Journal of Nano- and Electronic Physics
Vol. **18** No 2, 02021(5pp) (2026)

Журнал нано- та електронної фізики
Том **18** № 2, 02021(5cc) (2026)

REGULAR ARTICLE

A Multi Band Dual Slot CPW Fed Circular Ring Microstrip Patch Antenna for 5G mmWave Applications

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(Received 28 January 2026; revised manuscript received 20 April 2026; published online 29 April 2026)

This article presented a small circular ring patch antenna with multiple bands for 5G mmWave applications. By operating over five distinct frequency bands, this innovative approach increases performance metrics by the incorporation of a dual hexagon shaped slot into the patch. An antenna's return loss is substantially increased with the addition of the slot. A 2 mm thick silicon dielectric material with a dielectric constant of 11.7 was used in the proposed structure. The total dimension of the antenna is 10 × 10 × 2.07 mm^3. While maintaining a small radiator size, the suggested antenna accomplishes multi band operation. The developed radiator can function in five distinct frequency ranges, from 13.7 to 13.8 GHz, 18.4 to 18.6 GHz, 21.3 to 21.4 GHz, 21.9 to 22.1 GHz, and 23.6 to 23.7 GHz, with five distinct resonance frequencies of 13.75, 18.5, 21.35, 22.0, and 23.7 GHz, respectively. A peak gain of 7.9, 9.4, 9.2, 8.9 and 8.3 dBi, radiation efficiency of 77, 88, 84, 81 and 79% are attained at resonance. The suggested antenna has many benefits, such as a high radiation efficiency, a high gain, and support for multiple bands. In order to enhance performance over the operational frequency range with regard to the reflection coefficient (S_{11}), a thorough parametric analysis was carried out using the CST simulator. The effects of different conducting materials (iron, gold, and copper) and dielectric materials (FR-4, polyimide, and silicon) on the proposed antenna's response are also investigated. This article details the process for designing antennas and analyses their field and current distributions.

Keywords: Antenna, Multi band, Reflection coefficient, Radiation efficiency, Gain.

DOI: 10.21272/jnep.18(2).02021 PACS number: 84.40.Ba

1. INTRODUCTION

In today's wireless communication environment, antennas that offer a blend of cheap cost, radiation efficiency, profile, and high gain are becoming more and more important. It is expected that this need will rise. One of these solutions that stands out because to its highly desirable properties is the dielectric resonator antenna. There is a wide variety of sizes and forms available in the market for these antennas, but there are two primary factors in favour of the circular ring design. The first benefit is that it gives you two degrees of freedom, which means you can control the quality factor more precisely. Improving the antenna's performance demands fine-tuning this control. Secondly, the resonating antenna has the capability to manage three distinct modes. The ability to communicate on higher frequency bands requires antennas that are small, conformal, cheap, and easily fabricable in the context of wireless communication. With the constant improvement of high-speed and multifunctional electronics, a favorable environment for small multiband antennas is emerging [1-2]. Microstrip antennas are highly advantageous among multiband antennas due to their small size and low profile. Contrarily, microstrip patch antennas have a number of major drawbacks, such as low gain, high loss, poor radiation efficiency, and restricted bandwidth. A number of approaches are now under consideration as potential solutions to these problems [3]. Arrays of patch antennas, changing the substrate's thickness, building many layers of substrate, and altering the patch's basic geometry with metamaterials and metasurface [4]. An antenna measuring 70 × 70 mm^2 that uses a 3D-printed superstrate and operates at two frequencies achieves a peak-gain of 7.5 dBi, making it appropriate for use in the ISM band [6]. Another example is an FSS that uses concentric square loops as a conducting patch and metamaterial [5] to improve performance. A microstrip patch with dimensions of 40 × 49 mm^2 is suggested in reference [7] that employs a meta surface for polarization conversion by means of etching the corresponding split ring resonator. A compact circular radiating element with two resonant bands encompassing 2.39-3.75 GHz and 5.39-7.18 GHz, with an overall dimension of 30 × 40 mm^2, was proposed in [9] for a variety of wireless applications [8]. A new structure measuring

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Cite this article as: M. Valathuru et al., *J. Nano- Electron. Phys.* 18 No 2, 02021 (2026) https://doi.org/10.21272/jnep.18(2).02021

$35 \times 34 \times 1.6$ mm^3 was created by Nafis [10]. This design operates at 4.19 and 4.91 GHz, with a bandwidth of 4.4-5 GHz and 3.3-4.2 GHz. Additionally, flexible antennas for a variety of applications are being developed [11-13].

