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Design and Analysis of a Dual-Band 27/38 GHz Elliptical-Shaped Patch Antenna for 5G Applications

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This work describes the design of an elliptical shape patch antenna for 5G applications on a low-cost Rogers RO4003C substrate with a permittivity of 3.55 and a dimension of $14 \times 6 \times 0.2$ mm^3 in both bands (27 GHz and 38 GHz). The suggested antenna is made up of a patch with five ellipses and slots of identical shape, as well as a partial ground plane for increased bandwidth. At both bands, the antenna exhibits excellent matching. The results indicate the presence of two resonance frequencies at 27 GHz and 38 GHz that defines two distinct 10 dB return loss bandwidths of 0.490 GHz and 0.420 GHz, respectively. Furthermore, the resulting gain has a good value and is particularly impressive given the structure's small size, with a peak value of 5.731 dB at 26.75 GHz and a peak value of 4.75 dB at 38 GHz. This antenna was studied with the help of Computer Simulation Technology-Microwave Studio (CST). Parametric analyses have been carried out to find out the effect of ground plane length, effect of slot radius and effect of slot position on the performance the proposed antenna in order to provide optimal results. Sufficient impedance bandwidth, preferred unidirectional stable radiation patterns, satisfactory gain, radiation efficiency as well as a miniaturized size make the proposed antenna a suitable candidate for future 5G applications.

Keywords: 5G applications, Dual-band, Ellipse-shaped antenna, mm Wave, Patch antenna.

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1. INTRODUCTION

To meet the demand for increasing data rates and channel capacity, mobile phone networks have been built in stages, starting with the first generation (1G) and ending with the fourth generation (4G). However, due to an increase in the number of mobile users, mobile traffic is increasing year by year in global situations, and this trend is predicted to continue in the foreseeable future. As a result, the present 4G mobile network's available data rate and channel capacity will be insufficient to accommodate future mobile communication technology advances in the long run [1]. In addition to advances in wireless communications, the fifth generation (5G) network has created a great impact on economic and social development in recent years. 5G technology has risen to the top of the list of priorities for the post-2020 generation of wireless communication systems. 5G is a new technology that offers both evolutionary and revolutionary services aim to triple data transmission rates compared to the fourth generation (4G). It is the next generation of technology that will enable ultra-high data rates, extremely low latency, increased capacity, and high service quality. It's worth noting that 5G technology will open up new ways to overcome traditional development barriers [2]. Contrary to 3G and 4G, 5G technology is not just for digital networks; it is anticipated to have an impact on a variety of industries, including video games, connected cars, robots, and telemedicine [3]. 5G data range from 5 to 50 Gbit/s and require the use of efficient antennas to achieve the expected speed. The higher frequency spectrum for 5G technology includes frequency bands such as 24.25-27.5 GHz, 26.5-27.5 GHz, 37.0-40.0 GHz, and 37.0-43.5 GHz [4]. The mm-Wave spectrum between 28 GHz (27.5-29.5 GHz) and 38 GHz (37-38.6 GHz) is being heavily considered for next-generation 5G wireless systems, which would significantly improve performance compared to 4G systems [5, 6]. There are various types of antennas that meet the requirement of having a high gain for 5G applications, such as corrugated antennas, cavity-backed antennas, and SIW aperture antennas. Recently, much attention has been focused on the design of multi-functional antennas, which have a combination of characteristics in one single structure for different applications. Recently, microstrip antennas are promising candidates for 5G wireless communications because of their small size, light weight, low cost, ease of fabrication and integration, and their capability of integration with other systems. Higher gain and better radiation characteristics are the primary requirements for 5G antennas [7, 8]. Monopole antennas with shapes like the circular, square, triangular, rectangular, and rhombic are designed to improve and enhance performance to reach the best radiation and gain characteristics, and they are typically used as linearly polarized antennas. This is done to adapt to the rapid development in the wireless mobile communication field [9].

