, Q_2 \) are the quality factors of the both resonant circuits. The impedance of the proposed ESSPR is given in Eq. (17):

\[ Z_{ESSPR} = Z_{pg} + \frac{Z_{p}Z_{c}}{Z_{p} + Z_{c}} \]  
(17)

The designed patch radiator consists of a simple microstrip line feed which is considered as parallel combination of impedance \( Z_{ESSPR} \), inductance \( (L_m) \) and the capacitance \( (C_m) \) as shown in Figure 3. The term \( Z_{ESSPR} \) is considered to be the impedance of a rectangular patch radiator including partial ground plane, and the values of \( L_m \) and \( C_m \) are calculated by using Eqs. (18) and (19) [34]:

\[ C_m = W_2 \left( 10.1 \log \epsilon_{reff} + 2.33 \right) \times \frac{W_1}{W_2} - 12.6 \log \epsilon_{reff} - 317 \text{ pF} \]  
(18)
where \( W_1 \) and \( W_2 \) denote the width of the patch and the width of the microstrip feedline, respectively.

Also, the total input impedance is extracted by using Eq. (20) for the proposed designed antenna as

\[
Z_{in} = Z_{Lm} + \left( \frac{1}{Z_{cm}} \right) \left( Z_{Lm} + Z_{ESSPR} \right)
\]

where \( Z_{Lm} = j\omega L_m \) and \( Z_{cm} = j\omega C_m \).

Hence, various characteristics such as reflection coefficient, return loss and voltage standing wave ratio are evaluated by using Eqs. (21), (22), and (23):

\[
\Gamma = \frac{Z - Z_{Lm}}{Z + Z_{Lm}}
\]

where \( Z \) denotes the overall impedance of the microstrip line feed and is taken as 50 \( \Omega \). The relation between the return loss (RL) and reflection coefficient is given by:

\[
RL = -20 \log |\Gamma|
\]

Voltage standing wave ratio (VSWR) can be calculated using:

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

It can be noted from Figure 4 that the bandwidth of the ESSPR covers the n77, n78, and n79 bands. The Radiator6 has explicit features of simple design, miniaturized structure (0.34\( \lambda \times 0.34\lambda \times 0.02\lambda \)), and the simpler fabrication process. The comparative analysis of gain and directivity is illustrated in Figure 5 and Figure 6, respectively, which indicates that the proposed ESSPR is the best candidate to be used in sub-6 GHz devices due to its wide bandwidth and compact size.

| Parameter                     | Simulated | Measured |
|-------------------------------|-----------|----------|
| Highest frequency (f\(H\)) (GHz) | 5.34      | 4.72     |
| Lowest frequency (f\(L\)) (GHz) | 3.20      | 3.14     |
| Operating band (GHz)          | 3.20-5.34 | 3.14-4.72|
| Fractional bandwidth (%)      | 50.11     | 40.20    |
| Maximum gain (dB)             | 2.76      | 2.45     |
| Maximum radiation efficiency (%)| 96        | 92       |
| Minimum reflection coefficient (dB) | -24.64   | -33.21   |

Figure 14. Gain and radiation efficiency of the proposed ESSPR.

Figure 15. Simulated and measured normalized radiation patterns of the ESSPR, (a) E-plane (3.8 GHz), (b) H-plane (3.8 GHz), (c) E-plane (4 GHz) (d) H-plane (4 GHz), (e) E-plane (4.2 GHz), (f) H-plane (4.2 GHz), (g) E-plane (4.4 GHz) and (h) H-plane (4.4 GHz).
3. Simulated results of the ESSPR

The simulated results of the ESSPR are investigated and reported by examining the key geometrical parameters. The key geometrical parameters which are focused comprise of the radius of the semicircular patch (r), the major radius of the elliptical slot (Z), the length of the ground plane (Ad), and the width of the feed line (Fw). The effect on the performance of the ESSPR by varying the radius of the semicircular patch (r) is shown in Figure 7. It shows that as the radius r is increased from the nominal value of 9.7 mm (0.13λ), the drift is seen on the higher end of the frequency spectrum with a decrease in the magnitude of the reflection coefficient up to 35 dB. Figure 8 shows the variation of the reflection coefficient with the radius of the major-axis (Z) of the elliptical slot. It can be observed from Figure 8 that the resonant frequency decreases on increasing the value of Z. Further, the effect of the width of the feed line on the reflection coefficient is recorded in Figure 9. As the width of the feed line (Fw) is decreased, the reflection coefficient curve shifts to the higher end of the frequency spectrum with a slight increase in the amount of reflection. Also, as we increase the width of the feed line (Fw), then the patch radiator lowers its capacity to transmit the radiation. The length of the ground plane is varied to report its effect on the reflection coefficient curve shifts to the higher end of the frequency spectrum with a decrease in the magnitude of the reflection coefficient. It can be observed from Figure 9 that the results retrieved from the simulation and measurement setup show good agreement. The graph of the VSWR versus frequency of the ESSPR is illustrated in Figure 13. The operating frequency range, the fractional bandwidth and the minimum reflection coefficient obtained from the simulated results are 3.2–5.34 GHz, 50.11% and -24.64 dB, respectively. The operating frequency range, the fractional bandwidth and the minimum reflection coefficient obtained from the measured results are 3.14–4.72 GHz, 40.2% and -33.21 dB, respectively. The simulated and measured gain and radiation efficiency are shown in Figure 14. The minor variations might be due to fabrication errors and connector losses. The simulated maximum gain, simulated maximum radiation efficiency, measured maximum gain and measured maximum radiation efficiency of the ESSPR within the bandwidth are 2.76 dB, 96%, 2.45 dB and 92%, respectively. The results retrieved from the simulations and the experimental setup are compared in Table 5.

