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MICROSTRIP PATCH ANTENNA DESIGN WITH ENHANCED RADIATION EFFICIENCY FOR 5G 60 GHZ MILLIMETER-WAVE SYSTEMS

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Abstract: In this paper, a wideband, high-gain microstrip patch antenna design for 60 GHz applications is presented. The chosen substrate material is Rogers RT 5880, with a thickness of 1.6 mm, a relative permittivity of 2.2, and a loss tangent of 0.0009. Initially, a simple rectangular patch antenna is designed. To address the challenges of low gain and low radiation efficiency, two rectangular parasitic elements are introduced. These parasitic elements interact with the main radiator, resulting in improved gain and radiation efficiency. In the final step, an extended ground plane structure is adopted to further enhance return loss, radiation efficiency, and gain. The proposed antenna achieves a high gain of 13.10 dBi and a maximum radiation efficiency of 90% with a compact size of 13.6 × 10.6 mm^2. For bandwidth calculations, given that the 60 GHz frequency band is known for its challenging propagation environment, the -15 dB criteria is chosen instead of the commonly used -10 dB criterion. According to this -15 dB criterion, the antenna exhibits wideband behavior spanning from 55 to 65 GHz, offering an impressive impedance bandwidth of 10 GHz. This design demonstrates significant potential for 60 GHz applications.

Keywords: patch antenna, 60 GHz, enhanced radiation efficiency, high gain, extended ground structure

60 GHz Milimetre Dalga Sistemleri için Artırılmış Işıma Verimliliği ile Yüksek Kazançlı Mikroşerit Yama Anten Tasarımı

Öz: Bu makalede, 60 GHz uygulamaları için geniş bantlı, yüksek kazançlı bir mikroşerit yama anten tasarımı sunulmaktadır. Seçilen alttabaka malzeme 1.6 mm kalınlığında, 2.2 bağıl geçirgenliğine ve 0.0009 kayıp tanjant değerine sahip Rogers RT 5880'dir. İlk olarak, basit bir dikdörtgen yama anten tasarlanmıştır. Düşük kazanç ve düşük ışıma verimliliği zorluğuyla başa çıkmak için iki adet dikdörtgen parazitik eleman tanıtılmıştır. Bu parazitik elemanlar, ana ışıma elemanıyla etkileşime girer ve kazanç ile ışıma verimliliğini artırır. Son adımda ise geri dönüş kaybı, ışıma verimliliği ve kazancı daha da artırmak için genişletilmiş bir toprak düzlemi yapısı benimsenmiştir. Önerilen anten, 13.6 × 10.6 mm^2'lık kompakt boyutuyla 13.10 dBi 'lik yüksek kazanç ve %90'lık maksimum ışıma verimliliği elde etmektedir. Bant genişliği hesaplamaları için, 60 GHz frekans bandının zorlu yayılım ortamı göz önünde bulundurularak, ışıma verimliliği kriteri olarak kullanılan -10 dB kriteri yerine -15 dB kriteri tercih edilmektedir. Bu -15 dB kriterine göre, anten 55 ila 65 GHz aralığını kapsayan geniş bantlı bir davranış sergileyerek 10 GHz'lik etkileyici bir empedans bant genişliği sunmaktadır. Bu tasarım, 60 GHz uygulamaları için önemli bir potansiyel sunmaktadır.

Anahtar Kelimeler: Yama anten, 60 GHz, Artırılmış ışıma verimliliği, Yüksek kazanç, Genişletilmiş toprak yapısı

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1. INTRODUCTION

We find ourselves in an era where wireless technology has seamlessly integrated into every aspect of human existence. From education (Haleem et al., 2022) to communication (Vu Khanh et al., 2022) and healthcare (Attaran, 2022), technology permeates all areas of life. This significant reliance on wireless technology has made the current infrastructure and the presently used electromagnetic spectrum inadequate. The Federal Communications Commission allocated the 57–64 band as an unlicensed band (Alsaedi et al., 2023). Higher frequency bands mean greater bandwidth, higher data rates, ultra-fast downloads, lower latency, and smaller antenna sizes (Elayan et al., 2020). Although the 60 GHz band is used to improve the signal quality and network capacity, it has the disadvantage of higher atmospheric absorption and propagation losses (Oladimeji et al., 2022). As a result, its coverage area is limited, making it an ideal choice primarily for short-range indoor communications (Carneiro Souza et al., 2022).