The purpose of this work is to create a novel patch antenna and optimize its performance for 5G wireless applications at 27 GHz and 38 GHz. The main objective

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is to achieve broad bandwidth, standard gain, and high efficiency for 27 GHz and 38 GHz 5G band applications in a very compact size. The proposed antenna, designed using the substrate, requires a physical dimension of 14 × 6 × 0.2 mm^3. The suggested antenna structure is designed, simulated, and analyzed using the CST Microwave Studio electromagnetic 3D simulator tool. Sufficient impedance bandwidth, preferred unidirectional stable radiation patterns, satisfactory gain, radiation efficiency as well as a miniaturized size make the proposed antenna a suitable candidate for upcoming 5G applications.

2. ANTENNA DESIGN

Although several types of a microwave antenna ($f > 1$ GHz) are used, a microstrip antenna is the most commonly encountered [10]. In this work, we used an elliptical form patch antenna whose geometry has been modified in order to achieve optimum characteristics.

To design the proposed antenna, a CST Microwave Studio EM simulator has been used. The radiation element is depicted on a substrate of Rogers RO4003C with a permittivity of 3.55 with dimension 14 × 6 × 0.2 mm^3 and a partial ground plane with dimension 12.5 × 6 mm^2, the radiation element is fed by a microstrip line of 50 Ω impedance. The optimized design parameters of the proposed antenna are listed in Table 1, and the design structure is given in Fig. 1.

Table 1 – The design parameters of the proposed antenna

Parameter	Value (mm)
L_G	12.5
$W_G = W_{\mathrm{SUB}}$	6
L_{SUB}	14
X_{sc}	6
T_{SUB}	0.2
L_F	7.6
W_F	0.54
R_1	0.5
R_2	3.25
R_3	0.33
R_4	1.3

The patch contains 5 ellipses, each ellipse has an area of $\pi \times R_1 \times R_2 = 5.10$ mm^2 and an elliptical slot contains 5 ellipses, each ellipse has an area of $\pi \times R_3 \times R_4 = 1.34$ mm^2.

The slots are used to increase the bandwidth and miniaturize the patch antenna. As compared to the basic element, the slot loaded modified patch radiator has a significant improvement in terms of the reflection coefficient, operating bandwidth and gain.

2.1 Antenna Parameters Analysis

It is necessary to investigate the effects of major design parameters on the resonance performance of the proposed antenna. The area of elliptical slots, their positions, and ground plane length have a significant impact on the performance of the proposed antenna.

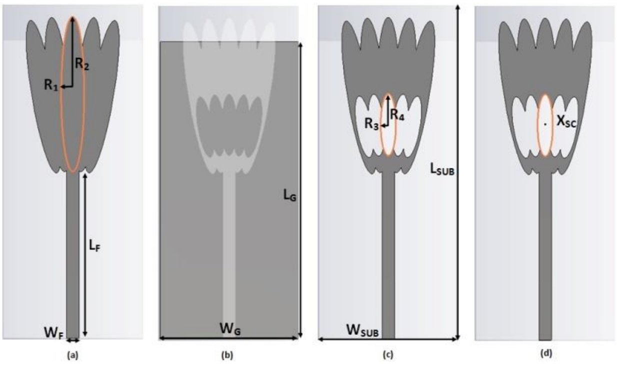


Fig. 1 – Geometry of the proposed antenna: (a) basic element without slots, (b) partial ground, (c) proposed antenna with slots, and (d) X_{sc} position of the slot

2.1.1. Effect of the Ground Plane Length on the Performance of the Proposed Antenna

A parametric analysis has been carried out to investigate the impact of the ground plane length on the resonant characteristics of the proposed antenna. The simulation results (reflection coefficient) depending on the variations of the ground plane length from $L_G = 6$ mm to $L_G = 12.5$ mm are shown in Fig. 2.

