Design of a Compact Circular Microstrip Patch Antenna for 5G Applications

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ABSTRACT

This paper presents the design and analysis of a compact circular microstrip patch antenna for 5G millimeter wave technology applications. The dimensions of the proposed patch are 5.959 mm × 5.959 mm × 1.400 mm. The antenna exhibits a resonant frequency of 28 GHz, a return loss of -45 dB, a bandwidth of 1.7638 GHz, and a gain of 0.1573. In order to meet the requirements of 5G applications at 28 GHz, a compact, high-gain, and large bandwidth antenna is necessary. The principal objective of this study is to enhance the performance of the antenna parameters, thereby achieving an optimal balance between size, gain, and bandwidth. A notable improvement in bandwidth and gain is achieved. The design, analysis, and optimization processes were conducted using the High Frequency Surface Structure (HFSS) software, which employs the Finite Element Method (FEM) numerical method.

Keywords-microstrip antenna; compact size; 5G applications; millimeter wave band

I. INTRODUCTION

Over the past few decades, there has been a significant increase in the demand for mobile connections, data rates, and mobile data traffic [1-3]. The rapid growth of the 5G network will have a profound impact on numerous industries, including blockchain, artificial intelligence, ultra-high definition, and Internet of Things (IoT) services such as smart grids, smart transportation, and smart cities. These sectors will be significantly enhanced by the advent of 5G [4-6]. A range of spectrum bands, including millimeter wave radio spectrum, which can carry massive volumes of data over short distances, may be used by 5G technology [7, 8]. To satisfy the needs of the new generation, the 20 GHz to 90 GHz band is used for 5G applications [9, 10]. The frequencies employed in 5G antenna design include 26 GHz, 28 GHz, 38 GHz, and 72 GHz. In comparison to other frequencies, the antenna operating at 28 GHz has been demonstrated to yield superior results [11].

Microstrip patch antennas are optimal for 5G applications, which utilize higher frequency ranges. Furthermore, microstrip patch antennas are cost-effective, have a low weight, are simple to manufacture, and are easy to integrate. Microstrip antennas are available in a wide variety of radiating patch shapes, including square, rectangular, circular, triangular, elliptical, and more. Patch antennas with square and circular shapes are more frequently employed since they are relatively simple to both design and analysis [13]. The circular patch antenna can be designed with greater ease and its radiation can be more readily controlled [14]. Furthermore, at the same design frequency, the circular patch antenna is approximately 16% smaller than alternative configurations [15, 16]. Nevertheless, the patch antenna is subject to limitations in bandwidth and gain. Consequently, extensive research has been carried out over the past few years with the objective of overcoming these limitations. Nowadays, the design of a low-profile microstrip antenna with a large bandwidth and high gain is a significant challenge. One method to improve the bandwidth and gain is the use of partial substrate removal in multiple layer dielectric substrate [17]. In research [18] a proximity coupled fed antenna is used to enhance the antenna's gain and bandwidth. A rectangular patch antenna with Electromagnetic Band-Gap (EBG) substrate is proposed in [19]. In [20] a stacked-patch geometry is proposed and in [21] parasitic elements are added. A design of a dual band Planar Inverted-F Antenna (PIFA) enhances the bandwidth [22]. This work presents a microstrip antenna with a wide bandwidth and low profile, designed for 5G communications. The proposed antenna is designed to resonate at 28 GHz and has a low-profile structure with dimensions of 5.959 mm × 5.959 mm × 1.400 mm

II. ANTENNA DESIGN

In the context of antenna design, it is assumed that the height of the substrate h, the resonant frequency f_r, and the dielectric constant of the substrate ε_r are known. The design parameters of a circular microstrip patch antenna are then determined using a set of simplified cavity model equations, and the radius of the circular patch is given by the following [23]:

$$R = \frac{F}{\left[1+\frac{2h}{\pi F \varepsilon_r}\left(ln\left(\frac{\pi F}{2h}\right)+1.7726\right)\right]^{0.5}} \quad (1)$$

with F being:

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \quad (2)$$

and R being the radius of the patch, h being the substrate thickness, f_r being the resonant frequency, and ε_r being the dielectric constant of substrate.