The normalized co-polar and cross-polar radiation patterns of the ESSPR in E-plane and H-plane are shown in Figure 15. From these patterns, it can be observed that the behavior of patterns are figure of eight and omnidirectional in E-plane and H-plane, respectively.

The proposed ESSPR offers miniaturization along with the wideband characteristics. The comparison of this design with the existing designs available in literature is shown in Table 6. The wavelength (λ) in the comparison table is calculated at the center frequency (fc) of 4.27 GHz. As observed from Table 6, the proposed ESSPR has a miniaturized area of (AESSPR) 0.1156λ2, which is the smallest. The proposed compact ESSPR is suitable for sub-6 GHz wideband applications.
5. Conclusion

A compact and miniaturized patch radiator for exhibiting wideband response in sub-6 GHz 5G frequency range has been designed and developed. An elliptical slot is engraved on the semicircular patch to achieve wide bandwidth i.e. from 3.2 GHz to 5.34 GHz. The designed antenna offers compact dimensions of 0.34\(\lambda\)\times 0.34\(\lambda\)\times 0.02\(\lambda\), where \(\lambda\) represents the wavelength at the center frequency of the operating band. The proposed radiator finds its suitability for sub-6 GHz wideband applications. The measured results confirm the wide bandwidth of 2.14 GHz i.e. 50% fractional bandwidth. The simulated and measurement results show good agreement. The antenna parameters confirm that the designed and developed compact wideband ESSPR is suitable for 5G communication devices.

Declarations

Author contribution statement

Ankush Kapoor: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ranjan Mishra, Pradeep Kumar: Conceived and designed the experiments; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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References

[1] M. Agiwal, A. Roy, N. Saxena, Next generation 5G wireless networks: a comprehensive survey, IEEE Commun. Surv. Tutorials 18 (3) (2016) 1617–1655.

[2] Strategy Analytics, Strategy analytics forecasts nearly 600 million 5G users by 2023. https://www.strategyanalytics.com/strategyanalytics/news/strategy-analytics-press-releases/2018-03-27/strategy-analyticsforecasts-nearly-600-million-5g-users-by-2023, (Accessed 29 May 2021).

[3] M.J. Marcus, ‘5G and ‘IMT for 2020 and beyond’ [spectrum policy and regulatory issues], IEEE Wireless Commun. 22 (4) (2015) 2–3.

[4] A. Kapoor, R. Mishra, P. Kumar, Novel wideband frequency selective surface based space borne filters for sub-6 GHz 5G devices, Int. Conf. Naasent Technol. Eng. (ICNTE) (2021) 1–6.

[5] A. Kapoor, R. Mishra, P. Kumar, Compact wideband-printed antenna for sub-6 GHz fifth-generation applications, Int. J. Smart Sens. Intel. Syst. 13 (1) (2020) 1–10.

[6] C.L. Bamy, et al., A compact dual-band Dolly-shaped antenna with parasitic elements for automotive radar and 5G applications, Heliyon 7 (issue 4) (2021).

[7] P.N. Shinde, J.P. Shinde, Design of compact pentagonal slot antenna with bandwidth enhancement for multiband wireless applications, Int. J. Electron. Commun. 69 (10) (2015) 1489–1494.

[8] F. Kurniawan, J.T. Sri Sumantyo, G.S. Prabowo, A. Munir, Wide bandwidth left-handed circularly polarized printed antenna with crescent slot, in: 2017 Progress in Electromagnetic Research Symposium (PIERS), 2017, pp. 1047–1050. St Petersburg, Russia, May 22–25.

[9] H.A. Ghali, T.A. Mostehly, Broad-band and circularly polarized space-filling-based slot antennas, IEEE Trans. Microw. Theory. Tech. 53 (6) (Jun. 2005).

[10] A. Kapoor, P. Kumar, R. Mishra, Analysis and design of a passive spatial filter for sub-6 GHz 5G communication systems, J. Comput. Electron. (2021).

[11] X. Tang, et al., Ultra-wideband patch antenna for sub-6 GHz 5G communications, in: 2019 International Workshop on Electromagnetics: Applications and Student Innovation Competition, IEMW, 2019, pp. 1–5.

