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REGULAR ARTICLE

Capturing of Radio Frequency Energy with a Compact Ultra-wideband Patch Antenna

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This article presents a novel design for a rectangular patch antenna that is specifically intended for RF energy harvesting applications. The design incorporates a hybrid strategy (HS) that combines a slotted patch and partial ground plane with a defected ground structure (DGS). This integration helps to optimize impedance matching, minimize return loss, and improve the overall performance of the antenna. The antenna is constructed on a 30 mm by 20 mm FR4 substrate, with a compact patch size measuring 18 mm × 14 mm. The FR4 substrate used has a tangent loss of 0.02, a thickness of 0.8 mm, and a dielectric permittivity of 4.4. To feed the antenna, a 50 Ω microstrip feed line is employed. The antenna operates at a frequency of 3.5 GHz, which falls within the ultra-wideband (UWB) range of 3.1 GHz to 10.6 GHz. The design and optimization of the antenna are carried out using HFSS v.15 software. The simulation results show outstanding performance of the antenna. It exhibits excellent impedance matching, with a return loss of – 29.43 dB. The antenna also boasts a wide bandwidth of 19.54 GHz, making it suitable for various RF energy sources. Additionally, the power transfer efficiency is high, with a VSWR of 1.0699. The antenna demonstrates effective energy capture, with a peak gain of 8.7 dB, and focused energy directionality, with a directivity of 10.21 dB. This antenna efficiently converts RF energy into electrical energy, achieving an efficiency rate of 96.14%. The antenna's compact size, along with its impressive characteristics, renders it suitable for a wide range of wireless energy harvesting applications.

Keywords: RF, HS, Gain, Bandwidth, Efficiency, UWB, Patch Antenna

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1. INTRODUCTION

The demand for wireless communication systems that are both low-power and energy-efficient is increasing. This is crucial to prolong the battery life of electronic devices. RF energy harvesting has emerged as a promising technology to wirelessly power these devices. To achieve optimal energy harvesting efficiency with-out compromising wireless communication capabilities, it is of utmost importance to design an efficient antenna. There have been various types of antennas pro-posed for RF energy harvesting systems, including patch antennas, dipole antennas, and monopole antennas. Patch antennas are commonly used for RF energy harvesting applications due to their cost-effectiveness, compact size, and flat structure. They are designed to collect and convert electromagnetic energy into usable DC voltage. Microstrip patch antennas, in particular, are popular because of their low profile, planar structure, and low weight [1, 2]. These antennas are de-sired to have a wide bandwidth, good gain, and an omnidirectional radiation pattern to maximize energy acquisition over a wide frequency range. They can cover different frequency bands, such as 2.4 GHz, 5.1 GHz, 5.8 GHz (Bluetooth/Wi-Fi), 2.3 GHz, 2.5 GHz, 3.5 GHz, and 5 GHz (WiMAX), for energy harvesting. Patch antennas can be designed with various shapes, such as circular and rectangular, and can be miniaturized for compact rectenna designs [3]. These antennas are crucial for increasing the proportion of energy obtained through RF energy harvesting technologies. Fig. 1 illustrates a basic block diagram of the RF energy harvesting system.

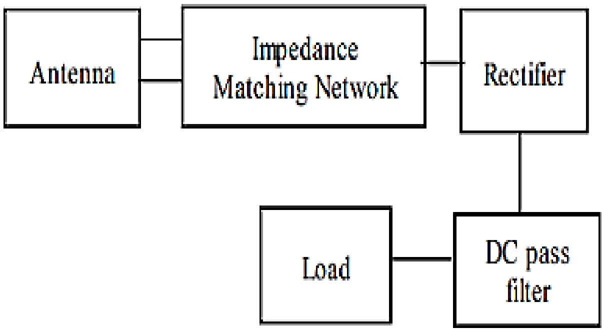

Fig. 1 – Block diagram of RF energy harvesting system [4]

In an RF energy harvesting system, the structure diagram typically comprises the following elements:

Antenna: The role of the antenna is to capture RF

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energy from the surrounding environment and trans-form the electromagnetic waves into electrical impulses.