A microstrip patch antenna with a Q-shaped slot for the unlicensed 60 GHz band is presented by Khan et al. The antenna has a compact size of 14 × 12.90 mm^2. It resonates at 60.06 GHz with a bandwidth of 12.11 GHz and achieves a peak gain of 8.62 dBi. In another study (Saini & Agarwal, 2018), a rectangular-shaped antenna for 5G mobile communications is introduced. The design consists of two U-shaped slots and two rhombic shapes radiating on the patch. The antenna resonates at 60.044 GHz, offering an impedance bandwidth of 3.29 GHz and a gain of 6.03 dBi, along with a size of 10 × 10 mm^2. Saini & Agarwal presented an E and H slotted rectangular-shaped microstrip patch antenna for 5G wireless applications. The results show that the antenna resonates at 59.9 GHz with a good return loss of -40.99 dB. The antenna has a small dimension of 8 × 8 mm^2 with a peak gain of 5.48 dBi. Alassawi et al. proposed a circular ring antenna for 5G applications. The design consists of two elliptical loops monopole antenna with a partial ground plane. The antenna operates at 60 GHz, offering a bandwidth of 2 GHz and a peak gain of 4.8 dBi. Hussein et al. designed a rectangular MSPA with inset fed for 60 GHz applications. The performance of the antenna is optimized by using frequency selective surfaces. The achieved impedance bandwidth is 1.173 GHz, along with a maximum gain of 10.8 dBi.

While there is some research in the literature on microstrip patch antennas at 60 GHz, further in-depth investigation is still needed. Designing a microchip patch antenna operating at 60 GHz represents a significant challenge, stemming primarily from the remarkable properties of this frequency band. At 60 GHz, electromagnetic waves show a significantly high absorption rate, and propagation losses become obvious. In the proposed paper, a wide-band high-gain rectangular patch antenna resonating at 60 GHz with an extended ground plane for future 5G applications is presented. The single element has a simple geometry with a compact size of 13.6 × 10.6 mm^2. The novelty of this work lies in utilizing the extended ground plane technique to achieve the desired resonance (60 GHz), higher gain (13.10 dBi), and enhanced radiation efficiency (< 90%).

2. ANTENNA STRUCTURE AND GEOMETRY

The CST microwave studio is used for design and simulation. A microstrip line feed rectangular patch antenna with an extended ground plane and two parasitic elements has been designed as shown in Figure 1. The overall dimension of the antenna is 13.6 × 10.6 × 1.6 mm^3. The single antenna is built on a Rogers RT5880 substrate with a thickness of 1.6 mm, a dielectric constant ε_r of 2.2, and a loss tangent tan(δ) of 0.0009. The dimensions of the feedline are determined by employing the characteristic equations presented in (1-7) to match the impedance of the microstrip feed line to 50 ohms. The dimensional parameters of the proposed antenna are shown in Table 1.

For $\frac{W_a}{h} \leq 1$

$$Z_0 = \frac{60}{\varepsilon_{reff}} \ln\left(\frac{8h}{W_a} + \frac{W_a}{4h}\right) \tag{1}$$

where,

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\frac{h}{Wa}}} + 0.004\left(1 - \frac{W_a}{h}\right)^2\right) \tag{2}$$

For $\frac{W_a}{h} \geq 1$

$$Z_0 = \frac{120\pi\sqrt{\varepsilon_{reff}}}{\frac{W_a}{h} + 1.393 + 0.667\ln\left(\frac{W_a}{h} + 1.444\right)} \tag{3}$$

where,

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\frac{h}{Wa}}} + 0.004\left(1 - \frac{W_a}{h}\right)^{-\frac{1}{2}}\right) \tag{4}$$

