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Design and Performance Improvement of a 3.5 GHz Elliptical Patch Antenna for 5G Sub-6 GHz/WiMAX Applications

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In this study, a small elliptical slotted elliptical microstrip patch antenna with a defected ground struc-ture in elliptical form is designed and simulated using CST Microwave Studio software for 5G Sub-6 GHz and WiMAX applications. The proposed design utilizes Rogers RT 5880 as the substrate with dimensions of 48×25.2 mm² and the antenna is excited using a microstrip feed line. The ground plane and patch both have elliptical forms oriented in opposite directions are used to improve the performance parameters of the antenna. The antenna resonates at 3.5 GHz and operates within the frequency range of 3.28 GHz to 3.79 GHz, achieving a wide bandwidth of 510 MHz which covers the most commonly used 5G Sub-6 GHz and WiMAX bands, a peak gain of 6.141 dB, and a radiation efficiency of 94.7% at 3.5 GHz. These simulation results show that the proposed elliptical patch antenna with elliptical slot on the patch plane and defected ground structure in elliptical form offers improved performance, making it a suitable candidate for 5G Sub-6 GHz and WiMAX applications.

Keywords: WiMAX, 5G, 6 GHz sub-band, Microstrip line-fed, Elliptical patch antenna, Defected ground

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1. INTRODUCTION

Since the introduction of 4G wireless networks, users have benefited from mobile broadband services that deliver performance nearly equivalent to wired connections. However, as the demand for greater data capacity, faster speeds, enhanced responsiveness, reliability, and energy efficiency continues to grow, attention has shifted towards the development of fifth-generation (5G) technology [1]. Today, 5G represents the latest advancement in cellular communications, offering the ability to transmit data at significantly higher rates. Extensive research has been undertaken to facilitate the deployment of 5G networks [2-6], with ongoing efforts to optimize the technology further. Among the proposed solutions, various antenna designs have been explored, with microstrip antennas gaining prominence due to their compact size, ease of fabrication, mechanical durability, compatibility, and scalability. Consequently, microstrip patch antennas have emerged as a preferred choice for 5G antenna design. The frequency spectrum allocated for 5G is categorized into two segments: (i) frequencies below 6 GHz and (ii) frequencies between 20 GHz and 80 GHz. The sub-6 GHz band, particularly the 3.4 GHz to 3.6 GHz range, has been widely adopted by numerous countries for 5G communication. Specifically, the 3.5 GHz frequency band has gained global recognition as a standard for 5G deployment [3]. Because of its larger band capacity and propagation characteristics, the 3.5 GHz frequency range presents an opportunity for 5G implementation in the 6 GHz sub-band, allowing for speedier network development. The deployment of 5G networks in mid-band frequencies, like the 3.5 GHz range, can be accelerated due to favorable propagation properties, allowing for the reuse of the existing macro site infrastructure originally designed for the 1.8 GHz spectrum. Moreover, these mid-band frequencies offer much greater capacity compared to lower frequency bands. As a result, there have been ongoing efforts to roll out 5G networks utilizing the 3.5 GHz frequency band. For the deployment of 5G, South Korea, China, Japan, and the United States are investigating the 3.5 GHz frequency spectrum. China granted 5G licenses for 3.4-3.6 GHz in June 2019, whereas South Korea held an auction in July 2018 for 3.42 - 3.7 GHz. In April 2019, Japan granted 3.6-4.1 GHz. In the near future, the United States intends to free up 200 MHz or more within the 3.7-4.2 GHz spectrum, commonly referred to as the Citizens Broadband Radio Service (CBRS) band. Eu-rope is also investigating the 3.4–3.8 GHz range; Ger-many, Finland, Italy, Spain, and the UK are among the nations doing [4].

In addition to 5G applications, various studies have explored the use of worldwide interoperability for microwave access (WiMAX) in the sub-6 GHz spectrum [7-8], as well as in frequencies above 18 GHz [9-10]. The

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most widely used WiMAX frequency band is 3.5 GHz (3.3–3.6 GHz), which falls within the sub-6 GHz range [M. Rezvani, L. Asadpor, R. Vahedpour, A compact dual-band microstrip monopole antenna for WiMAX and WLAN applications, 5th Iranian Conf. Eng. Electromagn. (2017) 1–4]. Some research has focused on designing a single antenna capable of supporting both 5G and WiMAX applications. A significant portion of these studies involve Multiple Input Multiple Output (MIMO) systems, which rely on multiband antennas for efficient operation [9-12]. Different structural variations have been studied i.e., Circularly polarized for 5G application [2], Tripple slot for 5G [5], Slot antenna [7], [11], C-shape and inverted L-shape slot antenna [8], Two element MIMO for 5G [9], Dual polarized MIMO for 5G [12], Symmetrical L-strips [13], Dual band in-verted F-loop [14], T-shape for 5G [15], Multi slotted antenna [16], Array antenna [17] etc.