Matching Network: The matching network ensures that there is impedance coordination between the antenna and the subsequent components of the system. Its purpose is to enhance the power transfer from the antenna to the rectifier.

Rectifier: The rectifier plays a vital role in the process of energy harvesting. Its function is to convert the alternating current (AC) signal received from the antenna into direct current (DC) voltage. This conversion is accomplished by utilizing diodes or other semiconductor devices to rectify the signal.

Energy Storage: The DC power generated by the rectifier is accumulated in an energy storage device, such as a battery, supercapacitor, or capacitor bank. This allows for the gathering of harvested energy for later utilization or for directly powering electronic de-vices. These components collaborate harmoniously to empower the RF energy harvesting system to capture, convert, and store RF energy for a multitude of applications.

Many research papers and studies have delved into the analysis, design, and optimization of systems that harvest RF energy using patch antennas. For instance, a novel wideband microstrip patch antenna featuring an integrated circular slot was developed [5]. This particular antenna design was meticulously crafted for the purpose of RF energy harvesting at a frequency of 2.65 GHz, with a focus on applications within the WiMAX spectrum.

Several research studies [6-8] have investigated the optimization of rectennas, which combine rectifiers and antennas. These rectennas are specifically de-signed to operate within certain frequency bands, such as the ISM band or the 2.45 GHz Wi-Fi frequency. In [9, 10], array antennas were explored, utilizing multiple rectangular microstrip patch antennas or an octagon-slotted planar circular ultra-wideband monopole to efficiently collect RF energy across a wide range of frequencies. Moreover, a single-band antenna design for RF energy harvesting at the 2.45 GHz frequency was examined in [11]. A dual-band rectifier for RF energy harvesting was proposed [12]. In order to address the challenges associated with battery maintenance, charging, and replacement, a study [13] investigated the utilization of a wideband antenna with a novel defected ground structure for RF energy harvesting. Additionally, [14] introduced a two-port innovative construction with a shared ground stub and enhanced isolation for Wi-Fi 2.4 GHz/LTE operations. As part of enhancing RF energy capture at 2.4 GHz, a new 3-point star rectifying antenna was designed and simulated in [15].

A study [16] was conducted to compare UWB microstrip antennas for RF energy harvesting and wireless communication. In another study [17], researchers introduced a dual-band microstrip patch antenna that eliminates unwanted signals to achieve spurious-free operation for RF energy harvesting. The authors aimed to minimize interference from spurious radiation, which can impact the efficiency of energy harvesting and disrupt desired signals. Additionally, a dual-band slotted rectangular antenna for microwave energy harvesting from the WiMAX band operating at 2.45 GHz and 3.84 GHz was presented in [18]. The design pro-posed by the authors enables efficient energy harvesting from these specific frequency bands. Moreover, [19] introduced a two-slot, dual-band, inset feed microstrip antenna specifically designed for RF energy harvesting. Furthermore, an Internet of Things application-specific device capable of high-gain RF energy collection at 2.45 GHz was introduced in [20]. These studies offer valuable insights into antenna design and optimization for RF energy harvesting, covering various frequency bands and addressing factors such as gain, efficiency, and bandwidth.

This study focuses on developing a rectangular patch antenna that integrates various strategies to enhance RF energy harvesting. The primary objective is to design an antenna with a wide bandwidth and optimal radiation properties, ensuring efficient RF energy capture while being compatible with matching circuits, rectifiers, and combiners. A wide bandwidth is essential for capturing a broad range of RF frequencies, enabling energy harvesting from diverse sources. Optimizing the antenna's radiation characteristics – such as achieving high gain, minimizing losses, and obtaining suitable radiation patterns – is critical for efficient energy capture and transmission. To maximize energy conversion and utilization, the antenna incorporates matching, rectifier, and combiner circuits, which are vital for processing and combining the harvested energy. This design is specifically tailored for RF energy harvesting applications, enabling effective energy conversion and utilization.

