A Flexible and Compact 28 GHz Inset Fed Rectangular Patch Antenna Based on Circuit in Plastic Technology for 5G System

Salem A. Almazok

Electrical & Computer Engineering Department, Faculty of Engineering, Alasmarya Islamic University, Libya

ABSTRACT
This paper presents the use of circuit in plastic (CiP) as a new technology to develop a polycarbonate substrate microstrip patch antenna (PSMPA) for a fifth-generation (5G) system. The proposed compact PSMPA operates at a resonant frequency of 28 GHz and uses silver as a conductor instead of copper. The polycarbonate substrate has a thickness of 3 mm and a dielectric constant of 2.9. The inset feed technique is used as a feeding scheme to match the patch and the 50 Ω microstrip line. The proposed PSMPA structure has been simulated using Computer Simulation Technology (CST) Microwave Studio and its performance has been evaluated and compared with similar existing designs in the literature. The proposed PSMPA shows a return loss ($S_{11}$) of -23.011 dB, bandwidth (BW) of 1.173 GHz, voltage standing wave ratio (VSWR) of 1.3560, gain (G) of 5.684dBi, and radiation efficiency ($\eta_{rad} (\%)$) of 70.14%.

Keywords: Antenna. Antenna parameters. Circuit in plastic. Fifth-generation. Patch antenna. 28GHz frequency band.

Author Email: salemalmazok1986@gmail.com

1 INTRODUCTION
The antenna is an essential component of the wireless communication system that serves as a transducer for transmitting and receiving radio electromagnetic waves. In such a situation, the antenna behaves like an electrical element or a conductive tool that results in converting electromagnetic waves or radio frequencies into electrical energy. Nowadays, there is a rapidly growing need for higher data rates in wireless mobile communication networks. Due to the requirements of compact systems with large bandwidth and high data rates, wireless technologies have evolved from the first generation (1G) to the fifth generation (5G). Unfortunately, the current operating mobile networks still cannot meet all the requirements of end-users. To solve this problem, the 5G mobile network system has been developed. It is expected that the 5G system will greatly improve the communication capacity by utilizing an enormous amount of millimeter-wave (mm-wave) spectrum band [1,2]. In addition, the 5G system is expected to support and offer an extremely high data rate, which is hundreds of times the capacity of the fourth generation (4G) system [1,3,4]. The 5G system offers several advantages. The main advantages include wide bandwidth, high-security features, higher energy efficiency, and the ability to support numerous users simultaneously at a high speed. 5G is also capable of supporting rich multimedia features such as interactive gaming and video conferencing [5,6]. To meet the above requirements, the antenna in the 5G system and its parameters such as gain, directivity, and bandwidth can affect the overall performance of the 5G system.
In the 5G system, the antenna must be broadband to allow a high bit rate so that multiple applications can be reached. It should also provide high gain to reduce obstacles to radio waves [2,7].

Due to the advancement in wireless mobile technology, antennas must be lightweight, easy to install, compact (low profile), small, easy to manufacture, compatible with non-planar and planar surfaces, and fit in the area designed for the antenna in the mobile phone [2,6]. The microstrip patch antenna (MPA) can meet the criteria for mobile and wireless communication technologies. The MPA has advantageous features such as low cost, low profile, ease of fabrication and feeding, operation in multiple bands, and compatibility with non-planar and planar surfaces [6], [8]. The MPA consists of three layers, the bottom ground layer and the top patch layer, which is usually made of copper as the conducting element. These two layers are separated by a dielectric substrate [9]. Although copper is one of the most commonly used conductive elements in MPA, it is a contaminated material in the environment. Some studies are focusing on the development of alternative materials that can replace copper [10].

Circuits in plastic (CiP) is a new technique presented to fabricate fully waterproof circuits inside their area in the heat treatment phase [11]. This new CiP technique proposed to use transparent plastic as a substrate to be used in humid, dusty, and massive impact environments. Moreover, silver paint was used as a conductor instead of copper to minimize the negative impact on the environment [10]. In this work, a 28GHz MPA for 5G applications based on CiP principle has been presented as new technology. The novelty in this work is the use of a new CiP technology concept to develop an MPA for a 5G system. The proposed antenna based on CiP technology uses silver as the conductor for the ground and patch layers and transparent plastic polycarbonate as the substrate. The proposed polycarbonate substrate microstrip patch antenna (PSMPA) uses the inset feed technique and is simulated using Computer Simulation Technology (CST) Microwave Studio [12]. The rest of this paper is organized as follows. Section 2 presents the materials and methods, Section 3 presents the calculations of the proposed PSMPA and the design process, Section 4 presents the simulation results and discussion, and finally, Section 5 presents the conclusion and outlook for future work.