Among the different configurations available for microstrip patch antennas, elliptical designs offer greater flexibility compared to more traditional shapes such as square, rectangular, or circular patches. Due to their elongated form and smoother taper, elliptical elements often provide better matching than circular ones. Additionally, elliptical structures tend to offer a broader operational frequency band than their circular counterparts. Despite these advantages, the design of elliptical-shaped antennas is relatively underexplored, and there is a limited amount of literature available on this topic.

The design of a small, 3.5 GHz elliptical slotted elliptical patch antenna for WiMAX and Sub-6 GHz applications is presented in this study. The ground plane and patch both have elliptical forms oriented in oppo-site directions are used to improve the performance parameters of the antenna. The antenna is implement-ed on a Rogers RT5880 substrate with optimized dimensions of $48 \times 25.2 \times 1.6$ mm^3. It achieves a wide bandwidth of 510 MHz, covering the frequency range of 3.28 GHz to 3.79 GHz, with high peak gain, directivity, efficiency, and excellent current distribution. The antenna effectively supports the widely used 3.5 GHz band, applicable for both the 5G Sub-6 GHz spectrum (3.3–4.2 GHz) and the WiMAX band (3.3–3.6 GHz), which falls within the Sub-6 GHz range.

The paper has the following structure: Together with the design and optimization procedure, Section 2 describes the suggested antenna arrangement. Section 3 delineates the outcomes and discourse of the simulation, scrutinizing pivotal performance indicators like gain, directivity, radiation patterns, bandwidth, return loss, efficiency, efficiency, and the Voltage Standing Wave Ratio (VSWR). The performance of the suggested antenna is compared to current designs in Section 4. Section 5 brings the task to a final conclusion.

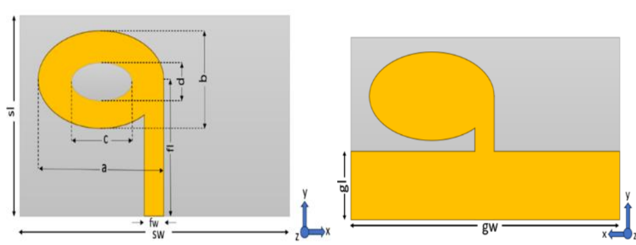
2. ANTENNA DESIGN

The two conducting layers that make up a microstrip patch antenna are called the patch and ground plane, and the dielectric substance that lies between them is called the substrate. The particular application determines which substrate material is best. For 5G and WiMAX applications, an elliptical microstrip patch antenna is created in this study to function in the 3.5 GHz frequency range.

Rogers RT/duroid 5880 is the substrate material used in this design because of its low moisture absorption and low dielectric loss, which make it perfect for high-frequency applications. The substrate's loss tan-gent is 0.0009, and its relative permittivity is 2.2. The ground plane is positioned at the bottom of the substrate height (h), which is 1.6 mm along the Z-axis, creating a coplanar waveguide structure. The dimensions of the substrate extend along the Y-axis and X-axis for length and width, respectively. The antenna is excited using a microstrip line-fed technique, with the matching line width set to 4.97 mm to achieve a characteristic impedance of 50Ω, positioned centrally on the substrate's width. The ground plane and patch both have elliptical forms oriented in opposite directions, and 0.035 mm thick annealed copper is used to produce the conductive layers. The antenna construction is shown in Fig. 1, and Table 1 has a summary of the optimal dimensional parameters.