Instead of using the real radius R for the circular microstrip antenna, an effective radius R_e is used as a correction factor:

$$R_e = R\left\{1+\frac{2h}{\pi\varepsilon_r h}\left[ln\left(\frac{\pi R}{2h}\right)+1.7726\right]\right\}^{1/2} \quad (3)$$

Length L_s and width W_s of the substrate can be calculated respectively [23] by:

$$L_s = 2\times 2a$$

$$W_s = 2\times 2a$$

Figure 1 illustrates the proposed circular patch antenna's geometry.

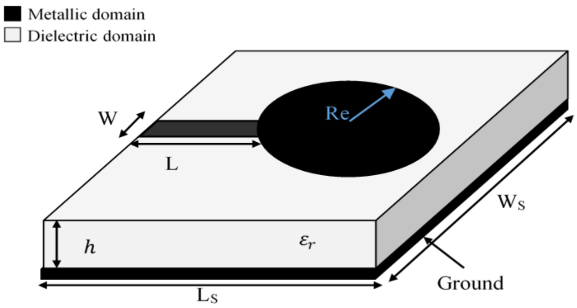

Fig. 1. Geometry of proposed microstrip circular patch antenna.

The antenna is printed on a FR4 substrate having relative permittivity of 4.4 and substrate thickness of 1.4 mm. The dimensions of ground plane, which is printed in the bottom side of the substrate, are 5.959 mm×5.959 mm. The radius of the circular slot is 1.49 mm. The detailed dimensions of the proposed antenna are shown in Table I.

TABLE I. DESIGN PARAMETERS OF THE ANTENNA

Parameter Name	Value
Resonant frequency (f_r)	28 GHz
Substrate length (L_s)	5.959 mm
Substrate width (W_s)	5.959 mm
Patch radius (R_e)	1.49 mm
Dielectric constant (ε_r)	4.4
Substrate thikness (h)	1.4 mm

The patch antenna is designed using (HFSS). The reflection coefficient S_{11} of the proposed design is shown in Figure 2 and it indicates a resonant frequency of 28 GHz, a return loss of -45 dB, a bandwidth of 1.7638 GHz and a gain of 0.1573. The 2D radiation plot of the proposed antenna is shown in Figure 3, at $phi = 0^{\circ}$ and $phi = 90^{\circ}$.

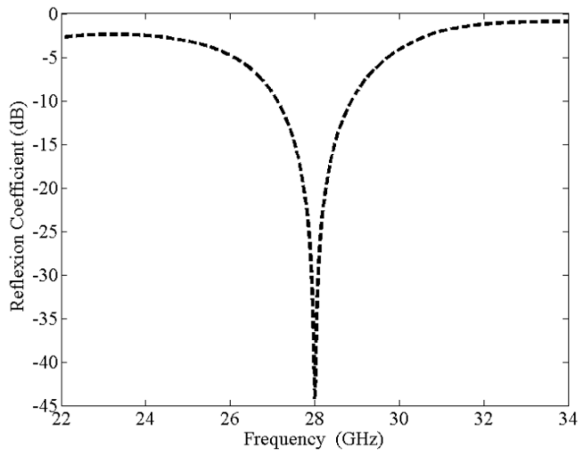

Fig. 2. Return loss S_{11} plot.

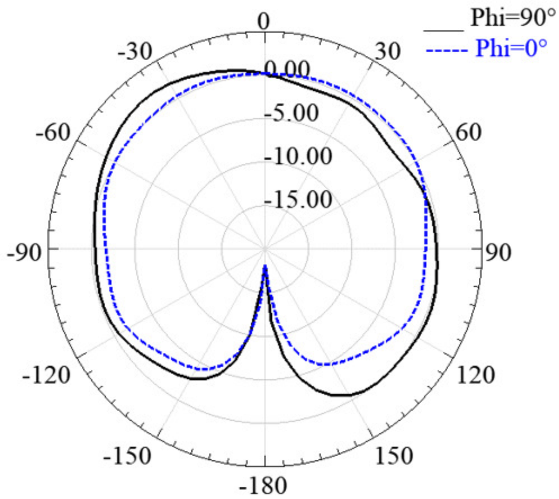

Fig. 3. Polar plot of far-field E – field pattern at 28 GHz.