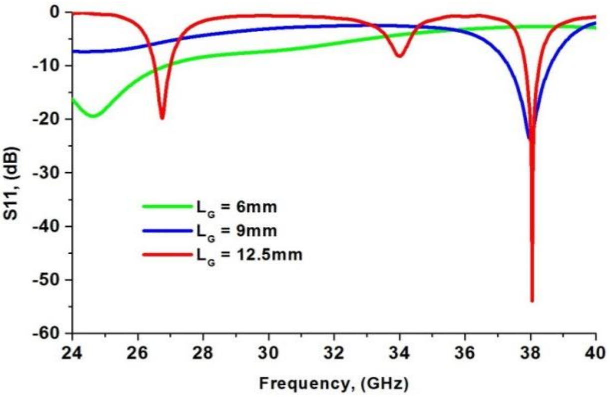


Fig. 2 – Influence of the ground plane length variations on the S_{11} parameter

As depicted in Table 2, variations in gain are also noticed due to variations in the ground plane length. The simulation results obtained through parametric observation are summarized in Table 2. When the ground plane length changes from $L_G = 6$ mm to $L_G = 12.5$ mm, there is a major change in the resonance response of the proposed antenna in terms of impedance matching and operating bandwidth. It can be seen in Fig. 2 and Table 2 that if the ground plane length is kept at the proposed value, $L_G = 12.5$ mm, the antenna resonates at 26.75 GHz and 38 GHz with sharp improved reflection coefficients of – 19.817 dB and – 53.983 dB, respectively, and offers – 10 dB impedance bandwidth of about 0.48 GHz (26.52 to 27 GHz) and 0.428 GHz (37.84 to 38.26 GHz) at 26.75 GHz and 38 GHz, respectively. The designed antenna provides optimum results in terms of dual band resonance with maximum reflection coefficients for the proposed dimension of $L_G = 12.5$ mm. Any further modifications in the dimension of L_G deteriorates the impedance characteristics of the antenna.

Table 2 – Simulated results of the antenna by varying dimensions of the ground plane length

Value of L_G (mm)	Frequency (GHz)	– 10 dB bandwidth (GHz)	Gain (dB)	S_{11} (dB)
6	24.6	4.11 (22.77-26.89)	5.215	– 19.07
9	38	1.32 (37.31-38.63)	5.94	– 22.17
12.5	26.75	0.48 (26.51-27)	5.731	– 19.81
	38	0.42 (37.84-38.26)	4.75	– 53.98

2.1.2. Effect of the Slot Radius on the Performance of the Proposed Antenna

A parametric analysis has been carried out to investigate the impact of the slot radius on the resonant characteristics of the proposed antenna. The simulation results (reflection coefficient) depending on the variations of a small elliptical slot radius from $R_3 = 0.26$ mm to $R_3 = 0.34$ mm are shown in Fig. 3. It can be observed that the best result is achieved when $R_3 = 0.33$ mm.

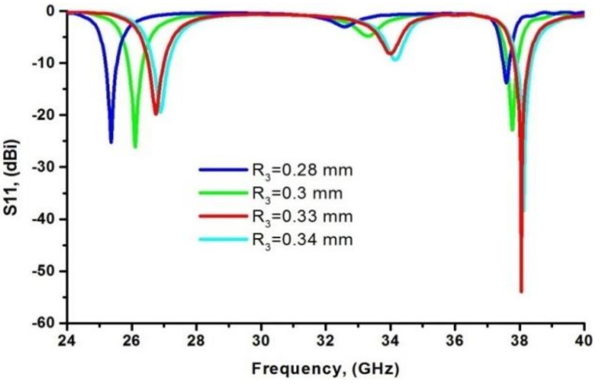


Fig. 3 – Influence of the slot small radius variations on the S_{11} parameter

The simulation results (reflection coefficient) depending on the variations of a large elliptical slot radius from $R_4 = 0.8$ mm to $R_4 = 1.5$ mm are shown in Fig. 4. It can be observed that the best result is attained when $R_4 = 1.3$ mm.