Table 1 – Elliptical antenna's dimensional parameters

Parameter's name	Symbol	Value (mm)
Width of Substrate	s_w	48
Ellipse Major Axis	a	22.15
Ellipse Minor Axis	b	11
Length of Substrate	s_l	25.2
Slot Major Axis	c	10
Slot Minor Axis	d	4
Feeding Line Length	f_l	18
Height of Substrate	h	1.6
Feeding Line Width	f_w	4.97
Length of Ground	g_l	8
Width of Ground	g_w	48



a b

Fig. 1 – Geometry of the proposed antenna: to view (a), back view (b)

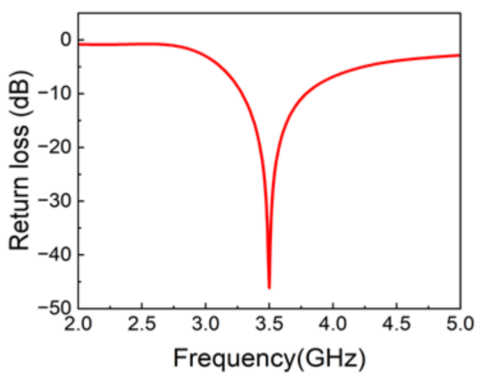
3. RESULTS AND DISCUSSION

The present investigation using CST Microwave Studio Suite 2018 to build and simulate an elliptical microstrip patch antenna with an elliptical slot. The dimensions of the antenna were determined using

Table 1. The antenna was successfully tuned to resonate at 3.5 GHz, achieving strong impedance matching and a wide impedance bandwidth, making it well-suited for 5G and WiMAX applications. The simulation outcomes for the key performance parameters of the antenna are discussed in the subsequent sections.

3.1 Return Loss (S11 Parameter)

The term "return loss" (also called the S-parameter, scattering parameter, or reflection coefficient) describes the difference between the power that an antenna receives and the power that is reflected back to the source. A negative return loss of less than – 10 dB is ideal for an active antenna. The return loss versus frequency plot for the proposed antenna is shown in Fig. 2(a). At the resonant frequency of 3.5 GHz, the return loss reaches a minimum value of – 46.15 dB, indicating excellent performance for both WiMAX and 5G applications. The antenna achieves an operating bandwidth of 510 MHz, further supporting its suitability for these applications. The frequency range of the antenna is 3.28 GHz to 3.79 GHz, and it resonates at 3.5 GHz.



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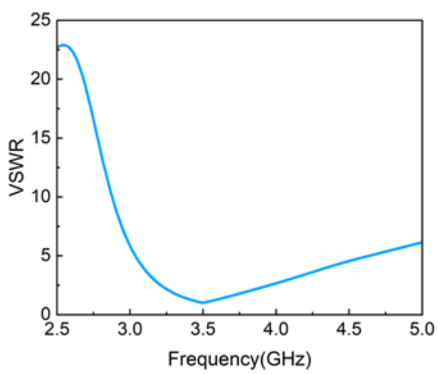


b

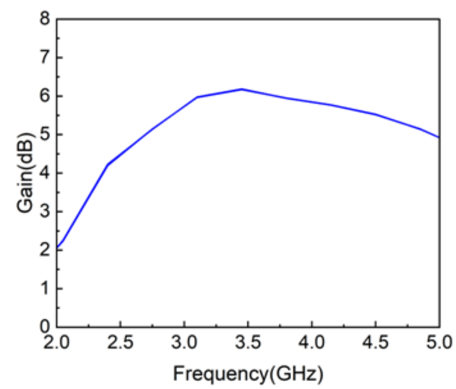
Fig. 2 – Return loss Vs frequency (a), VSWR Vs frequency plot (b) of the designed antenna

3.2 VSWR

The Voltage Standing Wave Ratio (VSWR) is a significant measure that is utilized to evaluate the performance of antennas. The VSWR in antenna theory quantifies the effectiveness of radio frequency power transfer from the source to the antenna over a transmission line. It indicates the level of impedance matching between the load and the transmission line. A perfect impedance match would result in a VSWR of 0; however, for practical antennas, a VSWR value between 0 and 2 is generally considered acceptable. The frequency vs. VSWR graph for the proposed antenna is depicted in Fig. 2(b). The antenna achieves a VSWR of 1.001, indicating near-perfect performance, at the resonant frequency of 3.5 GHz.

3.3 Gain

An antenna's gain is the amount of power it transmits in a given direction. To be more exact, directional gain is the ratio of the intensity of radiation in one direction to the intensity that would be produced if the antenna's accepted power were distributed evenly in all directions. The suggested antenna's gain vs frequency curve is shown in Fig. 3(a). With a gain of 6.141 dB at the target frequency of 3.5 GHz, the antenna is well suited for WiMAX and 5G applications.



