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Dual-polarized elliptic-H slot-coupled patch antenna for 5G applications

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Abstract: A dual-polarized, slot-coupled dielectric patch antenna design is presented in sub-6 GHz for 5G base stations. Proposed antenna is implemented using two dielectric patch layers (main patch and parasitic patch) above a feeding line layer. Excitation is realized by crossed elliptic-H slots in order to create orthogonal ± 45° polarizations. Through the use of patches at proper heights together with elliptic-H slots, significant improvement in impedance bandwidth, matching level, isolation and front-to-back ratio is acquired. Prototype antenna has an impedance bandwidth of 18.5% (3.23–3.85 GHz) for |S11|, |S22| < −15 dB, covering the 5G spectra of 3.30–3.80 GHz. The isolation between ports (|S21|) is obtained as < −25 dB in desired operating band. Antenna exhibits stable, broadside radiation patterns with half power beam-widths of 59°–64° and 69°–72° in E/H-planes, respectively. Gain of the antenna varies within the range of 7.9–8.4 dBi. Proposed antenna is also low profile (9.8 mm). It needs no reflector or cavity-backed structure and meets all the requirements of 5G base stations as an antenna element. Design details, numerical studies, and experimental results are presented.

Key words: Dual-polarization, slot coupling, isolation, low profile, broadband patch antenna, sub-6 GHz, 5G, base station antenna

1. Introduction

Along with the development of cellular communication in the last decade, continuous increase in number of users has led to demanding requirements for base station antennas such as low profile, wide operational bandwidth (BW), good impedance matching (|S11|, |S22| < −15 dB), high channel isolation (|S21| < −20 dB), high front-to-back ratio (FBR > 20 dB) and high cross-polar discrimination level (XPD > 20 dB). Dual-polarization is also employed in base stations antennas for diversity against multipath fading [1–3]. Furthermore, it enables the use of two well-isolated channels at both transmitting and receiving sides on the same physical antenna structure in a compact manner.

The literature has focused on different types of designs for dual-polarized antennas in sub-6 GHz region. Classical crossed-dipole antennas, which are composed of a pair of dipoles in 45° orientation, are most widely used since they can provide wide impedance BW and strong isolation [3, 4]. They also have high FBR since there is almost no backward radiation. However, they have generally high profile and bulky feeding structure with balun. Several crossed-dipole structures for 5G are designed in [5–7]. Although magneto-electric dipoles in [8–10], which can also be regarded as crossed-dipole antenna, are low profile, they have complex feeding and

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radiating structure.

Patch antennas are also widely used for dual-polarization due to their compactness, low profile, and ease of manufacturing [1]. Despite their narrow band nature in early time, different feeding techniques have been developed to extend their operating bandwidth. Probe feeding and slot coupling are common types for exciting the patches. Together with such feedings, multilayer stacked patches can also be employed for broadband operation. Several variations of probe feeding (meandering, and hook shapes, symmetric or antisymmetric feeds, etc.) for dual-polarized patch antennas are given in [11–16]. Other common type of feeding for dual-polarized patch antennas is slot coupling, again in single or multilayer configuration. Dual-polarization feature of antenna is implemented by either crossed slots centered on common ground or two separate slots in orthogonal placement [18–23]. The crossed-slot configuration is more common because of its single layer feeding, making the antenna low profile and compact. In [17], a dual-polarized stacked patch antenna is designed by utilizing a plus-like shaped slot. A four layer microstrip patch antenna is presented in [18] where the feeding lines for each polarization are mounted on separate layers and slots are etched on these layers accordingly. In [19], two modified-H slots are used to excite dual-polarization on the patch. [21, 22] report square shaped ring slot structure feeding a patch and Jerusalem crossed radiator, respectively. In [23], a broadband multilayer patch antenna containing a quasi-crossed-shaped slot is presented. Additional different designs of slot coupled patch antennas can be found in [24–26].