Z_0 denotes the characteristic impedance of the transmission line, W_a is the width of the feedline. L_a is the length of the feedline, ε_r is the dielectric constant and ε_{reff} is the effective permittivity. The calculations for the length and width of the feed line are determined using the provided equations below.

$$W_a = \frac{2h}{\pi}\left(B - 1 + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right]\right) \tag{5}$$

$$L_a = \frac{\lambda}{4\sqrt{\varepsilon_{reff}}} \tag{6}$$

$$Z_0 = \frac{60\pi^2}{4\sqrt{\varepsilon_r}} \tag{7}$$

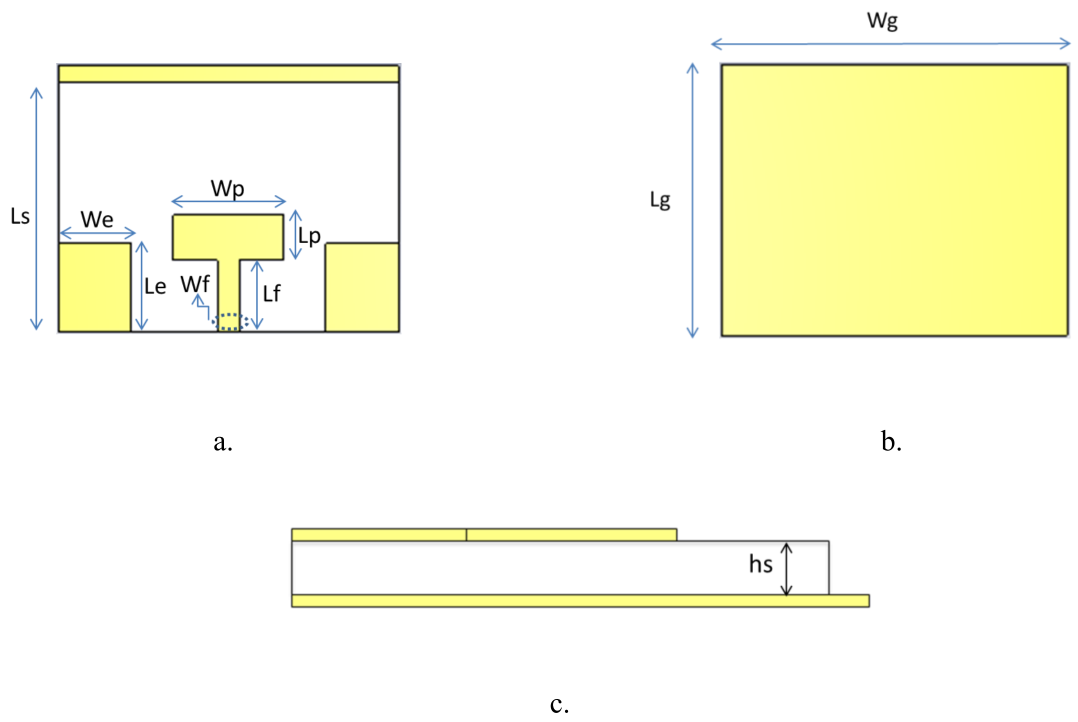


Figure 1:
The proposed single antenna element design a. Front-view b. Back-view c. Side view

Table 1. Final dimensional parameters of the proposed antenna (mm)

