Journal of Nano- and Electronic Physics
Vol. **17** No 2, 02023(5pp) (2025)

Журнал нано- та електронної фізики
Том **17** № 2, 02023(5cc) (2025)

REGULAR ARTICLE

A Triple Band Square Shape Multi-slot Defective Ground Structure Patch Antenna for C-, X-, and Ku-band Applications

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(Received 15 February 2025; revised manuscript received 23 April 2025; published online 28 April 2025)

In this article, a multi-slot defective ground structured microstrip patch antenna with a square shape for various letter band applications is proposed. The proposed structure was designed using a polyimide dielectric material with 2mm thickness, which has a dielectric constant of 3.5. The total size of the antenna is 20 × 20 × 2.07 mm^3. The proposed antenna achieves triple band operation while preserving a compact radiator size. The designed radiator has the capability to operate across three separate frequency bands, spanning from 4.2 to 5 GHz, 9.3 to 9.9 GHz, and 12.7 to 13.4 GHz, with three separate resonance frequencies of 4.6, 9.6, and 13.1 GHz, respectively. A peak gain of 8.2, 6.8 and 7.4 dBi, radiation efficiency of 91, 83 and 89 % are attained at resonance. A comprehensive parametric analysis was conducted utilizing the CST simulator to improve performance over the operational frequency range with respect to reflection coefficient (S_{11}). Additionally, we examine the impacts of various conductive materials (aluminum, gold, iron and copper) and dielectric materials (FR-4, Topas, Quartz Lossy and Polyimide) on the response of the suggested antenna. The antenna design methodology, as well as the analysis of field and current distributions are presented. The prescribed triple band defective ground structure patch antenna can be used for C-, X- and Ku-band applications.

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

DOI: 10.21272/jnep.17(2).02023 PACS number: 84.40.Ba

1. INTRODUCTION

In wireless communication, we need compact, conformal, inexpensive, and easily fabricable antennas in order to establish communication on higher frequency bands. A promising environment for multiband antennas with compact dimensions is presented by the continuous advancements in high-speed and multifunctional electronics [1-2]. The compact design and low profile of microstrip antennas make them particularly useful among multiband antennas. However, low gain, high loss, low radiation efficiency, and limited bandwidth are some of the significant disadvantages of microstrip patch antennas. There are several strategies being used to solve these Challenges [3]. Some of them include using arrays of patch antennas, modifying the thickness of the substrate, adding numerous substrate layers [4], and changing the patch's fundamental shape by using metamaterials and metasurface. For example, an FSS with concentric square loops as a conducting patch and metamaterial [5] is used to enhance performance; in this case, the antenna size is 70 × 70 mm^2 used, it will operate at two different frequencies and attain a 7.5 dBi peak-gain with 3D printed superstrate is suitable for ISM band applications [6]. In order to increase gain and radiation efficiency, the proposed dielectric resonator antenna [7] uses a triple-layer FSS as a superstrate, with a dimension of 45 × 42 mm^2. For applications involving vehicle communication, a square patch antenna loaded with varactors and featuring truncated corners is proposed. It operates at two distinct frequencies with a size of 42.5 × 28.5 mm^2. To achieve a peak gain of 13.1 dBi, a cross-shaped FSS is