In this paper, design of a simple, broadband, dual-polarized, slot-coupled patch antenna with low profile and easy fabrication is presented for 5G base stations to operate in 3.30–3.80 GHz band. Prototyped antenna exhibits 18.5% (3.23–3.85 GHz) impedance BW for \( |S_{11}|, |S_{22}| < -15 \) dB, isolation \( |S_{21}| < -25 \) dB, FBR > 23 dB and XPD > 22 dB with a gain of 7.9–8.4 dBi. Broadside, directional radiation patterns have been obtained with half power beamwidths (HPBW) of 59°–64° in E-plane and 69°–72° in H-plane. In addition to these performances, other outstanding feature of antenna can be counted as its simplicity and low-profile. It must be noted that slot-coupled patch antennas may be simple, low profile, however, their FBR performance is poor because of undesirable back radiation of the slots. Hence reflector plane or cavity backed structure, which increases antenna profile, is generally employed to make FBR higher. Proposed antenna has low-profile (9.8 mm) and good FBR with no reflector.

2. Antenna design

2.1. Geometry and configuration

The antenna comprises two dielectric patch layers (main and parasitic one) and a feedline layer, all separated by air. Height of the main patch layer is denoted by \( h_m1 \) whereas separation between the patch layers is denoted by \( h_m2 \). Patches are square-shaped whose lengths are \( L_m1 \) and \( L_m2 \). The feedline layer consists of a feeding network of the antenna at its bottom side and a common ground at its upper side. Elliptic-H slots are etched on this ground side. Feeding network is composed of two parts: matching section and 100 \( \Omega \) branch lines. Matching section provides broadband matching between input impedance of patches and 50 \( \Omega \) SMA port. It includes a two-section binomial transformer and an additional rectangular stub of size \( 3.1 \times 4.0 \) mm\(^2\). Sections of the transformer are approximately quarter wavelength (\( L_t1, L_t2 \)) at center frequency, \( f_c = 3.55 \) GHz (\( \lambda_c = 84.5 \) mm). Coupling to the slots is realized using two 100 \( \Omega \) microstrip branch lines which are connected to the matching section through a T-junction. Branch lines are separated by a distance \( L_d \) and terminated by L-shaped stubs in order to compensate the reactive component of the input impedance of the patches and
preclude the overlap. Due to the inevitable crossing between inner branches, a small air bridge is introduced here to avoid intersection. All dielectric layer are implemented by using FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) of height 1.6 mm. Geometry of the antenna is illustrated in Figure 1 while physical dimensions are given in Table 1.

**Figure 1.** Antenna geometry and configuration a) top view and cross-sectional view, b) elliptic-H slots, feedlines and binomial transformer.
Table 1. Dimensions of the proposed antenna.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Dimension [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground plane</td>
<td>Lg</td>
<td>110</td>
</tr>
<tr>
<td>Main patch length</td>
<td>Lm1</td>
<td>21</td>
</tr>
<tr>
<td>Parasitic patch length</td>
<td>Lm2</td>
<td>17.95</td>
</tr>
<tr>
<td>Lower/upper air height</td>
<td>hm1, hm2</td>
<td>3, 2</td>
</tr>
<tr>
<td>Slot major axis length</td>
<td>Lsl1</td>
<td>16.5</td>
</tr>
<tr>
<td>Vertical slot width</td>
<td>Lsl2</td>
<td>3.2</td>
</tr>
<tr>
<td>Stub length</td>
<td>Lst</td>
<td>2.35</td>
</tr>
<tr>
<td>1st binomial section length</td>
<td>Lbt1</td>
<td>11.55</td>
</tr>
<tr>
<td>2nd binomial section length</td>
<td>Lbt2</td>
<td>11.82</td>
</tr>
<tr>
<td>Branch separation</td>
<td>Ld</td>
<td>6.91</td>
</tr>
<tr>
<td>Rectangular stub length/width</td>
<td>Lrs1, Lrs2</td>
<td>3.1, 4</td>
</tr>
<tr>
<td>FR4 height</td>
<td>h</td>
<td>1.6</td>
</tr>
<tr>
<td>Overall antenna height</td>
<td></td>
<td>3+2+(3×1.6) = 9.8</td>
</tr>
</tbody>
</table>