Parameters	Values
Wg	13.6
Wp	4.4
We	2.9
Wf	0.9
Lf	2.85
Lg	10.6
Lp	1.8
Le	3.5
Ls	9.98
hs	1.6

a. Design Stages

Figure 2 illustrates the design stages of the single antenna element. In Stage 1, a simple rectangular patch antenna is designed; the antenna demonstrates a good impedance bandwidth and resonates at 60.50 GHz (Figure 3a.). However, it exhibits a relatively low efficiency of 72% (Figure 3b.). In Stage 2, the antenna's radiation efficiency is improved by strategically adding two parasitic elements. These parasitic elements, carefully selected in terms of size and location, create the phenomenon of mutual coupling with the main patch. Mutual coupling refers to the electromagnetic interaction between adjacent radiating elements, and in this case, it plays a vital role in shaping antenna performance. The mutual coupling effect leads to a redistribution of electromagnetic fields between the main patch and the parasitic elements, which changes the current distribution and radiation pattern. This reaction results in more efficient use of the radiated power. The modified configuration achieves resonance at 61.53 GHz and enhanced radiation efficiency, reaching 85% (Figure 3a). However, this improvement in radiation efficiency comes with a trade-off, as there is a noticeable reduction in return loss, indicating a less desirable impedance matching. For Stage 3 (proposed), an extended ground plane structure is introduced to achieve resonance at 60 GHz (Figure 3a.) and further improve impedance matching. This modification enhances current distribution, reduces backward radiation, and achieves an impressive radiation efficiency of 90% with a return loss of -42 dB (Figure 3b), making it well-suited for 60 GHz applications.