2 MATERIALS AND METHODS

To evaluate the performance of the proposed antenna and analyze the obtained results, firstly, the PSMPA design is needed, the designing process consists of multiple steps, these steps include identifying the operating resonant frequency and the bandwidth, selecting the substrate material type and its dimensions, determining the ground plane dimension, identifying the rectangular patch dimension and determining the feeding technique [13].

The PSMPA is designed to be inset feed broad-band and operated on the resonant frequency at 28GHz. The 28 GHz frequency band was specifically chosen for several reasons. First, there is a wide range of available and licensed mm-Wave bands around the 28 GHz band that is underutilized and can provide hundreds of megahertz to support 5G services [14,15].
Second, compared to other higher frequencies, the 28 GHz band is particularly well suited for creating multipath propagation environments and can be used for non-line-of-sight propagation [14]. In addition, the 28 GHz frequency band is one of the mm-Wave bands available in most countries around the world, making 28 GHz a globally harmonized frequency band [15]. The proposed PSMPA design uses new CIP technology so that silver material is used as a conductor for ground and patch layers, whereas transparent polycarbonate plastic is a substrate. Polycarbonate (PC) is classified under the thermoplastic noncrystalline polymers which is one of the plastic or polymer materials which represent the preferred materials for flexible antenna applications [16]. The used silver has a conductivity of 6.3012e+07 [S/m] and the used lossy PC for the substrate is a normal type with a dielectric constant $\varepsilon_r = 2.9$.

3 THE PROPOSED PSMPA CALCULATION AND DESIGN

Edges dimension calculations of the proposed PSMPA are performed to form the shape of the antenna and this calculation mainly depends on the operating frequency, the type of dielectric substrate, and its relative permittivity, which represent the design foundation of the PSMPA. In the first step, the maximum value for the thickness of the substrate was identified based on the following formulation [13].

\[
S_{th} \leq \frac{0.3c}{2\pi f_r \sqrt{\varepsilon_r}} \leq \frac{0.3 \times 10^8}{2 \pi \times 28 \times 10^9 \sqrt{2.9}} \leq 0.3\text{mm} \tag{1}
\]

Where $S_{th}$ is the substrate thickness, $c = 3 \times 10^8$ is the speed of electromagnetic waves in free space, $f_r$ is the resonant frequency and $\varepsilon_r$ dielectric constant.

The next step is to calculate the width of radiating patch based on the following calculation [13]:

\[
W_p = \frac{c}{2\pi f_r \sqrt{\varepsilon_r}} = \frac{3 \times 10^8}{2 \times 28 \times 10^9 \sqrt{2.9+1}} = 3.84\text{mm} \tag{2}
\]

Where $W_p$ is the patch width.

Regarding the length of radiating patch, the effective dielectric constant $ee\varepsilon_r$ of the substrate is needed to be calculated first. it is determined based on the following formula[13] :

\[
ee\varepsilon_r = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{\sqrt{2 + 12(\frac{S_{th}}{W_p})}} = \frac{2.9+1}{2} + \frac{2.9-1}{\sqrt{2 + 12(\frac{0.3}{3.84})}} = 2.63 \tag{3}
\]

After calculating $ee\varepsilon_r$, the patch effective length $l_e$ also need to be calculated according to the following equation [13] :

\[
l_e = \frac{c}{2\pi \sqrt{ee\varepsilon_r}} = \frac{3 \times 10^8}{2 \times 28 \times 10^9 \sqrt{2.63}} = 3.30\text{ mm} \tag{4}
\]

Next, the decrement value $\Delta l$ in patch length is also needed to be calculated to determine the final patch length, $\Delta l$ is calculated using the following formula [13]:

\[
\Delta l = \frac{0.412 \times S_{th} (ee\varepsilon_r+0.3) (\frac{W_p}{S_{th}} + 0.264)}{(ee\varepsilon_r-0.258)(\frac{W_p}{S_{th}} + 0.8)} = \frac{0.412 \times 0.3 \times 10^{-3} (2.63+0.3) (\frac{3.84}{0.3} + 0.264)}{(2.63-0.258)(\frac{3.84}{0.3} + 0.8)} = 0.15\text{ mm} \tag{5}
\]

Then, the value of patch length $L_p$ is calculated as following [13]:

---

Journal of Alasmerya University: Basic and Applied Sciences

مجلة الجامعة الأсмерية: العلوم الأساسية والتطبيقية
A Flexible and Compact 28 GHz Inset Fed Rectangular Patch Antenna Based on Circuit in Plastic Technology for 5G System

\[ L_p = l_e - 2\Delta l = 3.30 - 2(0.15) = 3\text{mm} \]

After determining the patch dimensions, the dimensions of the ground plane also need to be calculated. The length of the ground plane, \( L_g \), is calculated using the following equation [13]:

\[ L_g = L_p + 6S_{th} = 3 + 6(0.3) = 4.8\text{mm} \]

The width of the ground plane, \( W_g \), is calculated using the following equation [13]:

\[ W_g = W_p + 6S_{th} = 3.84 + 6(0.3) = 5.64\text{mm} \]

Taking into account that the dielectric substrate is placed and adjusted on the ground plane so that the substrate has assumed to have the same dimensions.