III. BANDWIDTH AND GAIN ENHANCEMENT

A. Gain Enhancement

In order to achieve an improvement in the gain, three modifications have been proposed to the antenna structure. A notch and two slots are inserted on the circular patch, and a rectangular slot is loaded on the feed line, as shown in Figure 4. Following an examination of the effects of varying slot dimensions and notch widths on gain and Ultra-Wideband (UWB) antenna requirements, it was determined that the optimal dimensions were L_n = 0.1 mm and W_n = 0.5 mm for the notch, L_f = 0.7 mm and W_f = 0.1 mm for the two slots on the patch, and L_r = 0.1 mm and W_r = 0. The two slots on the patch have a length of L_f = 0.7 mm and width W_f = 0.1 mm, while the rectangular slot on the feed line has a length of L_r = 0.1 mm and width W_r = 0.5 mm. The 2D radiation plot of the antenna 2 and its correspondent gain are shown in Figure 5. An improvement of the gain from 0.1573 to 3.2838 is achieved.

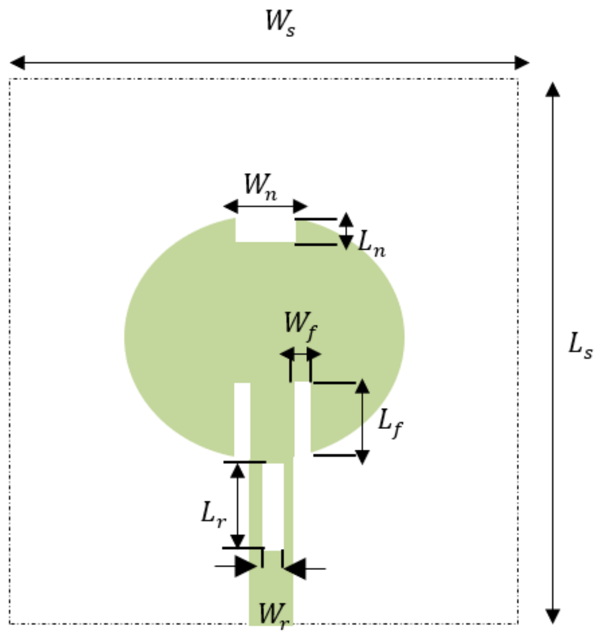

Fig. 4. Overview of proposed antenna 2 with slots and notch.

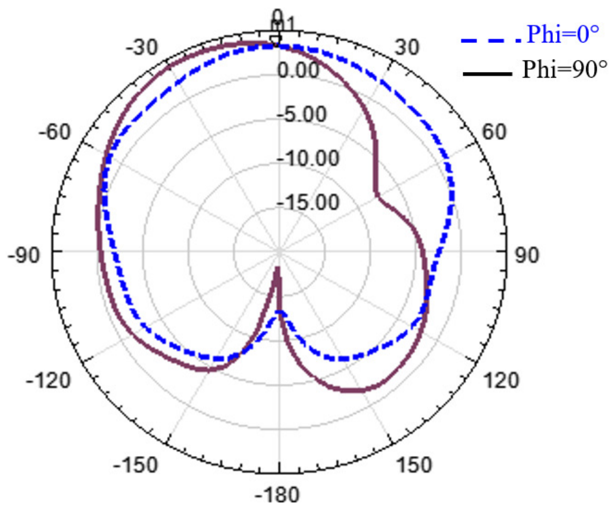

Fig. 5. Polar plot of Far-field E – field pattern of proposed antenna 2.