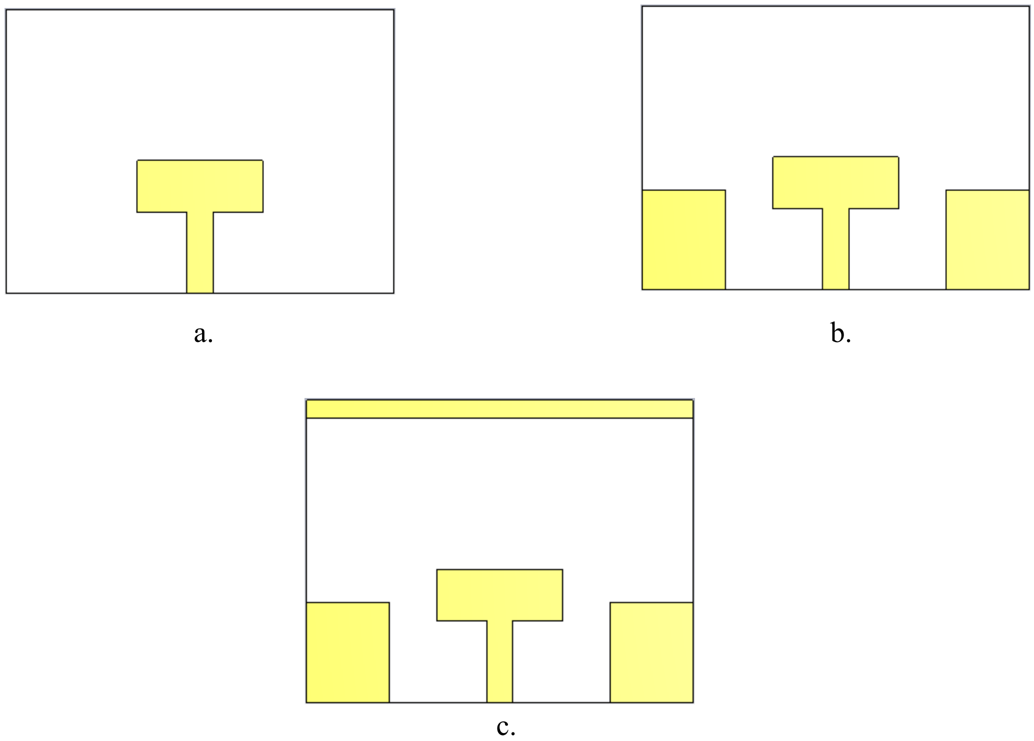
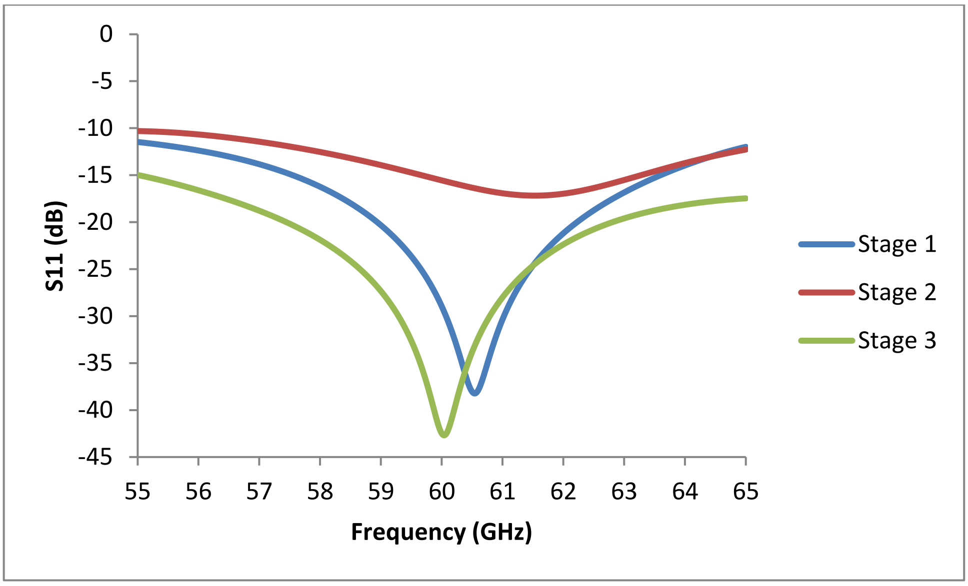
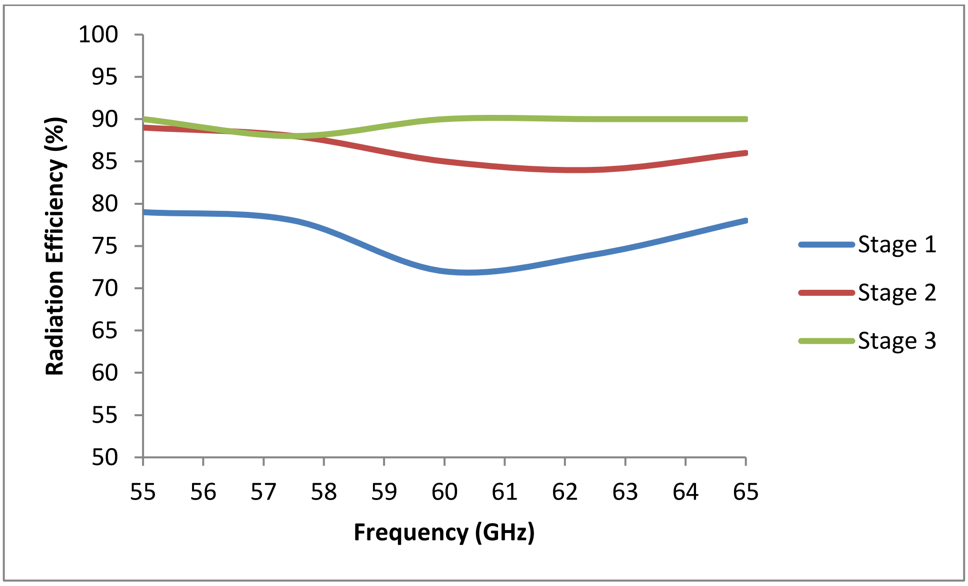


Figure 2:
Design stages of the single antenna element a. Stage 1 b. Stage 2 c. Stage 3 (Proposed)



a.



b.

Figure 3:
Single antenna design stages a. Reflection Coefficient b. Radiation Efficiency

3. SINGLE ANTENNA RESULTS AND DISCUSSION

The reflection coefficient curve of the single element is shown in Figure 4. The 60 GHz band is characterized by numerous reflections and propagation losses. To ensure reliable performance in this challenging environment, the -15 dB return loss criterion is adopted for specifying the operational bandwidth. According to the -15 dB criteria, the antenna has an impedance bandwidth of 10 GHz, spanning from 55 to 65 GHz. The desired operational bandwidth (57–64 GHz) is completely covered with an excellent return loss of -42 dB at the center frequency of 60 GHz.