[12] P.M. Mpeleetaal, A novel quad band ultra miniaturized planar antenna with metallic vias and defectected ground structure for portable devices, Heliyon 7 (3) (2021).

[13] Z. Ding, H. Wang, S. Tao, D. Zhang, C. Ma, Y. Zhong, A novel broadband monopole antenna with T-slot, CB-CPW, parasitic stripe and heart-shaped slice for 5G applications, Sensors 20 (24) (2020) 7002.

[14] Z. Ma, Y. Jiang, L-shaped slot-loaded stepped-impedance microstrip structure UWB antenna, Micromachines 11 (9) (2020) 828.

[15] D. Konbar, A.K. Behera, S.N. Mishra, D. Mishra, A high gain elliptical slot antenna for lower C-band and X-band application, J. King Saud Univ. Eng. Sci. (2020).

[16] D.K. Naji, Miniature slotted semi-circular dual-band antenna for WiMAX and WLAN applications, J. Electromagn. Eng. Sci. 20 (2) (2020) 115–124.

[17] N.H. Patel, Design of C-shaped patch antenna for multiband applications, Int. J. Eng. Res. Technol. 9 (6) (2020).

[18] A. Kapoor, R. Mishra, P. Kumar, Slotted wideband frequency selective reflectors for sub-6 GHz 5G devices, in: 2021 International Conference on Computing, Communication, and Intelligent Systems (ICCCIS), 2021, pp. 786–791.

[19] A. Kapoor, R. Mishra, P. Kumar, A compact high gain printed antenna with frequency selective surface for 5G wideband Applications, Adv. Electromagn. 10 (2) (2021) 27–38.

[20] M. Mabasso, P. Kumar, A dual band patch antenna for bluetooth and wireless local area networks applications, Int. J. Microw. Opt. Technol. 13 (5) (2018) 393–400.

[21] P. Kumar, J.L. Masa-Campos, Dual polarized microstrip patch antennas for ultra wideband applications, Microw. Opt. Technol. Lett. 56 (9) (2014) 2174–2179.

[22] A. Kunwar, A.K. Gautam, B.K. Kanaujia, K. Rambabu, “Circularly polarized D-shaped slot antenna for wireless applications”, Int. J. RF Microw. Computer-Aided Eng. (2019).

[23] J.H. Yoon, S.H. Ha, Y.C. Bhee, A novel monopole antenna with two arc-shaped strips for WLAN/WIMAX application, J. Electromagn. Eng. Sci. 15 (1) (2015) 6–13.

[24] S. Zebrini, et al., A compact semi-circular and arc-shaped slot antenna for heterogeneous RF front-ends, Electronics 8 (10) (2019) 1123.

[25] M.L. Meena, A. Gupta, Design analysis of a semi-circular shaped directional UWB antenna integrated with wireless multiband applications, Prog. Electromagn. Res. C 90 (2019) 155–167.

[26] P. Jha, S. Singh, R.L. Yadava, “Wideband sub-6 GHz micro-strip antenna: design and fabrication”, Lect. Notes Elect. Eng., vol 721, 2021.

[27] D.K. Rabaja, B.K. Kanaujia, Design and analysis of elliptical slot loaded microstrip antenna for C-Band communication, in: 2016 3rd International Conference on Computing for Sustainable Global Development, INDIACom, 2016, pp. 2910–2913.

[28] R. Azin, et al., Circular patch planar ultra-wideband antenna for 5G sub-6 GHz wireless communication applications, J. Optoelectro. Adv. Mater. 23 (3-4) (2021) 127–133.

[29] G.S. Mauro, G. Castorina, A.F. Morabito, L. Di Donato, G. Sorbello, Effects of Islandy backantennas embedded in concrete structures, Microw. Opt. Technol. Lett. 58 (2016) 2653–2656.

[30] N.P. Agrawall, G. Kumar, K.P. Ray, Wide-band planar monopole antennas, IEEE Trans. Antenna. Propag. 46 (2) (1998) 294–295.

[31] P. Li, J. Liang, X. Chen, Study of printed elliptical/circular slot antennas for ultrawide band applications, IEEE Trans. Antenn. Propag. 54 (6) (2006) 1670–1675.

[32] G. Kumar, K.P. Ray, Broadband Microstrip Antenna, Artech House, Boston, London, 2003.

[33] L.C. Chen, et al., Resonant frequency of circular disk printed circuit antenna, IEEE Trans. Antenna. Propag. 25 (1997) 595–596.

[34] R. Garg, P. Bhartia, I. Bahl, A. Ittipiboon, Microstrip Antenna Design Handbook, Artech House, Boston, London, 2003.

[35] A. Peram, A.S.R. Reddy, M.N.G. Prasad, Miniaturized single layer ultra wide band antenna, IEEE Trans. Antenn. Propag. 49 (7) (2001) 1275–1291.

[36] J.Y. Sze, K.L. Wong, Bandwidth enhancement of a microstripline-fed printed wide-slot antenna, IEEE Trans. Antenn. Propag. 49 (7) (2001) 1020–1024.