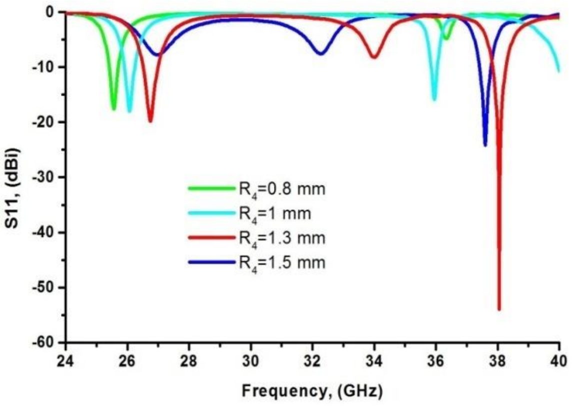


Fig. 4 – Influence of the slot large radius variations on the S_{11} parameter

2.1.3. Effect of the Slot Position on the Performance of the Proposed Antenna

A parametric analysis has been carried out to investigate the impact of the varying positions of the slot on the resonant characteristics of the proposed antenna. The simulation results (reflection coefficient) depending on the variations of the elliptical slot position (position of X_{SC}) from $X_{center} = 5.5$ mm to $X_{center} = 7$ mm are shown in Fig. 5. As per intended applications, the best result is obtained when $X_{center} = 6$ mm.

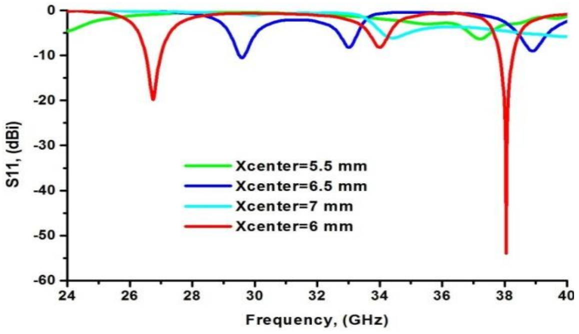


Fig. 5 – Influence of the slot position variations on the S_{11} parameter

3. RESULTS AND DISCUSSION

3.1 Reflection Coefficient

The comparison of variations of the reflection coefficient vs frequencies for the basic patch antenna with and without the presence of an elliptical slot and with a partial ground plane and a full ground plane is depicted in Fig. 6. The simulation results show that the reflection coefficients of the patch antenna with a slot and a partial ground plane present the value of $S_{11} = -19.817$ dB at 26.75 GHz with a bandwidth of 0.490 GHz, from 26.51 to 27 GHz, and the value of $S_{11} = -53.983$ dB at 38.048 GHz with a bandwidth of 0.420 GHz, from 37.84 to 38.26 GHz, completely covering two 5G frequency bands from 26.51 to 27 GHz and from 37.84 to 38.26 GHz. On the other hand, a single narrow resonance is observed at 30.15 GHz with a reflection coefficient of – 15.26 dB for the antenna structure without a slot and a full ground plane. The results achieved for the case with a partial ground plane and a patch antenna without a slot are not significant at all.

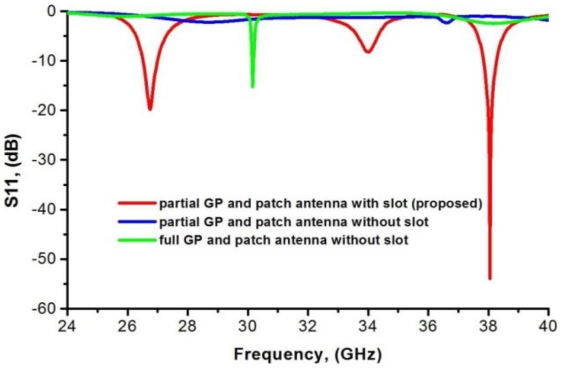


Fig. 6 – Comparison of the reflection coefficient vs frequencies of the proposed antenna with and without slots in the presence of a partial ground plane and another full ground plane

3.2 Gain

The variations of gain vs frequencies for the basic patch antenna with the presence of an elliptical slot are depicted in Fig. 7. In the patch antenna with a slot, it can be observed that the proposed work exhibits an average gain of 5.731 dB around of 28 GHz and a gain of 4.75 dB around of 38 GHz.