The used silver material as a conductor for ground and patch layers has thickness (Ag_{th}) of 0.015 mm. The thickness was chosen to be 0.015 mm to account for the fact that the thickness of the conductor is several times skin depth [17], so 0.015 mm was thick enough. Moreover, this thickness of silver (0.015 mm) is one of the options available on the market.

For calculating the inset feed depth, \( F_i \), the following formula is used to determine the inset depth [4]:

\[ F_i = 10^{-4}[0.001699\varepsilon_r^7 + 0.1376\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 25619.9\varepsilon_r^2 - 4043\varepsilon_r + 6697] \frac{L_p}{2} \]

\[ F_i = 10^{-4}[0.001699(2.9)^7 + 0.1376(2.9)^6 - 6.1783(2.9)^5 + 93.187(2.9)^4 - 682.69(2.9)^3 + 25619.9(2.9)^2 - 4043(2.9) + 6697] \frac{3 \times 10^{-3}}{2} = 1.17\text{mm} \]

Also, there are auxiliary parameters A and B that need to be determined to calculate the dimensions of the feed line with characteristic impedance \( Z_c = 50 \Omega \) [13]:

\[ A = \frac{Z_c}{60\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}} (0.23 + 0.11) = \frac{50}{60} \sqrt{\frac{2.9+1}{2}} + \frac{2.9-1}{2.9+1} (0.23 + 0.11) = 1.29 \]

\[ B = \frac{60\pi^2}{Z_c\sqrt{\varepsilon_r}} = \frac{60\pi^2}{50\sqrt{2.9}} = 6.95 \]

Considering auxiliary parameter A is lower than 1.52, the feed line length \( L_f \) and its width \( W_f \) can be determined from the following equations [13]:

\[ L_f = 3S_{th} = 3(0.3) = 0.9\text{mm} \]

\[ W_f = \frac{2}{\pi} \left\{ B - 1 - \ln(2B - 1) + \frac{\varepsilon_r-1}{2\varepsilon_r} \left[ \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r} \right] \right\} S_{th} \]

\[ W_f = \frac{2}{\pi} \left\{ 6.95 - 1 - \ln(2 \times 6.95 - 1) + \frac{2.9-1}{2 \times 2.9} \left[ \ln(6.95 - 1) + 0.39 - \frac{0.61}{2.9} \right] \right\} \times 0.3 \times 10^{-3} \]

\[ W_f = 0.79\text{mm} \]

The notch width \( g \) was selected to be \( g = 0.014 \text{ mm} \).

Up to this stage, the numerical model for the designing process of the proposed PSMPA is completed, the previous values were used for the initial design. However, The \( L_p \) is manually changed from 3 mm to 3.030 and \( W_p \) changed from 3.84 to 4.50 mm to adjust the resonant
frequency to be at 28 GHz and enhance the performance parameters of PSMPA. The change in \( L_p \) leads to an insignificant change in \( L_f \) to become 0.8851 mm instead of 0.9 mm. The PSMPA design parameters are tabulated in Table 1. The designed simulated PSMPA in CST studio is shown from the top and back view sides in Figure 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Thickness</td>
<td>( S_{th} )</td>
<td>0.3.</td>
</tr>
<tr>
<td>Patch Width</td>
<td>( W_p )</td>
<td>4.50.</td>
</tr>
<tr>
<td>Patch Length</td>
<td>( L_p )</td>
<td>3.030.</td>
</tr>
<tr>
<td>Ground Plane Width</td>
<td>( W_g )</td>
<td>5.64.</td>
</tr>
<tr>
<td>Ground Plane Length</td>
<td>( L_g )</td>
<td>4.8.</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>( \varepsilon_r )</td>
<td>2.9.</td>
</tr>
<tr>
<td>Substrate Width</td>
<td>( W_s = W_g )</td>
<td>5.64.</td>
</tr>
<tr>
<td>Substrate Length</td>
<td>( L_s = L_g )</td>
<td>4.8.</td>
</tr>
<tr>
<td>Feed Line Width</td>
<td>( W_f )</td>
<td>0.79.</td>
</tr>
<tr>
<td>Feed Line Length</td>
<td>( L_f )</td>
<td>0.8851.</td>
</tr>
<tr>
<td>Silver Thickness</td>
<td>( A_{s_{th}} )</td>
<td>0.015.</td>
</tr>
<tr>
<td>Inset feed depth</td>
<td>( F_i )</td>
<td>1.17</td>
</tr>
<tr>
<td>Notch Width ( g )</td>
<td>( G )</td>
<td>0.014</td>
</tr>
</tbody>
</table>