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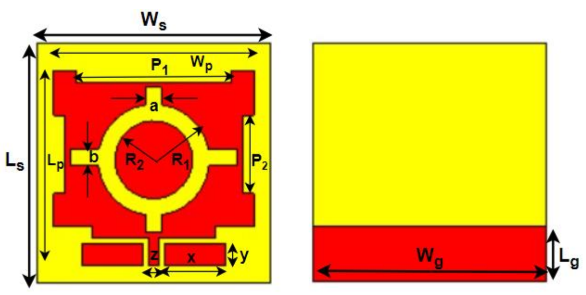
used [8]. A novel decoupling technique was employed in the 100 × 150 mm^2 size of UWB antenna, and antenna-elements were made of the metasurface layer to attain isolation of above 25 dB [9]. The mutual coupling in the MIMO antenna was reduced to 34 dB by using an *L*-shaped inverted slot [10]. By adding bottom rings and stubs, the half-hexagonal monopoles increased isolation by 20 dB and a variety of decoupling techniques are employed to optimize isolation [11]. The 2.2 GHz–12.3 GHz band was covered by a four-port vertical polarized antenna that was highly compact and had an isolation of over 15 dB. A Low mutual coupling was attained using a particular interlocking decoupling technique [12]. In order to obtain a minimum CCL of below 0.29 bits/Hz and improve isolation by – 22 dB, 2 × 2 and 4 × 4 very compact MIMO elements were equipped with "neutralizing lines," a very complex mutual coupling mechanism [13]. A parasitic novel structure was inserted between the patch elements of a pentagonal antenna structure [14] for multiple frequency and 5G applications [15], such as the array antennas or the circular-ring designs in [16-17], despite their size advantages, tiny designs have minimum matching impedance and poor reflection coefficient.

In response to the necessity of a multi-band applications with compact size, high efficiency and return loss, we designed square shaped multi slot defective ground structure antenna, which operates at three resonant frequencies of 4.6,9.6 and 13.1 GHz with reflection coefficient of – 16, – 11.7 and – 14.6 dB respectively. This low-profile antenna provides an excellent gain of 8.2, 6.8 and 7.4 dBi and radiation efficiency of 91, 83 and 89 % at resonance.

2. PRESCRIBED ANTENNA CONFIGURATION

The proposed antenna design contains a square square shaped multi-slot antenna with defective ground structure, as portrayed in Figure 1. The ground layer in the conventional three-layer arrangement is made of copper and has overall dimensions of 5 × 20 × 0.035 mm^3. The suggested antenna was designed using a polyimide middle layer and a relative dielectric value of 3.5, with a total size of 20 × 20 × 2 mm^3. A copper substance is used as a radiating patch with the overall dimension of 18 × 18 × 0.035 mm^3. The dimensions(mm) of the suggested antenna are $P_1 = 14$, $P_2 = 12$, $R_1 = 5$, $R_2 = 3.5$, $a = 1$, $b = 1$, $x = 5.5$, $y = 2.5$, $z = 1$.



(a) (b)

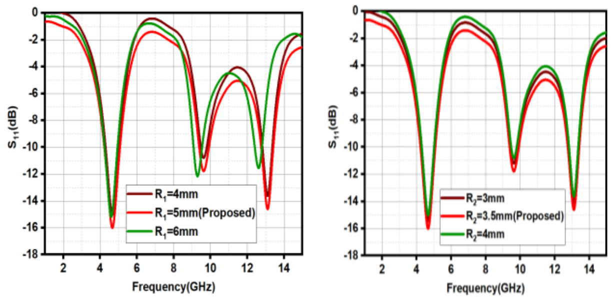
Fig. 1 – Proposed structure (a) Top view and (b) Back view

The CST tool is used to solve electromagnetic problems that require precise and speedy simulation results. Simple requirements for linear resource scaling in corresponding to the no. of mesh nodes are the main benefit of this tool. This enables the simple and effective control of large radiating structures.

3. PARAMETRIC STUDY

3.1 Impact of R_1 and R_2 Parameters

The capacitance value of the design is determined by the split gap, while the inductance value is determined by the parameters of the metal, which include its length, width, and thickness. The relative S_{11} plot is shown in Figure 2(a) after parametric analysis, with R_1 varied from 4 to 6 mm in 1 mm increments. By employing $R_1 = 4$ mm and 6 mm, the reflection coefficient is reduced. The highest reflection coefficient for all three resonant bands occurs only at $R_1 = 5$ mm, as shown in Figure 2(a). Similarly, the relative S_{11} plot is shown in Figure 2(b) when R_2 is varied in increments of 0.5 mm from 3 to 4 mm. R_2 = 3.5 mm yields the maximum reflection coefficient at three resonant bands, whereas R_2 = 3 mm and 4 mm yields the least reflection coefficient as depicted in Figure 2(b).