The rest of the paper is organized as follows: Section 2 presents the materials and methods used in this study, Section 3 provides a detailed description of the antenna structure, the outcomes of the simulations are discussed in Section 4, and Finally, Section 5 concludes the study by summarizing the key findings.

2. MATERIALS AND METHODS

2.1 FR4_Epoxy Substrate Material

FR-4 epoxy resin is a widely used and cost-effective substrate material for microstrip patch antennas. Its low dielectric constant (3.8 to 4.8) increases the electrical length of the patch while reducing the speed of electromagnetic wave propagation, enabling resonance at lower frequencies. With a low loss tangent (typically ≤ 0.02), FR-4 ensures optimal performance at high frequencies by minimizing signal losses, which is critical for efficient antenna operation. In microstrip patch antenna designs, the metal patch is placed on one side of the substrate, with the ground plane on the other. A thin metal feed line, often located on the back of the patch, delivers the signal to the antenna. Precise de-sign of the patch, ground plane, and feed line is essential to achieve the desired frequency, bandwidth, and radiation pattern.

2.2 Hybrid Methods

The hybrid strategy (HS) in antenna design combines a slotted patch (triangular-rectangular slot), a partial ground plane, and a defected ground structure (DGS) to enhance antenna performance. HS reduces return loss, ensuring efficient signal transmission and reception, and achieves excellent impedance matching for optimal power transfer and minimal signal reflections. It also expands the antenna's bandwidth, enabling it to operate across a wider range of frequencies and harvest energy from various RF sources. Additionally, HS increases antenna gain, improving signal strength and enhancing energy harvesting capabilities. It also boosts efficiency by maximizing the conversion of RF energy into usable electrical energy. In summary, the hybrid method optimizes antenna design by reducing return loss, improving impedance matching, and increasing bandwidth, gain, and efficiency, making it highly effective for energy harvesting applications.

3. ANTENNA DESIGN

The design of the hybrid strategy-based patch antenna incorporates three primary geometric structures, namely a rectangular patch with rectangular-right-angle triangular slots, a partial ground plane with a defected ground structure, and a microstrip feed line. The antenna's dimensions and parameters are as follows:

- The rectangular patch has a size of 18 × 14 mm ($W_P \times L_P$).
- The right-angle triangle features a hypotenuse (r) measuring 8.48 mm, while the other two adjacent sides (p and q) are both 6 mm.
- The rectangular slots on the patch have the following dimensions:

$$L_{p1} = 8 \text{ mm},\ W_{p1} = 2 \text{ mm}$$

$$L_{p5} = L_{p6} = W_{p2} = W_{p3} = W_{p4} = 0.5 \text{ mm}$$

$$L_{p2} = L_{p3} = L_{p4} = 7 \text{ mm}$$

$$W_{p5} = W_{p6} = 6.5 \text{ mm}$$

- The partial ground plane ($W_g \times L_g$) measures 20 × 14 mm and contains a single rectangular slot with dimensions ($W_{g1} \times L_{g1}$) of 3 × 2 mm
- The strip used for connecting the feed point to the antenna structure is 15 mm long (L_f) and 2 mm wide (W_f).
- The chosen dielectric substrate has a height (h) of 0.8 mm and is composed of FR4 material with a dielectric constant (ε_r) of 4.4. The dimensions of the FR4 substrate are ($W_s \times L_s$) = 20 × 30 mm
- Copper material is utilized for both the patch and the ground surface to ensure conduction
- The input impedance of the strip is set at 50 Ω to match the microstrip line.