*Figure 1. PSMPA top and back view sides: (a) PSMPA top view side; (b) PSMPA back view side.*
4 RESULTS AND DISCUSSION

The proposed designed PSMPA was simulated using CST Microwave Studio to evaluate its performance, there are five parameters were used for this purpose, these parameters include: return loss $S_{11}$, bandwidth BW, voltage standing wave ratio VSWR, gain G, and radiation efficiency $\eta_{rad}$ (%).

4.1 Return Loss $S_{11}$

Return loss $S_{11}$ is measured in dB and it represents the ratio between the incident power and reflected power of the MSPA [18,19], $S_{11}$ also named as reflection coefficient [13,18,19]. -10 dB value of $S_{11}$ is selected as the reference value which indicates that 90% of incidental power is received by the antenna and only 10% of the power is reflected, this percentage is considered good for the mobile communication system [13]. Hence $S_{11}$ should be a minimum -10 dB to provide effective performance [18,19]. Simply $S_{11}$ tells how much power is reflected. The lower $S_{11}$, the better performance of the antenna is achieved. Figure 2 shows the result of $S_{11}$ concerning the frequency. It can be observed from the figure that at 28 GHz, $S_{11}$ value is -23.011 dB which is considered a good value of $S_{11}$ as it means only 0.49% of the input power is reflected.

![Figure 2. $S_{11}$ with respect to frequency of PSMPA](image-url)
4.2 Bandwidth BW
The BW of the proposed PSMPA can be calculated as the difference between the frequencies where $S_{11}$ is lower than -10 dB [2], based on Figure 2, BW will be in this case the difference between 28.609 GHz and 27.436 GHz ($28.609 - 27.436 = 1.173$ GHz). Accordingly, the PSMPA has $BW=1.173$ GHz which is very good compare to others in the literature.

4.3 Voltage Standing Wave Ratio VSWR
VSWR is a quantity that represents the amount of reflected power from the antenna toward the transmitter [2]. In terms of MSPA, VSWR should not exceed 2 and less than 1 across the bandwidth of the antenna. In an ideal case, VSWR equals 1[4, 13]. Figure 3 shows VSWR versus the frequency of the proposed PSMPA. It can be observed from the figure that the value of VSWR at the resonant frequency is 1.1519. It is an acceptable VSWR value as it is lower than two.

4.4 Gain G and Radiation Pattern
To show the antenna gain and other antenna characteristics such as directivity and lobes features, a radiation pattern plot in 2-D and 3-D can be used [2]. The radiation pattern is an important parameter that indicates the amount of radiated energy by MPA [18,19]. In terms of gain, it can be defined as the ratio between the power density of the MPA at a specific point to the power density of the reference isotropic antenna at the same point when both antennas feed by the same power [6]. The introduced PSMPA shows a gain of 5.648 dBi at the resonant frequency as occurs in Figure 4 of the 3-D radiation pattern plot, which is considered a competitive value for compact MSPA.

![Figure 3. VSWR with respect to frequency of PSMPA.](image-url)
In addition, the PSMPA has 86.8° for half-power beamwidth and -14.9 dB for side lobe level value as shown in figure 5 of the 2-D radiation pattern plot.

**Figure 4. 3-D radiation pattern plot of PSMPA**

**Figure 5. 2-D radiation pattern plot of PSMPA.**

4.5 Radiation Efficiency $\eta_{rad}$ (%)

Radiation efficiency $\eta_{rad}$ (%) represents one of the useful performance parameters to indicate how much the antenna is good at transmitting and receiving electromagnetic waves. $\eta_{rad}$ (%) can be defined as the ratio between the total power radiated by MPA and total input...
power received by MPA [19]. \( \eta \text{rad} (\%) \) indicated how much of the input power received by MSPA radiated effectively in free space. The higher \( \eta \text{rad} (\%) \), the better performance of the antenna is obtained. The introduced PSMPA shows a radiation efficiency of -1.544 dB as indicated in Figure 4. This value is equivalent in percentage to 70.14 %, which can be considered a reasonable result.