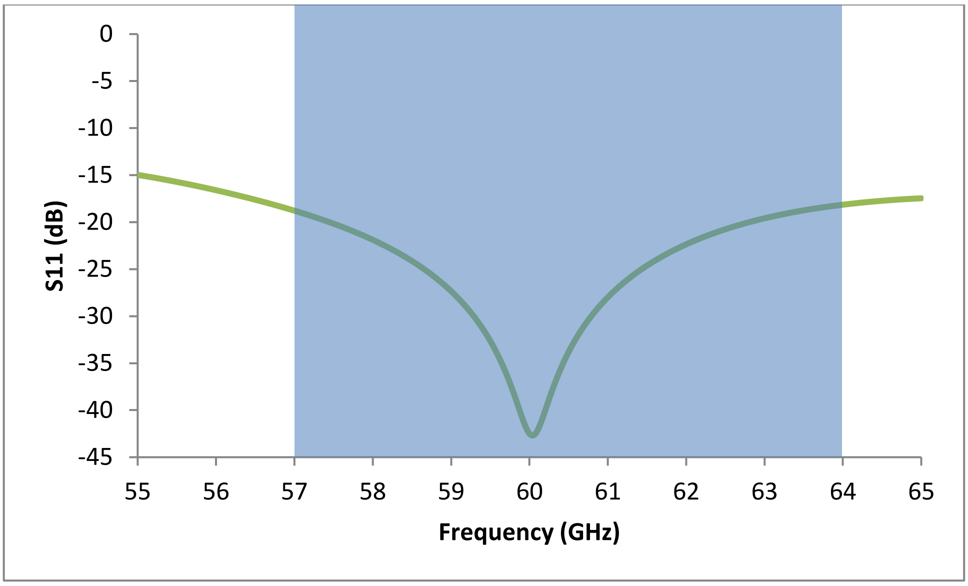
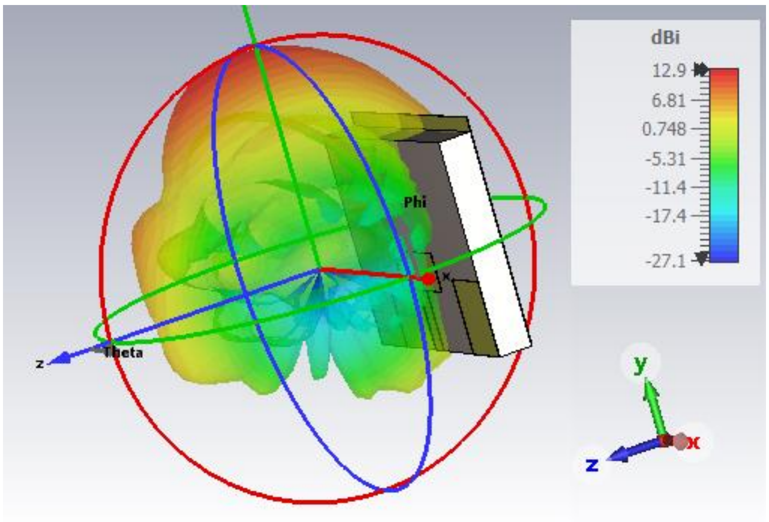
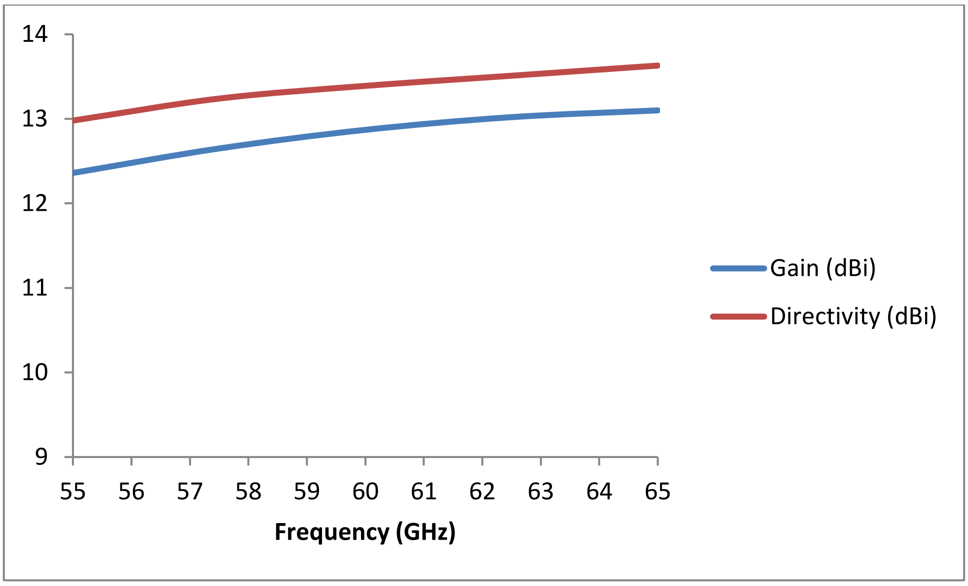