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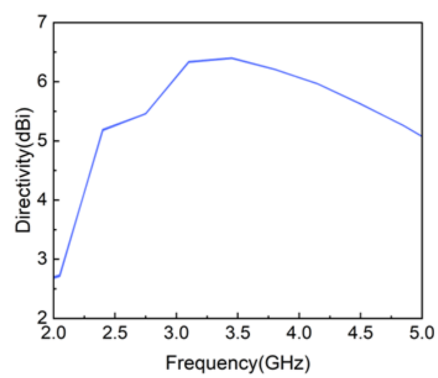

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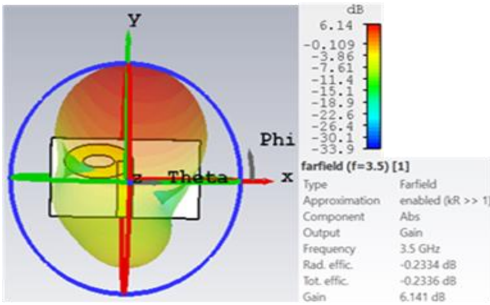
Fig. 3 – Gain VS frequency (a), Directivity VS frequency curve (b) of the proposed antenna



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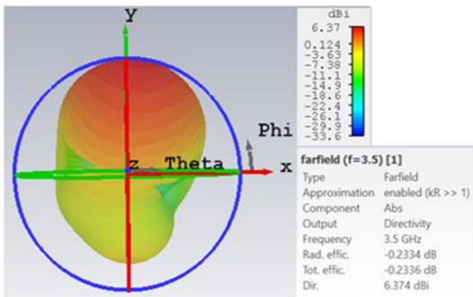


b

Fig. 4 – 3D Far field Gain pattern (a), Directivity pattern (b) of the designed antenna at 3.5 GHz

Fig. 4(a) illustrates the antenna's 3D far-field gain pattern at 3.5 GHz. As seen, the antenna has a maximum gain of 6.141 dB, radiation efficiency of – 0.2334 dB, and total efficiency of – 0.2336 dB at the resonant frequency of 3.5 GHz.

3.4 Directivity

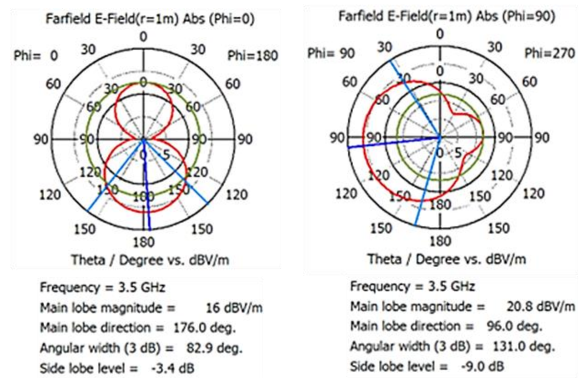
The ratio of an antenna's radiation strength in one direction to the average radiation intensity in all directions is known as directivity. In essence, it measures the antenna's capacity to focus radiation in a certain direction. Directivity is always greater than 1, indicating focused energy. Fig. 3(b) presents the directivity versus frequency curve for the designed antenna. At the resonant frequency of 3.5 GHz, the antenna achieves a directivity of 6.374 dBi, which exceeds the minimum required for 5G antenna applications.

Fig. 4(b) shows the antenna's 3D far-field directivity pattern at 3.5 GHz. The antenna's maximum directivity of 6.374 dBi is attained at the resonance frequency of 3.5 GHz.

3.5 Radiation Pattern

E-field polar form

The orientation of the E-field plane determines the polarization of an antenna. The antenna is said to be horizontally polarized when the E-field is located in the horizontal plane. The far-field E-field in polar form in the φ direction (for $\varphi = 0$ and 90°) of the designed antenna at 3.5 GHz is given in Fig. 5. For $\varphi = 0$, the main lobe direction is 176 degree and the main lobe magnitude 16 dBV/m. The beam angular width (3 dB) is 82.9 degree with the side lobe level of – 3.4 dB. For $\varphi = 90°$, the main lobe direction is 96 degree and the main lobe magnitude id 20.8 dBV/m. The beam angular width (3 dB) is 131 degrees with the side lobe level of – 9 dB.



a b

Fig. 5 – Polar Plot of far-field E-field in the φ direction at 0 degree (a) and 90 degrees (b)

3D Far field *E*-field pattern

The 3D far-field E-field radiation pattern of the designed antenna at 3.5 GHz is illustrated in Fig. 6. The results indicate that the maximum electric field strength (E_{max}) at 3.5 GHz reaches 20.91 dBA/m.