2.2. Working principles

Radiation from the patches occurs by coupling the electromagnetic energy to patches through elliptic-H slots excited by feed network. The heights of the patch layers are of critical importance for matching, BW, isolation and FBR. Although main patch layer (hm1) has dominant effect in overall design, parasitic patch layer (hm2) must also be considered in combination with it to reach desired technical specifications. The lower hm1 makes efficient coupling from slots to patch easier, hence resulting in good FBR, however this lower hm1 makes broadband operation difficult. The higher hm1 facilitates making antenna broadband but efficient coupling from slots to patch becomes more difficult, hence resulting in poor FBR. Therefore main patch layer must be placed at an optimum height (hm1) together with taking into account its interaction with parasitic patch layer (hm2). At first glance, existence of parasitic patch layer may be questioned because it increases overall antenna profile. However that is not the case because desired technical specifications cannot be attained with a single main patch. In this work, the principal idea is to place main patch at the lowest possible height to have good FBR, and at the same with the proper combination of patches, to reach desired impedance BW, matching level, isolation while also keeping antenna low profile, as it will be more clear in Section 3.

In this study, contrary to conventional rectangular-H slots, center of the slots are redesigned in elliptic form. As addressed in [27], elliptic slot is a simple technique for broadband power transfer between microstrip transitions and employed here as coupled-feeding mechanism. Axial ratio of the ellipse, specifically length of its major axis, controls the level of the coupling. Tapered line nature of elliptic-H slots supports more number of modes to excite patches and hence provide appreciable improvement in impedance BW, matching level and isolation.

Figure 2 plots surface current distributions on the main and parasitic patches at 3.30 GHz and 3.80 GHz as the antenna is excited at port-1. As can be seen in Figure 2a, current amplitude on the main patch gradually increases towards edges at 3.30 GHz in symmetry with +45° diagonal line while the currents are weaker on the parasitic patch. At 3.80 GHz, stronger coupling occurs between two patches and current amplitude on the parasitic patch increases while the main patch has more uniform distribution. This phenomenon indicates the
resonant behaviour around 3.80 GHz is mostly governed by the parasitic patch.

3.3 GHz

(a)

3.8 GHz

(b)

Figure 2. Surface current distributions on the main and the parasitic patches (a) at 3.3 GHz, (b) at 3.8 GHz.
3. Numerical studies

3.1. Parametric analysis

Proposed antenna is modeled and simulated in Ansoft HFSS. Its electrical performances are numerically analyzed in terms of impedance matching (|S_{11}|) and isolation (|S_{21}|) with parametric studies. Each parametric study is carried out by sweeping one parameter within a range while the rest is kept unchanged. Since the dual-polarization is obtained using symmetric feeding lines, only |S_{11}| results are reported at Port-1. Upper and lower boundaries of the band of interest (3.30 - 3.80 GHz) are shown with vertical black dashed lines in the figures.

|S_{11}| and |S_{21}| characteristics of proposed antenna as a function of the main patch height (h_{m1}) are given in Figure 3. In this parametric analysis, h_{m1} is swept in 2–4 mm range by 1 mm steps. Despite the fact that antenna covers larger BW when h_{m1} = 2 mm, stronger isolation and better matching level with sufficiently large BW are obtained at h_{m1} = 3 mm. The same procedure is also carried out for the parasitic patch layer height (h_{m2}) and the best performance is achieved when h_{m2} = 2 mm as shown in Figure 4. With these values (h_{m1} = 3 mm, h_{m2} = 2 mm), effect of parasitic patch can be seen better in Figure 5a that desired matching level and impedance BW cannot be achieved with a single main patch. Figure 5b shows simulations of antenna radiation patterns in H-plane plane (\theta = 90^\circ, -180^\circ < \phi < 180^\circ) by changing h_{m1} with fixed h_{m2} = 2 mm. It is observed that FBR gets better at lower h_{m1} values. As a result, principal design idea to place main patch at the lowest possible height to have good FBR and utilize parasitic patch to reach desired matching level, impedance BW and isolation is consistent. Moreover, overall antenna height can still be kept low profile without using any reflector.