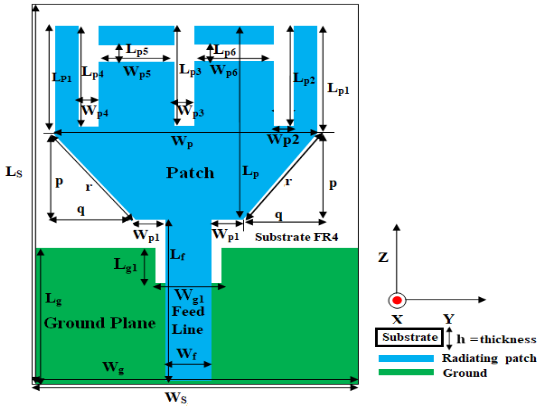

Fig. 2 – Proposed antenna structure

4. SIMULATED RESULT AND DISCUSSION

The effectiveness of the suggested design for the patch antenna is assessed and modeled using the HFSS v.15 software. Through the simulation results, valuable insights are gained regarding the antenna's performance, allowing for a thorough assessment of its capability to fulfill the required performance objectives.

4.1 Return Loss

Return loss is a measurement of the efficiency of power transfer from the feed point to the antenna. It is a critical parameter that ensures proper impedance matching. Impedance matching refers to the process of designing the input impedance of the antenna to align with the output impedance of the associated RF circuitry, or vice versa. This optimization aims to maximize power transfer and minimize reflections at the load terminal. In the industry, a standardized characteristic impedance of 50 Ω is typically employed to achieve impedance matching. The reference level for measuring return loss is set at -10 dB, indicating excellent performance where 90% of the power is successfully received by the antenna, and only 10% is reflected. Fig. 3 graphically represents the return loss (RL) of the proposed antenna. The antenna has been observed to resonate at various frequencies such as 3.6 GHz, 6.2 GHz, 7.6 GHz, 11.8 GHz, 15 GHz, 17.8 GHz, 20 GHz, and 21.6 GHz. The corresponding return losses for these frequencies are recorded as – 18.74 dB, – 22.84 dB, – 29.43 dB, – 18.02 dB, – 13.33 dB, – 21.84 dB, – 12.28 dB, and – 11.95 dB, respectively. These return loss values indicate the effectiveness of power transfer and impedance matching. The antenna exhibits its best impedance matching at 7.6 GHz, with a return loss of – 29.43 dB. This return loss value indicates a strong agreement between the feed line and the radiating patch, ensuring effective absorption of incoming RF energy for energy harvesting purposes. A return loss of – 29.43 dB indicates that only 0.11 % of the incident power is reflected back to the source, and 99.89 % of the available power is effectively transmitted into the antenna.

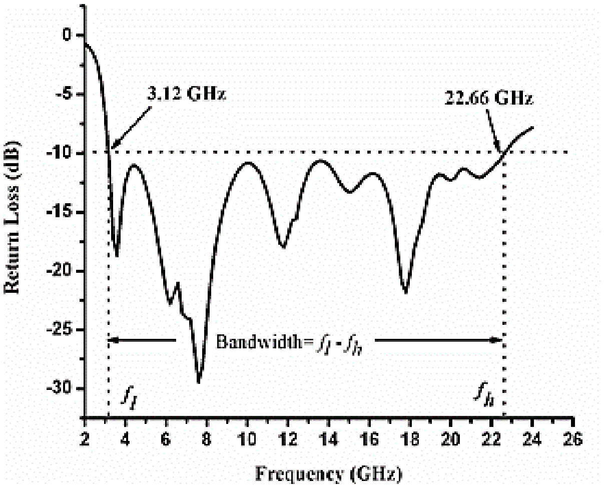

Fig. 3 – Return loss of the proposed antenna

4.2 Bandwidth

The return loss graph is used to calculate the bandwidth of an antenna. The bandwidth is determined by the frequency range where the return loss is lower than – 10 dB, as shown in Fig. 3. The bandwidth can also be expressed as a percentage of the center frequency of the frequency band. In this case, the bandwidth (BW) is calculated by subtracting the lower cut-off frequency (3.12 GHz) from the higher cut-off frequency (22.66 GHz), resulting in an estimated bandwidth of 19.54 GHz. Having a wide bandwidth means that the antenna is capable of capturing RF energy from a broad range of frequencies, making it suitable for various wireless communication scenarios. This versatility is valuable in applications where the antenna needs to support multiple frequency bands or operate in environments with changing signal conditions.