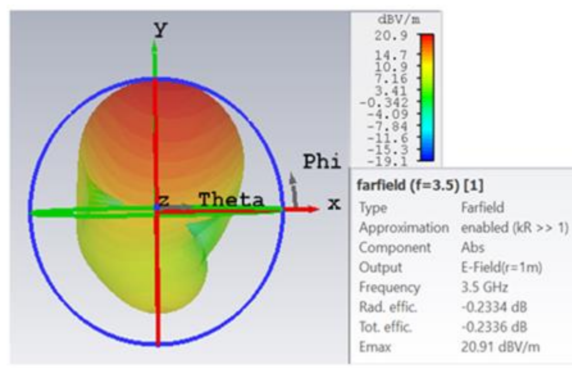


Fig. 6 – 3D Far field E-field pattern of the proposed antenna at 3.5 GHz

3.6 Efficiency

The ratio of the radiated power to the input power that the antenna element receives determines the efficiency of a microstrip patch antenna. Antenna efficiency is affected by a number of parameters, such as power wasted in any associated loads, dielectric loss, conductor loss, cross-polarization loss, and reflected power (VSWR). Fig. 7 presents the plots of percentage radiation efficiency and total efficiency across the frequency range, with the antenna achieving a peak efficiency of 94.7 % at its resonant frequency of 3.5 GHz.

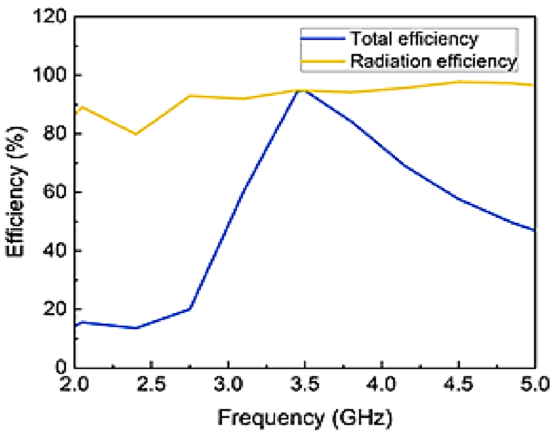


Fig. 7 – Radiation and Total Efficiency Vs. Frequency plot of the proposed antenna

3.7 Surface Current Density

The surface currents of an antenna are a result of the movement of charges across its surface. Fig. 8 shows the surface current density pattern for the suggested antenna configuration. Maximum surface current density for the elliptical patch antenna measured at the resonance frequency of 3.5 GHz is 59.4 A/m, with the majority of this concentration occurring in the bottom part of the feed line and along the lower borders of the patch.

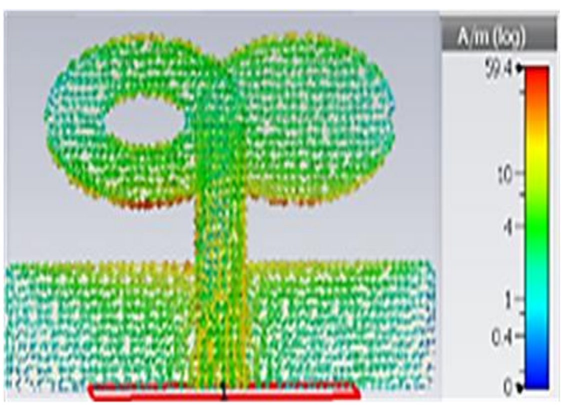


Fig. 8 – Surface current density distribution (b) Smith chart of the designed antenna

4. PERFORMANCE COMPARISON BETWEEN THE PRESENT WORK WITH THE REPORTED WORKS

Table 2 summarizes the comparison between the performance of the proposed antenna and other designs available in the literature. It is evident from the table that the proposed antenna has a relatively smaller size compared to other designs using the Rogers RT5880 substrate, as outlined in [4, 6, 18]. At 3.5 GHz, our design achieves the lowest return loss, along with superior gain and bandwidth when compared to the others. While reference [21] reports a higher gain, it comes at the cost of a larger antenna size, narrower bandwidth, and reliance on the FR4 substrate. In contrast, the FR4-based designs in [13, 16, 20] are more compact, but their gain values are lower than those of the proposed antenna. The radiation efficiency of our design is also on par with the highest values reported in the literature. Therefore, the proposed slotted elliptical patch antenna, built on the Rogers RT5880 substrate, pro-vides a good balance of size reduction, acceptable re-turn loss, bandwidth, gain, and efficiency, making it suitable for WiMAX applications and 5G Sub-6 GHz. The use of Rogers RT5880, a low-loss dielectric material, enhances performance but comes with a higher cost compared to FR4. Nevertheless, the proposed antenna offers improved overall performance while maintaining a compact form factor.