This article presents a novel approach that uses a hexagon-shaped slot and circular ring to improve the gain, return loss, and compactness of multi-band patch antennas. An intermediate layer of silicon with a permittivity of 11.7 was used to form the ground and radiating planes, with copper that was 0.035 mm thick. In order to evaluate the proposed antenna's performance, previous research is compared with its dimensions, operating frequencies, gain, VSWR, and return loss.

2. PRESCRIBED ANTENNA CONFIGURATION

As seen in Fig. 1, the suggested design comprises of a hexagon slot-type antenna on a circular ring. The ground layer of the traditional three-layer construction is made of copper and measures $10 \times 10 \times 0.035$ mm^3. The total dimensions of the intermediate silicon layer are $10 \times 10 \times 2$ mm^3. The radiating patch has an overall dimension of $8 \times 8 \times 0.035$ mm^3. The specified structure's measurements are as follows: $a_1 = 6$, $a_2 = 4$, $a_3 = 2$, $b = 2.5$, $c = 1$, and $d = 0.5$.

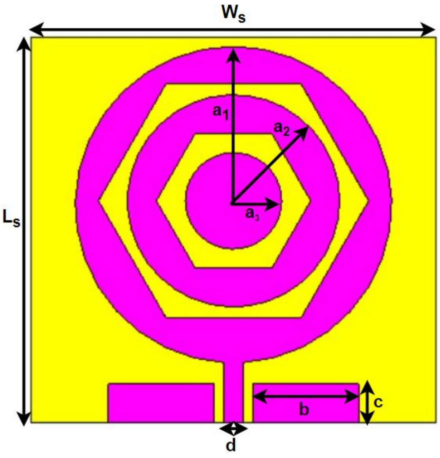


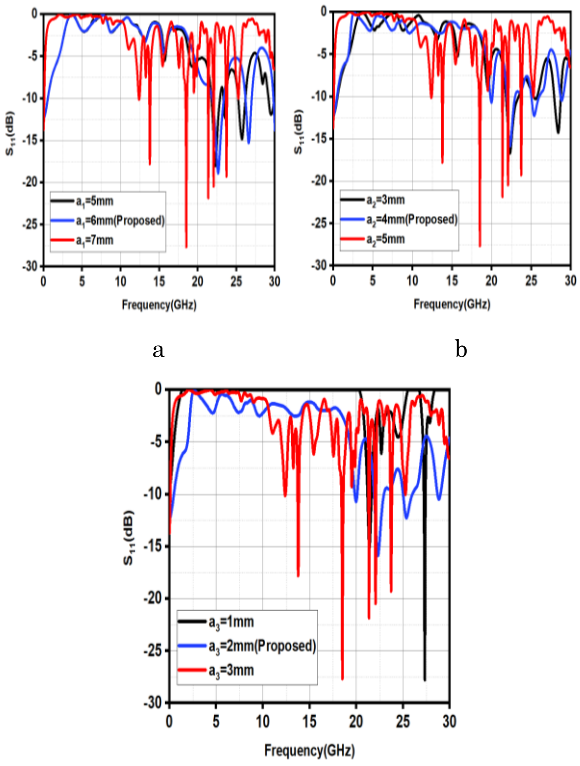
Fig. 1 – Top perspective of the suggested antenna

The CST tool is used to tackle electromagnetic problems that require precise and fast simulation results. The primary benefit of this tool is that it has simple needs for resources to scale linearly with regard to the number of nodes in the mesh. This makes controlling massive radiating structures easy and effective.

3. PARAMETRIC STUDY

3.1 Impact of a_1, a_2 and a_3 Parameters

The split gap determines the design's capacitance value, whereas the metal's dimensions – such as length, width, and thickness – determine the inductance value. Fig. 2(a) displays the relative S_{11} plot following parametric analysis, where a_1 is changed from 5 to 7 mm in increments of 1 mm. The return loss is decreased by using $a_1 = 5$ mm and 7 mm. According to Fig. 2(a), the largest return loss for each of the five resonant bands only appears at $a_1 = 6$ mm. In a similar manner, Fig. 2(b) displays the relative S_{11} plot when a_2 is changed in 1 mm increments from 3 to 5 mm. Fig. 2(b) shows that the return loss is lowest at $a_2 = 3$ mm and 5 mm, while the highest return loss is obtained at $a_2 = 4$ mm for all five resonant bands. Fig. 2(c) demonstrates that when a_3 is changed from 1 to 3 mm in 1 mm increments. As shown in Fig. 2(c), $a_3 = 2$ mm produces the highest return loss, while $a_3 = 1$ mm and 3 mm produces the lowest return loss.