4.3 VSWR

Voltage Standing Wave Ratio (VSWR) measures the impedance matching between an antenna and its feedline, also known as standing wave ratio. A high VSWR indicates that the antenna reflects a significant portion of the signal instead of radiating it. Ideally, the VSWR should be between 1 and 2 to minimize reflection losses. A lower VSWR signifies better impedance matching, resulting in increased power delivery to the antenna. VSWR arises from impedance mismatches between input and reflected signals in the connector. As shown in Fig. 4, the VSWR for the designed antenna at 7.6 GHz is 1.0699, which is below 2, indicating a near-perfect match. This means approximately 99.89 % of power is efficiently supplied to the antenna, leading to a minimal mismatch loss of 0.004955 dB and negligible power loss during RF signal transmission and reception.

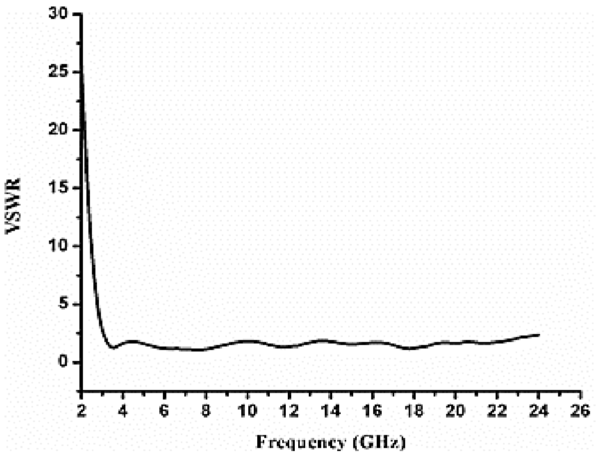

Fig. 4 – VSWR of the proposed antenna

4.4 Radiation Pattern

The radiation pattern of an antenna is a significant attribute that describes how it disperses energy in various orientations. In this particular instance, the antenna exhibits a bidirectional radiation pattern, signifying that it emits most of its power in two primary directions. Fig. 5 visually represents this pattern. When the angle φ is 0°, the antenna emits its maximum power of 10.3 dB, while at 90°, it emits 9.37 dB. It should be noted that the radiation pattern can differ based on the antenna's design and unique characteristics. Analyzing the radiation pattern enables us to as-certain the antenna's directionality and coverage, which is pivotal for applications such as wireless communication, radar systems, and satellite communication.

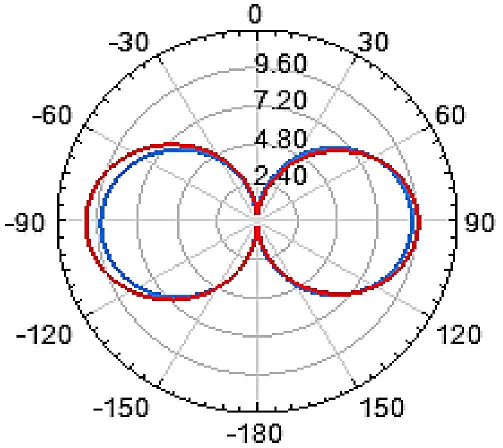

Fig. 5 – 2D far-field radiation pattern of the proposed antenna

4.5 Directivity

Directivity refers to the ability of an antenna to focus electromagnetic energy in a particular direction. In Fig. 6, the simulation results display the directivity of the proposed antenna across different operating frequencies. The peak directivity falls within the range of 2.54 dB to

10.21 dB, spanning from 3.12 GHz to 22.66 GHz. At 22.60 GHz, the suggested antenna achieves a maximum directivity of 10.21 dB, which indicates the antenna's ability to focus the captured energy in a specific direction.