Figure 4:
S11 parameter of the single antenna element

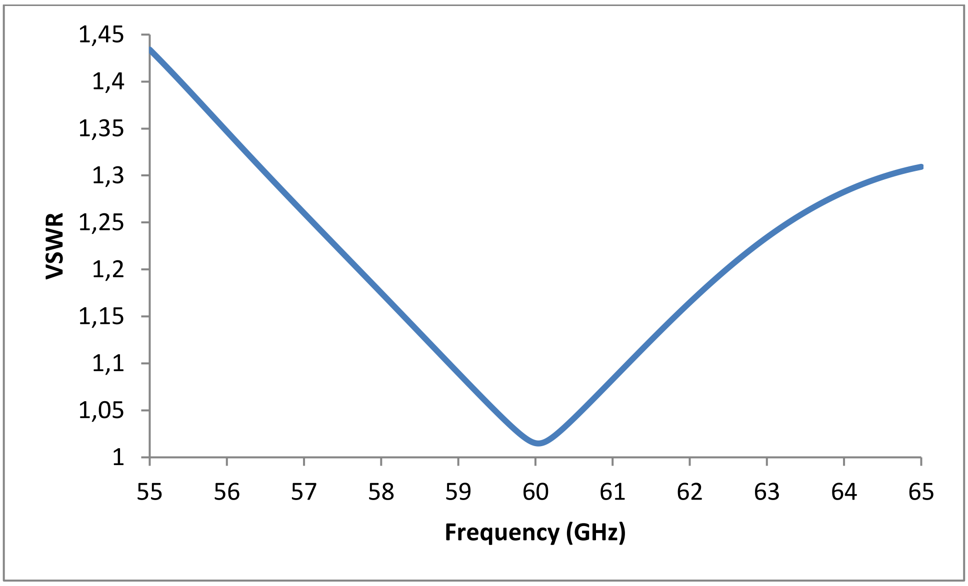
The 3D radiation pattern, gain, directivity, and Voltage Standing Wave Ratio (VSWR) of the proposed antenna design are shown in Figure 5. The gain and directivity are 12.87 dBi and 13.39 dB, respectively, at the operating frequency of 60 GHz. In Figure 5b, it is well noticed that the gain variations are within the acceptable range for mm-wave 5G systems (nearly 0.74 dBi). The VSWR over the entire bandwidth is $1 < VSWR < 2$, which indicates good impedance matching between the feedline and the radiating patch of the proposed antenna (Colaco & Lohani, 2020).



a.