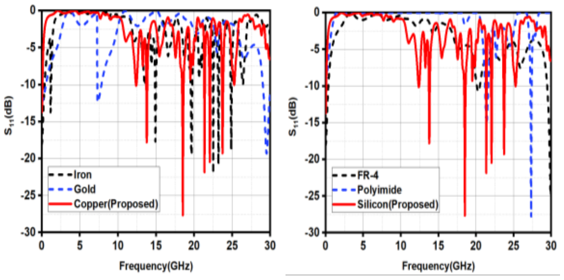
a b

c

Fig.2 – S_{11}(dB) graphs produced by changing the parameters (a) a_1, (b) a_2, and (c) a_3 using parametric analysis

3.2 Impact on Various Conductive and Dielectric Materials

Distinct variations in reflection coefficient have been identified through impact analysis of different conducting and dielectric materials. In order to create an efficient structure in the suggested design, appropriate material substitutes must be used. Three conducting materials – copper, gold, and iron – were taken into consideration when creating the topmost layer of the design. Among the conductive materials shown in Fig. 3(a), copper may produce the highest S_{11}. Copper has been chosen as the conducting material, as indicated by the red spectrum. Additionally, parametric analysis for a number of dielectric materials is performed. Dielectric materials such as FR-4, polyimide, and silicon were taken into account in this research. According to the investigation, the silicon substrate material design produces the highest reflection coefficient, as seen in Fig. 3(b).



a b

Fig. 3 – S_{11}(dB) Plot for a variety of (a) conductive and (b) dielectric materials used in the design analysis

4. RESULTS AND DISCUSSIONS

A plot of the reflection coefficient for the suggested design is shown in Fig. 4. First resonance of the proposed antenna occurs at 13.75 GHz with a 0.1 GHz bandwidth (13.7 to 13.8 GHz) with S_{11} of – 17.7 dB, second resonates at 18.5 GHz with a 0.2 GHz bandwidth (18.4 to 18.6 GHz) with S_{11} of – 27.6 dB, third resonates at 21.35 GHz with a 0.1 GHz bandwidth (21.3 to 21.4 GHz) with S_{11} of – 21.8 dB, fourth resonates at 22 GHz with a 0.2 GHz bandwidth (21.9 to 22.1 GHz) with S_{11} of – 20.3 dB, and fifth resonates at 23.7 GHz with a 0.2 GHz bandwidth (23.6 to 23.8 GHz) with S_{11} of – 19.7 dB respectively. Fig. 5 shows the VSWR of the proposed design. All of the operating bands' resonance frequencies have VSWR values lower than 1.2, as seen in the Fig. 5. In order to optimize the feed length and perform a thorough study of the microstrip feed with a circular ring, the proposed antenna is designed to couple electromagnetic (EM) energy into it. Furthermore, the resonating bands experience a larger return loss due to the deployment of the hexagon slot. Fig. 5 shows that at resonance, the VSWR values are 1.2, 1.06, 1.09, 1.14, and 1.18. The suggested antenna exhibits minimum reflection at five resonant bands, as indicated.

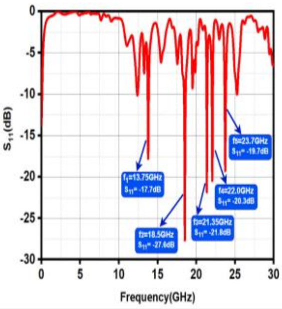


Fig. 4 – Return loss frequency plot

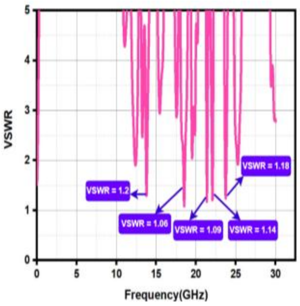


Fig. 5 – VSWR plot

The proposed design functions at five resonant frequencies: 13.75, 18.5, 21.35, 22, and 23.7 GHz, achieving peak gains of 7.9, 9.4, 9.2, 8.9, and 8.3 dBi at resonance, as illustrated in Fig. 6. It also demonstrates high radiation efficiencies of 77, 88, 84, 81, and 79% at resonance, as indicated in Fig. 7, respectively.