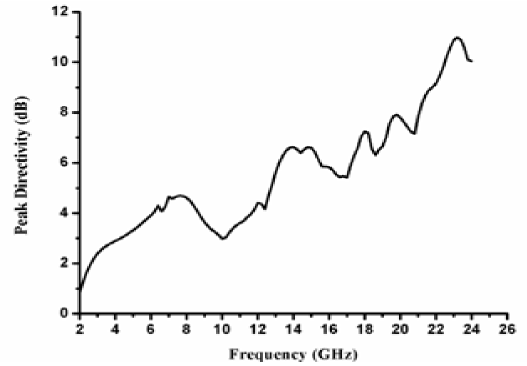

Fig. 6 – Peak directivity of the proposed antenna

4.6 Gain

The gain of an antenna refers to its ability to focus and direct radio waves in a specific direction. In the case of the proposed antenna, it is able to convert electrical energy into radio waves with varying degrees of gain within the frequency range of 3.12 GHz to 22.66 GHz. Fig. 7 shows that the peak gain of the antenna ranges from 2.38 dB to 8.7 dB within this frequency range. At a frequency of 21.60 GHz, the antenna achieves its maximum gain of 8.7 dB, which indicates its effectiveness in capturing energy efficiently. This characteristic makes the antenna well-suited for targeted energy harvesting applications, where it can efficiently capture and convert radio waves into usable electrical energy. Additionally, the high gain of the antenna means that it can transmit and receive signals over longer distances with greater efficiency. This is particularly useful for applications that require long-range communication, such as satellite communication where signals need to be transmitted and received over vast distances.

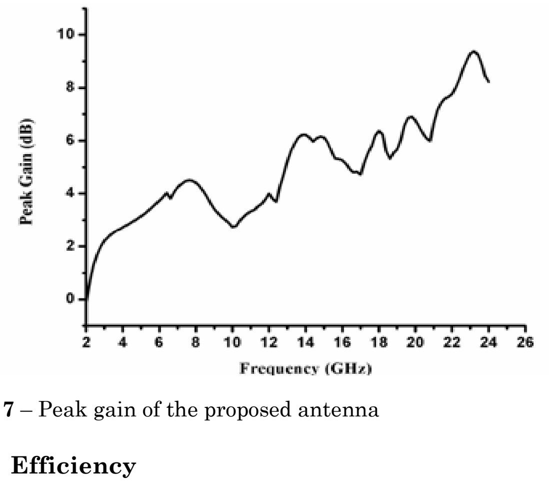

Fig. 7 – Peak gain of the proposed antenna

4.7 Efficiency

Antenna efficiency measures how effectively input power is converted into radiated electromagnetic energy, typically expressed as a percentage. Higher efficiency indicates minimal energy loss as heat or reflection. Factors influencing efficiency include design, size, construction materials, operating frequency, and environmental conditions such as interference or nearby obstacles. Larger antennas and those well-matched to the source or transmission line generally achieve higher efficiency. The proposed antenna achieves an outstanding efficiency of 96.14%, showcasing its ability to convert RF energy into electrical energy with minimal losses. This high efficiency ensures optimal performance in energy-harvesting applications.

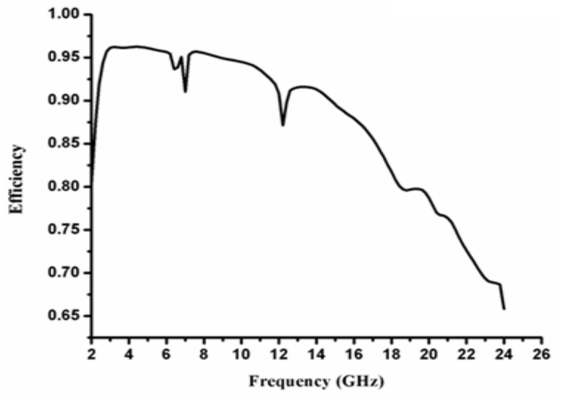

Fig. 8 – Efficiency of the proposed antenna

Studying antenna technologies for capturing ambient energy benefits wireless communication networks by enhancing energy efficiency, reducing costs, promoting sustainability, improving reliability, and driving innovation. These antennas harness energy from sources like solar, wind, or RF signals, minimizing waste and dependence on traditional power. This not only lowers operational costs but also reduces carbon emissions, supporting global sustainability goals.