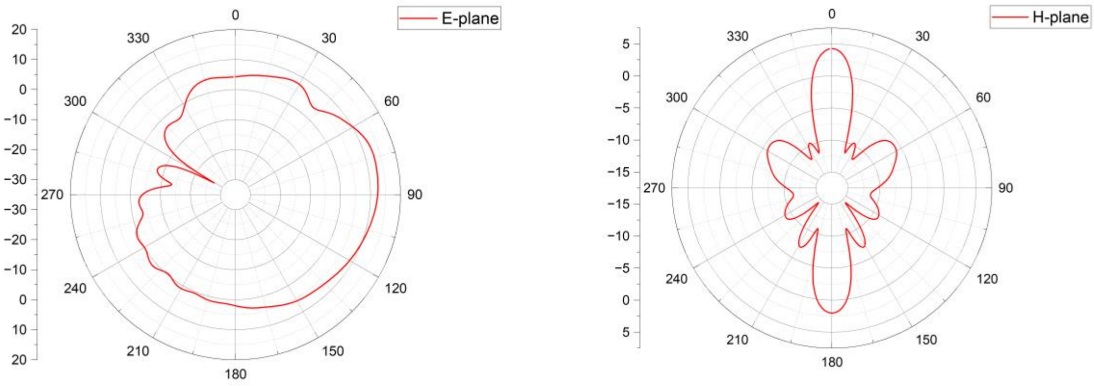
b.



c.

Figure 5:
Single antenna a. 3D radiation pattern b. Gain and Directivity c. VSWR

The 60 GHz antenna exhibits different radiation patterns in both the E-plane and H-plane. In the E-plane (Figure 6a.), it demonstrates an omnidirectional pattern with an angular width of 52.6 degrees, making it well-suited for point-to-multipoint (P2MP) communications (Gomez-Barquero et al., 2018). On the other hand, the H-plane (Figure 6b.) reveals a bidirectional radiation pattern with an angular width of 17 degrees, making it suitable for point-to-point (P2P) communication applications (Ghassemi & Wu, 2012).



a. b.

Figure 6:
Simulated radiation patterns a. E-plane b. H-plane

A comparison between the single-element design and others is presented in Table 2. It is well observed that the proposed antenna offers a wider bandwidth, higher gain, and better radiation efficiency, making it a suitable choice for 60 GHz mm-wave systems.

Table 2. Comparison of the proposed single antenna design with previous works

Ref	Bandwidth (GHz)	Antenna Dimensions (mm^2)	Peak Gain (dBi)	Radiation Efficiency (%)
(Khan et al., 2021)	58.7 - 61.8	14 × 12.90	8.62	82.15
(Saini & Agarwal, 2018)	59.3 - 60.9	10 × 10	6.03	68
(Saini & Agarwal, 2017)	58.8 - 61	8 × 8	5.48	71
(Alassawi et al., 2021)	59.2 - 61	9 × 11	4.8	NA
(Tran & Nguyen-Trong, 2021)	59.9 - 60.4	NA	10.8	60
This work	**55 - 65**	13.6 × 10.6	**13.1**	**90**

4. CONCLUSION

In this study, a microstrip patch antenna for 60 GHz applications is presented. The proposed antenna features a simple rectangular shape along with two parasitic elements. The inclusion of these parasitic elements results in enhanced radiation efficiency, increasing it from 72% to 85%. The radiation efficiency is further improved by introducing an extended ground structure, resulting in a maximum radiation efficiency of 90%, a peak gain of 13.10 dBi, and resonance at 60 GHz. Covering the entire unlicensed bandwidth from 57 to 64 GHz, the proposed design emerges as a promising and suitable choice for 60 GHz applications.

CONFLICT OF INTEREST

The authors confirm that they have no conflicts of interest or shared interests with any institution, organization, or individual.

AUTHOR CONTRIBUTION

Sanaa Iriqat contributes to determining the conceptual and design processes, conducting data analysis and interpretation, and writing the original draft. Sibel Yenikaya contributes by managing the conceptual and design processes, reviewing, editing, and providing supervision.

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