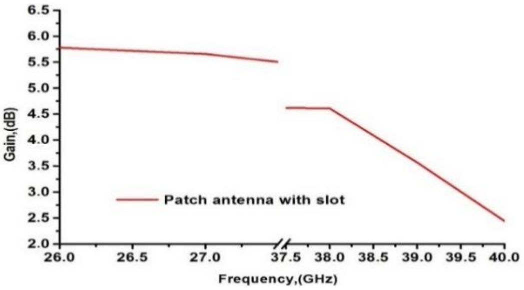


Fig. 7 – Gain vs frequencies of the proposed antenna with slots

2.2. Radiation Efficiency

Fig. 8 illustrates the efficiency of radiation for the basic patch antenna with the presence of an elliptical slot. We have to note that the efficiency is 98.26 % at a frequency of 27 GHz, and it is valued at 96.82 % at a frequency of 38 GHz.

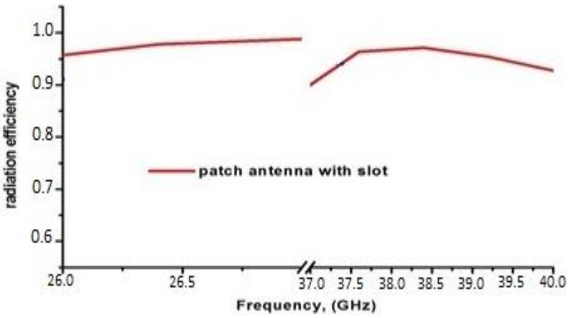
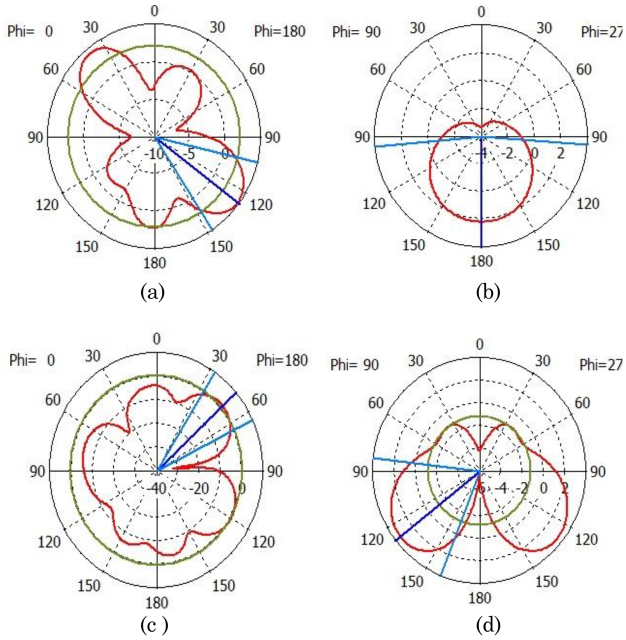


Fig. 8 – Radiation efficiency vs frequency of the proposed antenna with slots

3.3 Radiation Pattern

Fig. 9 illustrates the radiation pattern of the proposed antenna for both bands of 27 and 38 GHz. It can be observed that at 38 GHz, the designed antenna exhibits an almost omnidirectional radiation pattern in the *E*-plane (*XZ*-plane) (Fig. 9c), and a bidirectional radiation pattern in the *H*-plane (*YZ*-plane) is shown in Fig. 9d. At 26.7 GHz, we can see that the radiation pattern of the proposed antenna for the *H*-plane (Fig. 9b) remains directional, and for the *E*-plane (Fig. 9a) it is bidirectional. The designed antenna exhibits stable radiation patterns over the operating bands which is a primary requested for 5G wireless communication applications.