![Figure 3](image-url). |S_{11}| and |S_{21}| as a function of the main patch height.

Figure 6 illustrates |S_{11}| and |S_{21}| of the antenna regarding axial ratio of the elliptic-H slots, Ax. This analysis is carried out as Ax is increased from 14.5 to 18.5 with increment of 1. When Ax = 16.5, antenna has two resonance points at 3.39 GHz and 3.74 GHz and 20% impedance BW for |S_{11}| < -15 dB. Furthermore, the highest isolation is attained at this value of Ax. However, isolation does not vary much with respect to Ax in desired operating band and its typical value is maintained to be |S_{21}| < -26 dB.
3.2. Effect of elliptic-H slot

Contribution of elliptic-H slots on the antenna performance is evaluated by comparing it with rectangular-H slots having the same length \((L_s = 15.98 \text{ mm})\) and area \((A_x \approx 11.186 \text{ mm}^2)\). Results of this comparison is illustrated in Figures 7 and 8. It is observed in Figure 7 that elliptic-H slots improve matching level and impedance BW with respect to rectangular-H slots. Improvement in matching level means more efficient energy coupling from slots to patches. The isolation is also improved in the desired band approximately by 3.5 dB with elliptic-H slots.

The mechanism for the isolation improvement can be demonstrated by examining the currents on the slot plane of feedline layer at 3.55 GHz. As shown in Figure 8, the current distribution between the elliptic-H
Figure 6. Effect of $A_x$ of elliptic-H slots on $|S_{11}|$ and $|S_{21}|$.

Figure 7. Comparison of elliptic-H slots and rectangular-H slots.

slots, especially around the center where most mutual coupling occurs between ports, are weaker than that of the rectangular-H slots. This weaker flowing current results in improvement in the isolation. As a result, one can say that use of elliptic-H slots helps to have desired matching level, impedance BW, and isolation.

4. Antenna performance

Proposed antenna is prototyped in accordance with descriptions in Section 2 and is shown in Figure 9. Air layers are formed by using plastic separators with appropriate heights. Overall size of the prototype is 110 $mm \times 110 mm \times 9.8 mm$. The numerical results are experimentally verified by S-parameters ($|S_{11}|$, $|S_{22}|$, and $|S_{21}|$) and radiation patterns (copol, crosspol) measurements. S-parameters are measured by HP 8720D vector network analyzer and radiation pattern measurements are performed in an anechoic chamber that is controlled by a MATLAB-based graphical user interface. The antenna is mounted on an absorptive structure in order to
Figure 8. Current distributions on the slot plane with elliptic-H slot and rectangular-H slot at 3.55 GHz.

Figure 10 plots the simulated and measured S-parameters of proposed antenna. They are consistent with the simulations. Antenna exhibits 18.5% impedance BW for $|S_{11}|, |S_{22}| < -15$ dB along 3.20–3.85 GHz.
Figure 9. Prototype antenna: a) feedline, b) elliptic-H slot, c) top view, and d) side view.

However $-10$ dB impedance BW ranges from 3.15 GHz to 3.96 GHz being 23.7%. Slight discrepancy between $|S_{11}|$ and $|S_{22}|$ is caused by the air bridge. The measured $|S_{21}|$ is $<-25$ dB in desired operating band (3.30–3.80 GHz).

The normalized copol and crosspol radiation patterns in E/H-planes are measured at 3.30 GHz, 3.55 GHz, 3.80 GHz frequencies within the operating band and plotted in Figure 11. Antenna exhibits stable, symmetric, directional patterns in both planes. Measured HPBWs are $64^\circ$, $62^\circ$, and $59^\circ$ in E-plane and $72^\circ$, $71^\circ$, and $69^\circ$ in H-plane at the corresponding frequencies, respectively. Gain of the antenna is measured to be about 7.9–8.4 dBi (Figure 12). XPD level within $\pm 15^\circ$ of bore-sight is $>22$ dB and FBR is $>23$ dB.
Figure 10. Measured and simulated S-parameters of the prototype.