B. Bandwidth Enhancement

In order to enhance the bandwidth of the proposed antenna, a novel Defected Ground Structure (DGS) is incorporated beneath the antenna 2, as shown in Figure 6. An in-depth parametric analysis was performed in order to identify the optimal radius dimension of the circular DGS. An increase in the bandwidth from 1.7638 GHz to 12.2 GHz (Figure 7) is observed for a radius of the DGS R = 1.2 mm. Nevertheless, the gain has decreased to 0.4172, as shown in Figure 8.

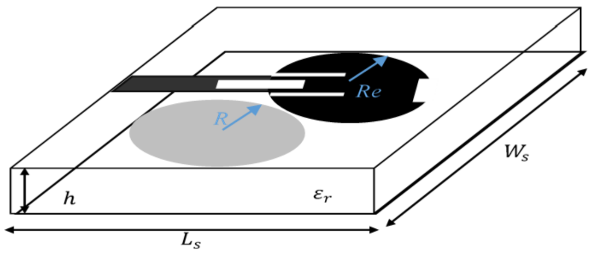

Fig. 6. Geometry of proposed antenna 3 with circular DGS.

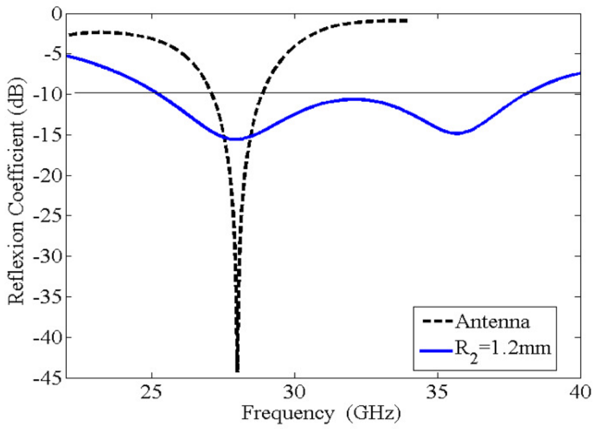

Fig. 7. Reflection coefficient of proposed antenna 3.

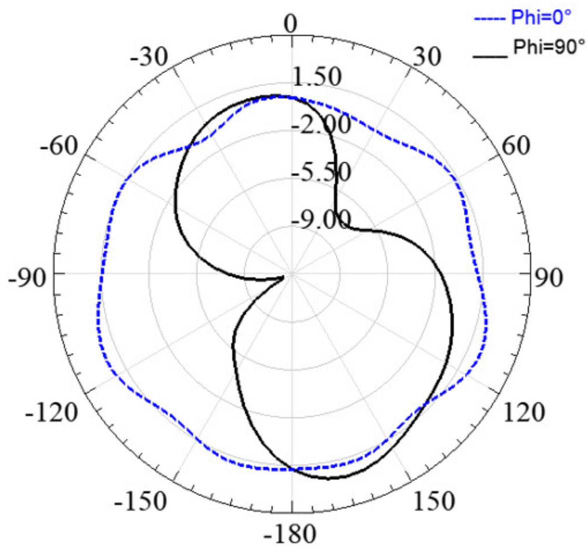

Fig. 8. Polar plot of Far-field E – field pattern and gain of antenna 3 at 28 GHz.

C. Bandwidth and Gain Enhancement

It is proposed that a second metallic ground plane be added at a distance of 2 mm from the DGS, as shown in Figure 9. The obtained results are satisfactory, as the UWB of 13.75 GHz was successfully obtained, as well as a considerable improvement in gain from 0.4172 to 5.8174, as can be seen in Figure 10 and Figure 11, respectively.

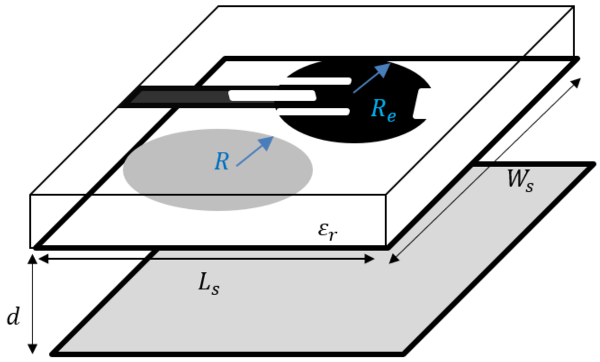

Fig. 9. Geometry of proposed antenna 4.