4.6 Comparison of the Introduced PSMPA with other Similar Designs

The obtained simulation results of the proposed PSMPA and other results of similar patch antennas presented in the literature are organized in Table 2. The results in Table 2 indicate that the proposed PSMPA shows the lowest \( S_{11} \) value in comparison with antennas design introduced in [4,20,21], the lower \( S_{11} \) implies less power is reflected and better performance of the antenna is achieved. Regarding BW, The introduced PSMPA indicates the widest bandwidth in comparison to designs cited in [4,20,21]. The wider bandwidth is suitable for a 5G system which needs wide bandwidth. Furthermore, from Table 2 the proposed design shows lower VSWR than designs cited in [4,20,21]. The VSWR of the proposed antenna structure is closer to the ideal value of 1. On the other hand, the proposed design exhibits relatively low realized gain compare to the gain (IEEE) of antenna reported in [20] and also lower than realized gain of antenna reported in [4]. Moreover, the realized gain of the proposed structure is relatively lower than the gain of the antenna cited in [21]. In terms of \( \eta \text{rad} (\%) \), the introduced design shows a reasonable percentage of radiation efficacy, and it is 0.04 % lower than the antenna design reported in [4]. In general, the simulation results of the proposed PSMPA structure indicates a competitor performance in comparison with similar previous designs introduced in the literature.

Table 2. Comparison of simulation results between introduced PSMPA and similar published researches.

<table>
<thead>
<tr>
<th>Work Ref. No.</th>
<th>( S_{11} ) (dB)</th>
<th>BW(GHz)</th>
<th>VSWR</th>
<th>G</th>
<th>( \eta \text{rad} (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>-13.48</td>
<td>0.847</td>
<td>1.5376</td>
<td>6.630dB</td>
<td>70.18%</td>
</tr>
<tr>
<td>[20]</td>
<td>-14.15084</td>
<td>0.8</td>
<td>1.4878</td>
<td>6.061dBi</td>
<td>-</td>
</tr>
<tr>
<td>[21]</td>
<td>-12.59</td>
<td>0.582</td>
<td>1.77</td>
<td>6.69 dB</td>
<td>-</td>
</tr>
<tr>
<td>Present research</td>
<td>-23.011</td>
<td>1.173</td>
<td>1.3560</td>
<td>5.684dBi</td>
<td>70.14%</td>
</tr>
</tbody>
</table>

5 CONCLUSION AND FUTURE WORK

This work introduces the use of CiP as new technology to design a 28 GHz inset feed polycarbonate substrate microstrip patch antenna PSMPA for a 5G system. The conducted simulations using CST Microwave Studio indicate that the introduced design has \( S_{11} \) value of -23.011 dB, 1.173 GHz bandwidth value, and VSWR is 1.3560 in comparison with similar structures. The proposed structure shows better performance in terms of \( S_{11} \), BW and VSWR. However, the limitation of the proposed design is relatively lower gain and radiation efficiency compared to similar structures presented in the literature. The scope for future work can be done to improve the gain and radiation efficiency of the proposed PSMPA structure.
A Flexible and Compact 28 GHz Inset Fed Rectangular Patch Antenna Based on Circuit in Plastic Technology for 5G System

6 REFERENCES

تصميم هوائي شريطي مستقبل مرن ومضغوط بتجزئة داخلية عند تردد 28 جيجاهرتز

١٠ سالم عبدالله المزوعق
قسم الهندسة/कर्नाटक वर्सिटी और الحاسوب، كلية الهندسة، الجامعة الأسرمية الإسلامية، زليتن، ليبيا

الملخص

يتم في هذا البحث كيفية تطبيق تقنية الدائرة البلاستيكية (CTP) لتحسين نوعية هوائي شريطي الدقيق (PSMPA) بسعة عالية. تم استخدام تقنية مضغوط المضمن 28 جيجاهرتز لتحسين الإفرازات الشارقة الداخلية (SWR) في النظام. المحاكاة الكبيرة والبلاستيكية سهلة الاستخدام، حيث يتم تقييمها بواسطة محاكاة الكبيرة. يتم استخدام تقنية مضغوط المضمن 28 جيجاهرتز لتحسين إفرازات الشارقة الداخلية (SWR).

الكلمات المفتاحية:
- البلاستيك
- محاكاة الكبيرة
- الدائرة البلاستيكية
- هوائي شريطي الدقيق
- النطاق التردد
- انتشار الإشارة
- كفاءة الإشارة
- التردد

البريد الإلكتروني للباحث:
salemalmazok1986@gmail.com