Figure 11. Measured co/crosspol patterns in (a) E-plane and (b) H-plane.
Figure 12. Measured and simulated gain of proposed antenna.

Figure 13. Measurement environment. a) S-parameter measurement, b) radiation pattern measurement.
5. Conclusion
Throughout this paper, dual-polarized, broadband, slot-coupled patch antenna in a simple configuration is
designed and investigated for sub-6 GHz 5G base stations. Desired operating band is 3.3–3.8 GHz. Proposed
antenna is made up of main patch and parasitic patch layers above feedline layer and is excited by crossed elliptic-H slots. In summary, antenna exhibits 18.5% (3.23–3.85 GHz) impedance BW for $|S_{11}|$, $|S_{22}| < -15$ dB, isolation $|S_{21}| < -25$ dB. Antenna also has stable radiation patterns with HPBW s of 59°–64° and 69°–72° in E/H-planes, respectively with gain of 7.9–8.4 dBi. XPD level and FBR are > 22 dB and > 23 dB, respectively.

Simulated and measured radiation patterns show that proposed antenna is low profile with good FBR. As mentioned earlier, slot coupled antennas, in general, have poor FBR performance due to back radiation of slot. And in order to improve FBR, additional reflector plane or cavity backed structure is employed at the expense of increasing the antenna profile. In this design, placement of the main patch at a reasonably low height, then use of parasitic patch in combination with it, and use of elliptic-H slot all together provide the solution and helps to reach design specifications for impedance BW, matching level, isolation and good FBR. The overall height (9.8 mm) of the proposed antenna is still low profile as it can be verified among similar works in Table 2.

Table 2 lists the performances of proposed work and some other similar existing works, which are designed to operate in the same band (3.3–3.8 GHz). In order to make full comparison, note that [5, 6] are crossed-dipole antennas whereas [8] is magneto-electric dipole. [12, 16] are patch antennas with capacitively coupled probe feeds while [19] and [21–24] are slot coupled patch antennas. As can be seen from Table 2, proposed antenna outperforms the cited research by satisfying all the requirements of base station antenna. Considering the numerical and experimental results, proposed dual polarized single element antenna can be a good candidate to be used in the massive MIMO arrays of 5G base stations.

| Ref. | Antenna type | BW (GHz, %) | $|S_{21}|$ [dB] | FBR [dB] | Height [mm] | Refl. 1 |
|------|--------------|-------------|----------------|---------|-------------|--------|
| [5]  | Crossed-dipole | 3.20–3.90, 19.7% < −15 dB | < −40 | > 31 | 14 | N/A 2 |
| [6]  | Crossed-dipole | 3.50–5.10, 37.2%, < −15 dB | < −20 | > 10 | 17 | N/A |
| [8]  | Magneto-electric dipole | 3.05–4.55, 36.6%, < −15 dB | < −17 | > 20 | 21 | N/A |
| [12] | Probe-fed patch | 3.15–4.55, 37%, < −10 dB | < −38 | > 12.5 | 12.7 | N/A |
| [16] | Probe-fed patch | 2.86–4.12, 36%, < −15 dB | < −30 | > 28 | 13.4 | N/A |
| [19] | Slot-coupled patch | 3.30–3.80, 14%, < −10 dB | < −20 | > 30 | 37.2 | W 3 |
| [22] | Slot-coupled patch | 3.23–3.80, 17%, < −10 dB | < −50 | > 10 | 10.5 | W/O 4 |
| [23] | Slot-coupled patch | 3.25–3.80, 15.6%, < −15 dB | < −25 | > 18 | 12.2 | W |
| [24] | Slot-coupled patch | 3.30–3.60, 8.9%, < −15 dB | < −25 | > 16 | 18.8 | W |
| **This work** | Slot-coupled patch | 3.20–3.85, 18.5%, < −15 dB | < −25 | > 23 | 9.8 | W/O |

1 Refl: Reflector.
2 N/A: Not applicable.
3 W: With reflector.
4 W/O: Without reflector.

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