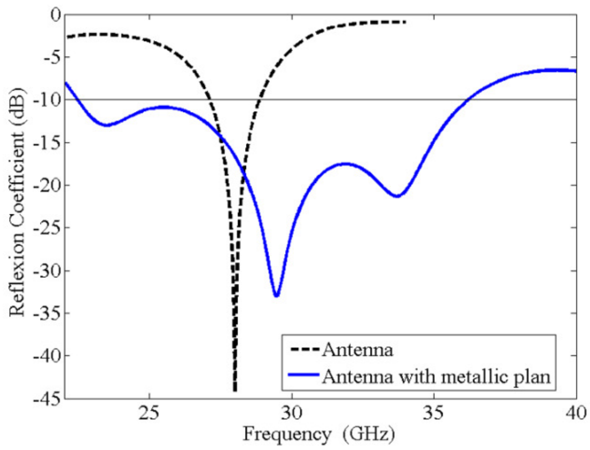

Fig. 10. Return loss S_{11} of antenna 4.

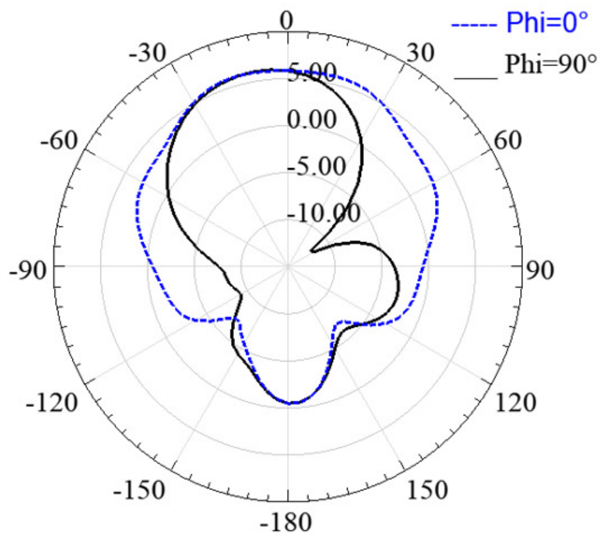

Fig. 11. Polar plot of Far-field E – field pattern and gain of antenna 4 at 28 GHz.

Table II presents a comparison of the observed results of the proposed antenna with those of the existing design for 5G applications.

TABLE II. COMPARISON WITH EXISTING WORKS

Reference	Dimensions (mm)	Frequency (GHz)	Return loss (dB)	Bandwidth (GHz)
[24]	6 × 6	28.5	-32.86	1.6369
[25]	6 × 6	28.45	-40	1.3
[26]	6 × 6	26	-33.40	3.56
[27]	7.4 × 6.25	39.22	-31.25	3.225
[28]	15 × 8	28	-24	0.280
[8]	6.285 × 7.235	27.954	-13.48	0.847
[11]	7 × 7	28	-27.79	2.62
Proposed antenna4	5.959 × 5.959	29. 5	-32.9	13.75

IV. CONCLUSION

The objective of this study is to develop a compact circular microstrip patch antenna for 5G applications. The proposed antenna operates at a frequency of 28 GHz with a gain of 0.1573 and a bandwidth of 1.7638 GHz. The incorporation of a DGS and the implementation of modifications to the patch and the feed line result in an enhancement in the gain and the bandwidth. The new antenna operates from 22.46 GHz to 36.21 GHz, with a gain of 5.8174, which covers the 5G spectrum in different countries, such as the 26 GHz band in Europe and the 28 GHz band in the USA, without increasing the size of the antenna. The proposed antenna is well-suited to mobile devices or devices where space is a significant constraint.

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