Table 2 – Comparison of the proposed antenna with other designed antennas at 3.5 GHz.

Ref. No.	Dielectric material	S11 (dB)	Gain (dB)	BW (MHz)	Efficiency (%)	Size (mm^2)
[3]	FR4 EPOXY	-30	5.01	NR	96.6	48×25.2
[4]	Rogers RT5880	-41.31	4.45	1133	NR	55×40
[5]	FR4	-34	3.14	NR	NR	80×80
[6]	Rogers RO4350	-15	2.5	230	95	40×35
[8]	FR4	-20	4.3	743	95	60×32
[13]	FR4	<-30	3.13	NR	NR	28×32
[16]	FR4	NR	2.69	NR	79.6	20×30
[18]	Rogers RT5880	-14.13	4.660	129.7	61.51	46.45×27.6
[19]	FR4	-24	NR	NR	NR	75×150
[20]	FR4	-32	1.9	NR	93.8	20×12
[21]	FR4 Epoxy	-26.46	6.391	194.7	NR	40×45
[22]	Double line PCB	-16.32	3.6544	39.2	NR	45×35
This work	Rogers RT5880	-46.15	6.141	510	94.7	48×25.2

5. CONCLUSION

In this work, we design, simulate, and assess the performance of a small, elliptical slotted elliptical microstrip patch antenna designed for 5G Sub-6 GHz and WiMAX applications using CST Microwave Studio software. The Ground plane and patch both have elliptical forms oriented in opposite directions are used to improve the performance parameters of the antenna for the targeted wireless communication systems. The antenna is constructed on a Rogers RT 5880 substrate, with dimensions of $48 \times 25.2 \times 1.6$ mm^3, and is excited via a microstrip line feed. It resonates at 3.5 GHz, covering an operating frequency range of 3.28 GHz to 3.79 GHz. The elliptical slot and partial ground configuration result in a substantial bandwidth of 510 MHz. The antenna demonstrates excellent performance, achieving a maximum radiation efficiency of over 94%, a peak gain of 6.14 dB, and a return loss of -46.15 dB at its resonant frequency. These simulated results indicate that the proposed design offers high gain, efficiency, and a broad bandwidth, making it an ideal candidate for 5G and WiMAX wireless communication applications. Future work will involve the fabrication and experimental testing of the proposed antenna, along with a comparison of the simulated and measured performance. Further improvements can be achieved by modifying the slots in the patch and ground plane or by using alternative substrate materials. Additionally, integrating this single-element antenna into an array on a single substrate may result in enhanced gain, directivity, and efficiency compared to the individual element design.

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Проєктування та покращення характеристик еліптичної патч-антени на 3,5 ГГц для застосувань у 5G Sub-6 ГГц та WiMAX

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У цьому дослідженні розроблено та змодельовано компактну еліптичну мікросмужкову патч-антену з еліптичним прорізом та дефектною опорною структурою (DGS) еліптичної форми, з використанням CST Microwave Studio, для 5G у Sub-6 ГГц діапазоні та WiMAX. У конструкції використано підкладку Rogers RT 5880 з розмірами 48 × 25,2 мм², а живлення антени здійснюється через мікросмужкову лінію. Як патч, так і земляна площина мають еліптичну форму, орієнтовану у протилежних напрямках, що дозволяє покращити параметри роботи антени. Антена резонує на частоті 3,5 ГГц і працює у діапазоні 3,28 – 3,79 ГГц, забезпечуючи широку смугу пропускання 510 МГц, яка охоплює основні діапазони 5G Sub-6 ГГц і WiMAX. Ключові характеристики: Пікове підсилення: 6,141 дБ, ККД випромінювання: 94,7% при 3,5 ГГц. Результати моделювання демонструють, що еліптична патч-антена з еліптичним щілинним отвором на патчі та еліптичним дефектом на опорній площині забезпечує покращену продуктивність, роблячи її перспективною для застосування в мережах 5G Sub-6 ГГц і WiMAX.

Ключові слова: WiMAX, 5G, Sub-6 ГГц, Мікросмужкове живлення, Еліптична патч-антена, Дефектна опорна структура.