(a) (b)

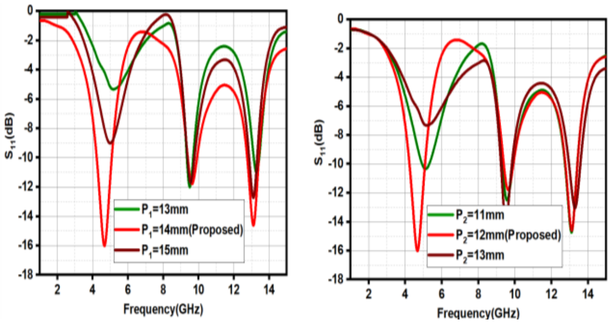
Fig. 2 – S_{11} (dB) plots obtained through parametric analysis by altering (a) R_1 and (b) R_2 parameters

3.2 Impact of P_1 and P_2 Parameters

The relative S_{11} plot is shown in Figure 3(a) after parametric analysis, with P_1 varied from 13 to 15 mm in 1 mm increments. By using P_1 = 13 mm and 15 mm, decreases the reflection coefficient. The highest reflection coefficient for all three resonant bands occurs only at P_1 = 14 mm, as shown in Figure 3(a). When P_2 is varied in increments of 1 mm from 11 to 13 mm, Figure 3(b) similarly depicts the relative S_{11} plot. As shown in Figure 3(b), the smallest reflection coefficient is achieved at P_2 = 11 mm and 13 mm, whereas the highest reflection coefficient for three resonant bands is achieved at P_2 = 12 mm.

3.3 Influence on Various Types of Conductive and Dielectric Materials

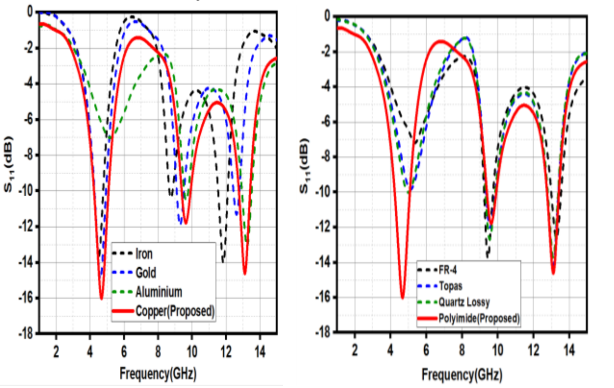
Analyzing the impacts of various conducting and dielectric materials has revealed differences in reflection coefficient. The utilization of suitable material alternatives is essential for the development of an effective structure in the proposed design.



(a) (b)

Fig. 3 – S_{11} (dB) plots obtained through parametric analysis by altering (a) P_1 and (b) P_2 parameters

While designing the uppermost layer of the design, five conductive materials were considered: gold, aluminum, iron and copper. The copper material may yield the highest S_{11} of the conductive materials investigated in Figure 4(a). The red spectrum indicates that copper has been selected as the conducting material. Furthermore, parametric analysis is carried out for a several dielectric materials. The dielectric materials considered in the study include FR-4, Topas, quartz lossy and polyimide. Figure 4(b) shows that the Polyimide substrate material design yields the highest reflection coefficient based on the analysis.



(a) (b)

Fig. 4 – S_{11} (dB) Plot for different materials utilized in the design analysis (a) conductive and (b) dielectric

4. RESULTS AND DISCUSSIONS

Figure 5 displays the proposed design's reflection coefficient plot. First resonance of the proposed antenna occurs at 4.6 GHz with a 0.8 GHz bandwidth

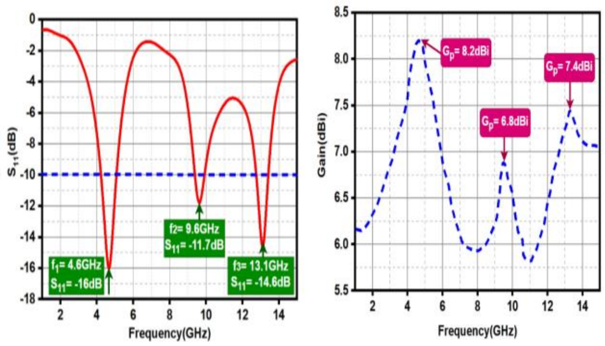
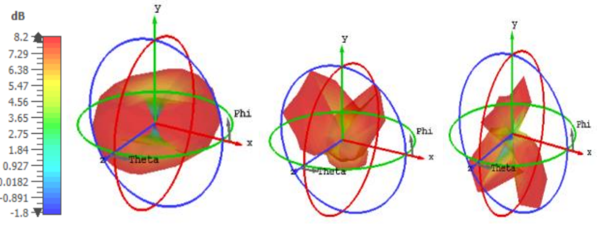