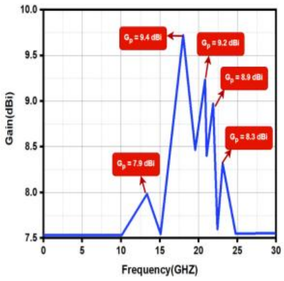


Fig. 6 – Peak gain

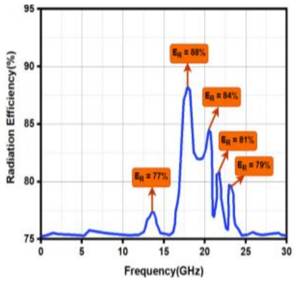
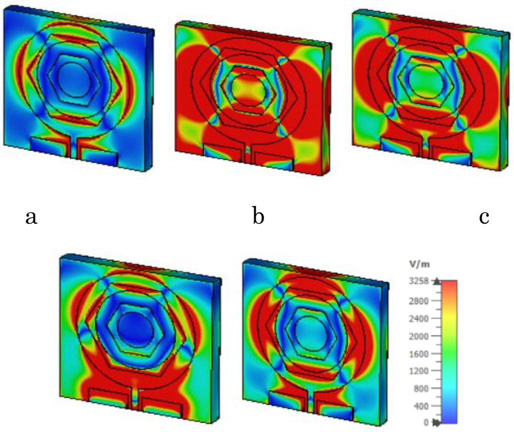


Fig. 7 – Radiation efficiency

4.1 Various Current Distributions

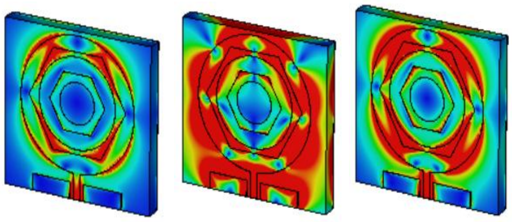
Fig. 8(a) shows that the radiating patch with the hexagon slot operates along the vertical axis of the antenna and has the lowest electric field strength at 13.75 GHz on both its upper and lower sides. As seen in Fig. 8(b), the electric field is strongest at 18.5 GHz inside the circular ring, and as shown in Fig. 8(c-e) for the area around the circular ring, it is strong at 21.35 GHz, 22 GHz, and 23.7 GHz, respectively. Fig. 9(a) shows that at 13.75 GHz, a horizontally extending minimum magnetic field is visible below the patch's circular ring along the antenna. Fig. 9(b-e) shows that at 18.5 GHz, 21.35 GHz, 22 GHz, and 23.7 GHz, the magnetic field is stronger. Because of this, the electric and magnetic fields are moving in opposition to one another. The feed line has the lowest current distribution for 13.75 GHz operation, as shown in Fig. 10(a-e). The circular ring radiating patch's corners display the largest current distribution at frequencies of 18.5 GHz, 21.35 GHz, 22 GHz, and 23.7 GHz, whereas the surface current distribution spreads horizontally at all other frequencies.



a b c

d e

Fig. 8 – Electric Field Distribution at (a) 13.75 GHz (b) 18.5 GHz (c) 21.35 GHz (d) 22 GHz (e) 23.7 GHz



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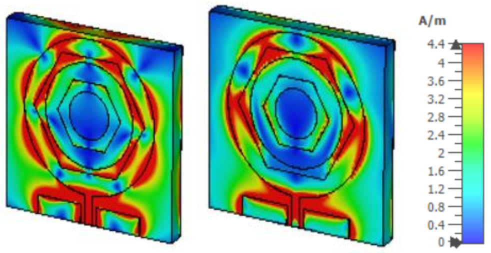
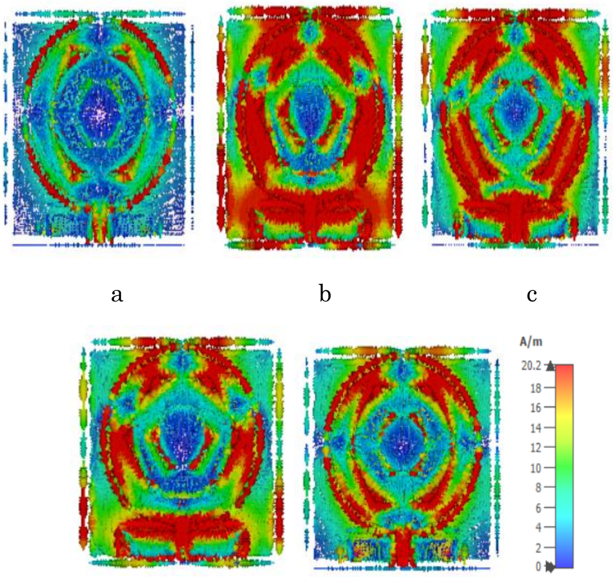


d e

Fig. 9 – Magnetic Field Distribution at (a) 13.75 GHz (b) 18.5 GHz (c) 21.35 GHz (d) 22 GHz (e) 23.7 GHz



a b c

d e

Fig. 10 – Surface Current Distribution at (a) 13.75 GHz (b) 18.5 GHz (c) 21.35 GHz (d) 22 GHz (e) 23.7 GHz

4.2 Performance Comparison with other Reported Works

The proposed antenna's performance is compared to the existing literature in Table 1. This recommended patch antenna maintains a small size while offering superior radiation efficiency and gain.