(a) (b)

(c) (d)

Fig. 9 – Radiation patterns of the proposed antenna: (a) *E*-plane at 26.7 GHz, (b) *H*-plane at 26.7 GHz, (c) *E*-plane at 38 GHz, and (d) *H*-plane at 38 GHz

4. COMPARISON OF THE PROPOSED ANTENNA WITH OTHER EXISTING ANTENNA DESIGNS

The performance characteristics of the proposed antenna have been compared with other reported works, and the analyzed observations are summarized in Table 3. The proposed antenna maintains good stability among the characteristic parameters (gain, bandwidth, return loss) for dual-band resonances at 28 GHz and 38 GHz by maintaining compact dimension. The geometrical configuration of the proposed antenna is novel compared to other structures reported in the literature for next generation 5G applications.

Table 3 – Comparison of performance of designed antenna with some other existing antennas

References	Performance measure					
	Size (mm^2)	Center frequency	Gain (dB)	Bandwidth (GHz)	Maximum reflection coefficient (S_{11})	Radiation efficiency (%)
[1]	10.591 × 13.80	38.1	4.43	3.7	– 34	97.94
[11]	15 × 15	29.7	5.42	6.4	– 35.8	85
[12]	1.3 × 1.2	28	3.75	3.34	– 41	–
		38	5.06	1.395	– 18	–
[13]	30 × 35	28	8.3	4.1	– 41.5	79
[14]	55 × 110	27.946	7.18	–	– 27.84	91.24
		37.83	9.24		– 18.35	89.63
Proposed antenna	6 × 14	26.75	5.731	0.490	– 19.817	98.26
		38.048	4.75	0.420	– 53.983	96.82

5. CONCLUSIONS

An ellipse-shaped compact patch antenna has been proposed that operates in dual bands (26.51-27 GHz) and (37.84-38.26 GHz), having bandwidth of 490 MHz and 420 MHz respectively for 5G mm wave applications. Compared to the basic patch antenna, the modified slot loaded patch radiator exhibits significant improvements in the reflection coefficient, operating bandwidth, and gain. The proposed antenna shows a stable radiation pattern with a peak gain of 5.731 dB at 26.75 GHz and 4.75 dB at 38 GHz and maximum radiation efficiency of 98.26 % for the first band and 96.82 % for the second band. Hence, the proposed antenna is suitable for 5G wireless communication systems.

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Розробка та аналіз дводіапазонної (27/38 ГГц) патч-антени еліптичної форми для додатків 5G

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У роботі описується конструкція патч-антени еліптичної форми для додатків 5G на недорогій підкладці Rogers RO4003C з діелектричною проникністю 3,55 і розміром 14 × 6 × 0,2 мм^3 в двох діапазонах (27 ГГц і 38 ГГц). Запропонована антена складається з ділянки з п'ятьма еліпсами та щілинами однакової форми, а також часткової площини заземлення для збільшення смуги пропускання. На обох діапазонах антена демонструє чудове узгодження. Результати вказують на наявність двох резонансних частот 27 ГГц і 38 ГГц, які визначають дві різні смуги пропускання зворотних втрат 10 дБ, рівних відповідно 0,490 ГГц і 0,420 ГГц. Крім того, результуюче підсилення має гарне значення та є особливо вражаючим, враховуючи невеликий розмір структури, з піковим значенням 5,731 дБ на частоті 26,75 ГГц і піковим значенням 4,75 дБ на частоті 38 ГГц. Ця антена була досліджена за допомогою Computer Simulation Technology-Microwave Studio (CST). Для отримання оптимальних результатів було проведено параметричний аналіз, щоб з'ясувати вплив довжини заземленої поверхні, вплив радіуса щілин та положення щілин на характеристики запропонованої антени. Достатня смуга пропускання імпедансу, бажані односпрямовані стабільні діаграми спрямованості, задовільний коефіцієнт підсилення, ефективність випромінювання, а також мініатюрний розмір роблять запропоновану антену придатним кандидатом для майбутніх застосувань 5G.

Ключові слова: Додатки 5G, Дводіапазонний, Еліпсоподібна антена, Мм-хвиля, Патч-антена.