Fig. 5 – Reflection coefficient vs Frequency plot

(4.2 to 5 GHz) with S_{11} of – 16 dB, while the proposed design additionally resonates at 9.6 GHz with a 0.6 GHz bandwidth (9.3 to 9.9 GHz) and at 13.1 GHz with a 0.7 GHz bandwidth (12.7 to 13.4 GHz) with S_{11} of – 11.7 dB and – 14.6 dB respectively.



(a) (b) (c) (d)

Fig. 6 – Relative peak gain of the proposed design (a) Simulation (b) at 4.6GHz (c) at 9.6GHz (d) at 13.1 GHz

The proposed design operates at three resonant frequencies 4.6, 9.6 and 13.1 GHz produces an excellent peak gain of 8.2, 6.8 and 7.4 dBi at resonance as depicted in Figure 6(a-d), produces a high radiation efficiency of 91,83 and 89 % at resonance as shown in Figure 7 respectively.

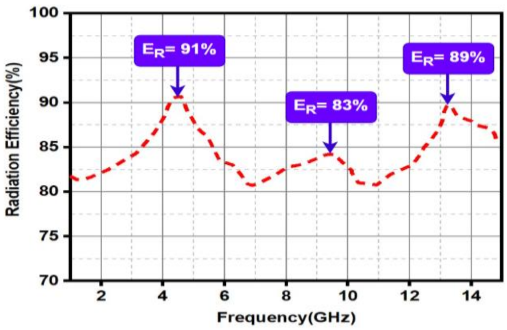
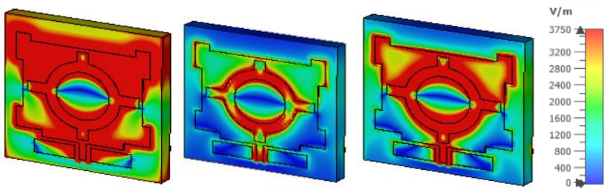


Fig. 7 – Radiation efficiency of the suggested design

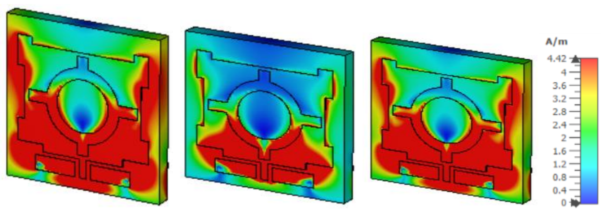
4.1 Various Current Distributions

The highest electric field intensity at 4.6 GHz is observed on the upper and lower sides of the radiating patch with circular slot and extends along the vertical - direction of the antenna, as seen in Figure 8(a). Figure 8(b) shows that the electric field is less intense at 9.6 GHz in the circular slot, while Figure 8(c) shows that the electric field is strong at 13.1 GHz in and around the circular slot. A maximum magnetic field is observed below the patch's circular slot in Figure 9(a), spreading horizontally along the antenna at 4.6 GHz. Figure 9(b-c) illustrates that the magnetic field is less intense at 9.6 and 13.1 GHz. Consequently, the magnetic and electric fields propagate in opposing directions. Figure 10(a-c) shows that for 4.6 GHz operation, the feed line exhibits the maximum current distribution. At 9.6 and 13.1 GHz frequencies, the surface current distribution spreads horizontally, with the corners of the square-shaped radiating patch showing the lowest current distribution.