Table 1 – Comparing with recently reported research

Ref.	Year of Publ.	Ant. Dimension (mm^2)	Bandwidth (GHz)	Peak Gain (dBi)	Radiation Efficiency (%)
[6]	2023	70 × 70	2.39 – 2.52 5.76 – 5.95	7.8 and 6.8	90 and 80
[5]	2022	40 × 52	2.3 – 2.8 4.9 – 5.8	3.50 and 3.53	79 and 88
[10]	2024	42 × 42	9.4 – 10.6 12.8 – 13.9 15.5 – 15.7	2.6, 7.27 and 11.3	68, 79 and 92
[12]	2024	6 × 6	7.4 – 7.6 9.8 – 12.6	1.21 and 1.09	86 and 91
This Work	–	10 × 10	13.7 – 13.8 18.4 – 18.6 21.3 – 21.4 21.9 – 22 23.6 – 23.7	7.9, 9.4, 9.2, 8.9 and 8.3	77, 88, 87, 81 and 79 %

5. CONCLUSION

This article showcases a microstrip patch antenna with a circular ring form that was specifically intended for 5G mmWave applications. The suggested antenna is 10 × 10 × 2.07 mm^3 in size, with copper and silicon constituting the upper and intermediate conducting layers, respectively. Antenna performance is satisfactory when it is designed with appropriate dimensions, which produce excellent outcomes. The prescribed structure resonates at five different frequencies at 13.75, 18.5, 21.35, 22.0, and 23.7 GHz with peak gain of 7.9, 9.4, 9.2, 8.9 and 8.3 dBi, radiation efficiency of 77, 88, 84, 81 and 79 % and VSWR of 1.2, 1.06, 1.09, 1.14 and 1.18 respectively. Hence, the antenna that was suggested is highly recommended for 5G mmWave applications.

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Багатодіапазонна двослотова кругла кільцева мікросмужкова патч-антена з живленням від CPW для застосувань у міліметровому діапазоні 5G

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У цій статті представлено невелику круглу кільцеву патч-антену з кількома діапазонами для застосувань 5G mmWave. Працюючи в п'яти різних частотних діапазонах, цей інноваційний підхід підвищує показники продуктивності завдяки включенню подвійного шестикутного пазу в патч. Втрати на відбиття антени значно збільшуються з додаванням пазу. У запропонованій структурі було використано кремнієвий діелектричний матеріал товщиною 2 мм з діелектричною проникністю 11,7. Загальний розмір антени становить 10 × 10 × 2,07 мм^3. Зберігаючи невеликий розмір випромінювача, запропонована антена забезпечує багатодіапазонну роботу. Розроблений випромінювач може працювати в п'яти різних діапазонах частот: від 13,7 до 13,8 ГГц, від 18,4 до 18,6 ГГц, від 21,3 до 21,4 ГГц, від 21,9 до 22,1 ГГц та від 23,6 до 23,7 ГГц, з п'ятьма різними резонансними частотами 13,75, 18,5, 21,35, 22,0 та 23,7 ГГц відповідно. При резонансі досягається піковий коефіцієнт підсилення 7,9, 9,4, 9,2, 8,9 та 8,3 дБі, а також ефективність випромінювання 77, 88, 84, 81 та 79 %. Запропонована антена має багато переваг, таких як висока ефективність випромінювання, високий коефіцієнт підсилення та підтримка кількох діапазонів. Для покращення продуктивності в робочому діапазоні частот щодо коефіцієнта відбиття ($S11$) було проведено ретельний параметричний аналіз за допомогою симулятора CST. Також досліджується вплив різних провідних матеріалів (залізо, золото та мідь) та діелектричних матеріалів (FR-4, поліімід та кремній) на характеристику запропонованої антени. У цій статті детально описано процес проектування антен та проаналізовано розподіл їхнього поля та струму.

Ключові слова: Антена, Багатодіапазонна, Коефіцієнт відбиття, Ефективність випромінювання, Коефіцієнт підсилення.