Integrating ambient energy capture improves network reliability, especially in off-grid or remote areas, ensuring consistent connectivity and bridging the digital divide. This fosters universal connectivity, particularly in underserved rural regions. In Bangladesh, RF energy harvesting through patch antennas offers a sustainable energy solution, reducing reliance on fossil fuels and imports. It expands electricity access in re-mote areas, powering essential devices and enhancing quality of life. The technology also supports national energy goals and aligns with the UN Sustainable Development Goal of universal energy access. Additionally, RF energy harvesting facilitates smart city initiatives by powering IoT devices, improving infrastructure, and enabling applications like traffic management and waste monitoring. These advancements pro-mote sustainability, innovation, and connectivity, shaping a more inclusive and technologically advanced future.

5. CONCLUSION

In this paper, a compact rectangular patch antenna with a hybrid strategy for RF energy harvesting in wireless communication systems has been successfully developed and simulated. The simulation results demonstrate the antenna's effectiveness, achieving a return loss of – 29.43 dB, ensuring excellent impedance matching and efficient RF energy absorption. The antenna offers a wide bandwidth of 19.54 GHz (3.12 GHz to 22.66 GHz) with return loss below – 10 dB, enabling energy harvesting across diverse frequencies. It achieves minimal power loss with a VSWR of 1.0699, a peak gain of 8.7 dB for strong signal performance, and a directivity of 10.21 dB, enhancing energy harvesting efficiency. With an impressive efficiency of 96.14%, the antenna effectively converts RF energy into electrical energy, making it a promising solution for sustainable, energy-efficient wireless communication systems. Its robust performance and dual functionality—energy harvesting and reliable communication—highlight its potential for future wireless network advancements.

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Захоплення радіочастотної енергії за допомогою компактної надширокосмугової патч-антени

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У цій статті представлено новий дизайн прямокутної патч-антени, спеціально призначеної для застосування у збиранні радіочастотної (RF) енергії. Конструкція використовує гібридну стратегію (HS), що поєднує прорізаний патч та часткову заземлюючу площину зі структурою дефектного заземлення (DGS). Це інтегрування допомагає оптимізувати погодження імпедансу, мінімізувати коефіцієнт зворотних втрат і покращити загальну продуктивність антени. Антена виготовлена на підкладці FR4 розміром 30 мм × 20 мм, а її компактний патч має розміри 18 мм × мм. Використана підкладка FR4 характеризується тангенсом втрат 0,02, товщиною 0,8 мм і діелектричною проникністю 4,4. Живлення антени здійснюється через мікросмужкову лінію з хвильовим опором 50 Ом. Антена працює на частоті 3,5 ГГц, що входить до надширокосмугового (UWB) діапазону 3,1 – 10,6 ГГц. Проектування та оптимізація антени виконані за допомогою програмного забезпечення HFSS v.15. Результати моделювання демонструють відмінні характеристики антени. Вона забезпечує чудове погодження імпедансу, із зворотними втратами – 29,43 дБ. Антена також має широку смугу пропускання 19,54 ГГц, що робить її придатною для роботи з різними джерелами радіочастотної енергії. Крім того, ефективність передачі потужності є високою, із коефіцієнтом стоячої хвилі (VSWR) 1,0699. Антена ефективно захоплює енергію, забезпечуючи піковий коефіцієнт підсилення 8,7 дБ та фокусовану спрямованість випромінювання, з директівністю 10,21 дБ. Вона ефективно перетворює радіочастотну енергію в електричну, досягаючи коефіцієнта корисної дії (ККД) 96,14%. Компактні розміри антени, а також її виняткові характеристики роблять її придатною для широкого спектру застосувань у бездротовому збиранні енергії.

Ключові слова: RF, HS, Підсилення, Смуга пропускання, Ефективність, UWB, Патч-антена.