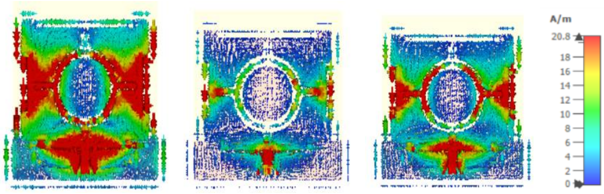
(a) (b) (c)

Fig. 8 – Electric field distribution at (a) 4.6 GHz (b) 9.6 GHz (c) 13.1 GHz



(a) (b) (c)

Fig. 9 – Magnetic field distribution at (a) 4.6 GHz (b) 9.6 GHz (c) 13.1 GHz



(a) (b) (c)

Fig. 10 – Surface current distribution at (a) 4.6 GHz (b) 9.6 GHz (c) 13.1 GHz

4.2 Performance Comparison with Other Reported Works

Table 1 compares the performance of the suggested antenna with the literature that has been presented. This suggested multi-slot defective ground structure patch antenna in the shape of a square provides excellent radiation efficiency and gain while maintaining compact size.

Table 1 – Comparison with recently reported work

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
[4]	2021	45 × 42	3.09 and 6	7.5 and 8.1	84 and 90
[5]	2022	40 × 52	2.3 – 2.8 4.9 – 5.8	3.50 and 3.53	79 and 88
[15]	2024	27 × 27	2.13 – 2.88 5.65 – 6.01	2.65 and 2.84	95 and 73
[17]	2024	26 × 26	3.2 – 3.51 5.24 – 5.52	2 and 2.34	Not Mentioned
[16]	2024	16 × 16	8.7 – 9.2	7.3	82
This Work	----	20 × 20	4.2 – 5 9.3 – 9.9 12.7 – 3.4	8.2, 6.8 and 7.4	91, 83 and 89

5. CONCLUSION

This article introduces a square shaped multi-slot defective ground structure antenna for triple-band applications. The proposed antenna has a total dimension of 20 × 20 × 2.07 mm^3, a copper and polyimide materials are used as top conducting and middle layer. An antenna that is designed with optimal dimensions yields superior results, leading to satisfactory antenna performance. The proposed antenna achieves 8.2 dBi, 6.8 dBi, and 7.4 dBi of peak gain, and 91 %, 83 %, and 89 % radiation efficiency at 4.6, 9.6, and 13.1 GHz frequencies, respectively. Hence, the suggested antenna is strongly recommended for use in C-, X- and Ku-band applications.

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Тридіапазонна квадратна багатослотова патч-антена з дефектною заземлювальною структурою для застосувань у діапазонах C, X та Ku

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У цій статті пропонується багатощілинна мікросмужкова патч-антена зі структурою дефектної землі квадратної форми для різних застосувань з літерними діапазонами. Запропонована структура була розроблена з використанням поліімідного діелектричного матеріалу товщиною 2 мм, який має діелектричну проникність 3,5. Загальний розмір антени становить 20 × 20 × 2,07 мм3. Запропонована антена забезпечує роботу в трьох діапазонах, зберігаючи при цьому компактний розмір випромінювача. Розроблений випромінювач має можливість працювати в трьох окремих частотних діапазонах: від 4,2 до 5 ГГц, від 9,3 до 9,9 ГГц та від 12,7 до 13,4 ГГц, з трьома окремими резонансними частотами 4,6, 9,6 та 13,1 ГГц відповідно. При резонансі досягається піковий коефіцієнт посилення 8,2, 6,8 та 7,4 дБі, а також ефективність випромінювання 91, 83 та 89 %. Було проведено комплексний параметричний аналіз з використанням симулятора CST для покращення продуктивності в робочому діапазоні частот щодо коефіцієнта відбиття (S11). Крім того, ми досліджуємо вплив різних провідних матеріалів (алюміній, золото, залізо та мідь) та діелектричних матеріалів (FR-4, Topas, кварц з втратами та поліімід) на характеристику запропонованої антени. Представлено методологію проектування антени, а також аналіз розподілу поля та струму. Запропонована тридіапазонна патч-антена з дефектною заземлювальною структурою може бути використана для застосувань у C-, X- та Ku-діапазонах.

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