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Four-element Microstrip Patch Antenna Array for Low-Power RF Energy Harvesting

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***Abstract*—This article presents the design and simulation of a four-element microstrip patch antenna array specifically tailored for low-power radiofrequency energy harvesting. The proposed antenna array aims to efficiently capture and convert RF energy into usable electrical power, making it suitable for various wireless energy harvesting applications. The design process involves optimizing the patch geometry and dimensions, as well as the array configuration, to achieve enhanced power harvesting performance. The simulations explore the antenna array's characteristics, including its radiation pattern, return loss, and power conversion efficiency, which are evaluated and analyzed. The results demonstrate the effectiveness and potential of the proposed design, peak gain of 4.87 dBi and a VSWR of 1.04, for low-power RF energy harvesting systems.**

***Index Terms*—IoT, ambient electromagnetic signals, radiofrequency energy harvesting, rectenna, smart cities**

I. Introduction

Radiofrequency (RF) energy harvesting is the capture and conversion of stray electromagnetic signals into a usable form, i.e. electricity [1] [2] [3] [4]. Harvested energy can be used to power low-energy wireless devices and sensors that land in applications in the Internet of Things (IoT) [5] [6], smart cities [7] [8], and remote monitoring systems [9] [10]. Among the plethora of antenna types, microstrip patch antennas have been greatly considered due to their compact form factor, ease of fabrication, and compatibility with RF frequencies [11]. The geometry of such antennas allows relative ease in integrating multiple patches in an array to improve the performance of RF energy harvesting systems [12]. Multiple antennas arranged in an array have several key advantages such as gain, improved directivity, and increased power-handling capacity [13]. Maximizing captured RF can be attributed to the successful combination of stray RF signals into a coherent form for energy conversion.

In the process of designing the antenna array, various parameters need to be carefully considered. The choice of substrate material, patch element dimensions, feed network design, and impedance matching techniques significantly impact the overall performance and power transfer efficiency [14]. Through analytical models and electromagnetic simulations, these parameters can be fine-tuned to achieve the desired level of performance for RF energy harvesting.

Furthermore, the rectifier circuit plays a vital role in converting the captured RF energy into usable DC power. Selecting an efficient rectification technique, such as a voltage multiplier circuit or a low-dropout regulator, ensures high conversion efficiency and minimal power loss. This paper presents the design of an RF energy harvesting system that seeks to maximize collection performance for potential use in mobile device charging. Fig. 1 shows the focus of the study on RF energy harvesters for wireless power transmission systems. The potential applications of the 2x2 microstrip patch antenna array for RF energy harvesting vastly include applications in wireless sensor networks, smart buildings, environmental monitoring systems, and various IoT devices, enabling self-sustaining and autonomous operation. Additionally, its compact size and versatility make it suitable for integration into wearable electronics, portable devices, and other energy-constrained scenarios.

II. Methodology

The general setup of an antenna system found in RF energy harvesters is presented in Fig. 1. This setup includes an impedance matching circuit which is necessary when the model of the antenna and the rectifying circuit is not yet matched. The RF energy harvester is desired to provide an output voltage of 5V to meet the requirements of the storage unit and the load.

A. Antenna

An inset-fed microstrip patch antenna (Fig. 2) is utilized due to its ease of manufacturing and the low cost of the materials

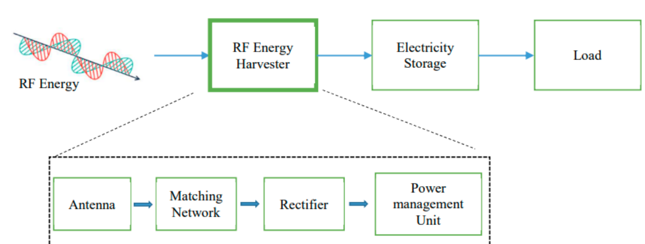

Fig. 1. Components of RF energy harvester in a wireless power transmission system

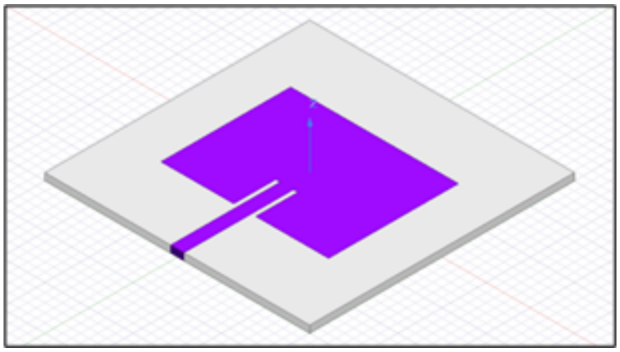

Fig. 2. Microstrip patch antenna

needed. The inset feeding technique has several advantages that are considered in the selection: flexibility in impedance match, compactness, and versatility for different patch antenna designs. The antenna is created by etching a conductive patch on an FR-4 PCB with a substrate having a relative permittivity of 4.4. The position and dimension of the patch are identified using (1) to (3).

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{2}$$

$$L = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} \tag{3}$$

However, the initial calculations and simulations result in the need for additional antennas to meet the output voltage requirement. Hence, a 2x2 patch array becomes the basis for the antenna design.

B. Rectifier circuit, matching network, and electrical load

The rectifier circuit is modeled as a four-stage voltage multiplier with Schottky diodes and a capacitor network (Fig. 3). The rectifier circuit resonates at a target operating frequency of 2.4 GHz covering the IEEE 802.11 b/g/n WiFi channels. Due to the low voltage measured in the feed line, there is a need to multiply the input four times to meet the required 5V output of the rectifier. A 50-Ω T-network is used to match the antenna to the rectifier.

C. Simulation Tools

The design of the antenna is created using Ansys High-Frequency Simulation Software (Ansys HFSS) and then exported to Advanced Design System (ADS) to simulate the RF response of the antenna and the rectifier circuit. An Sparameter simulation and a harmonic balance configuration were conducted to validate the conversion process from RF energy input to the dc voltage output.

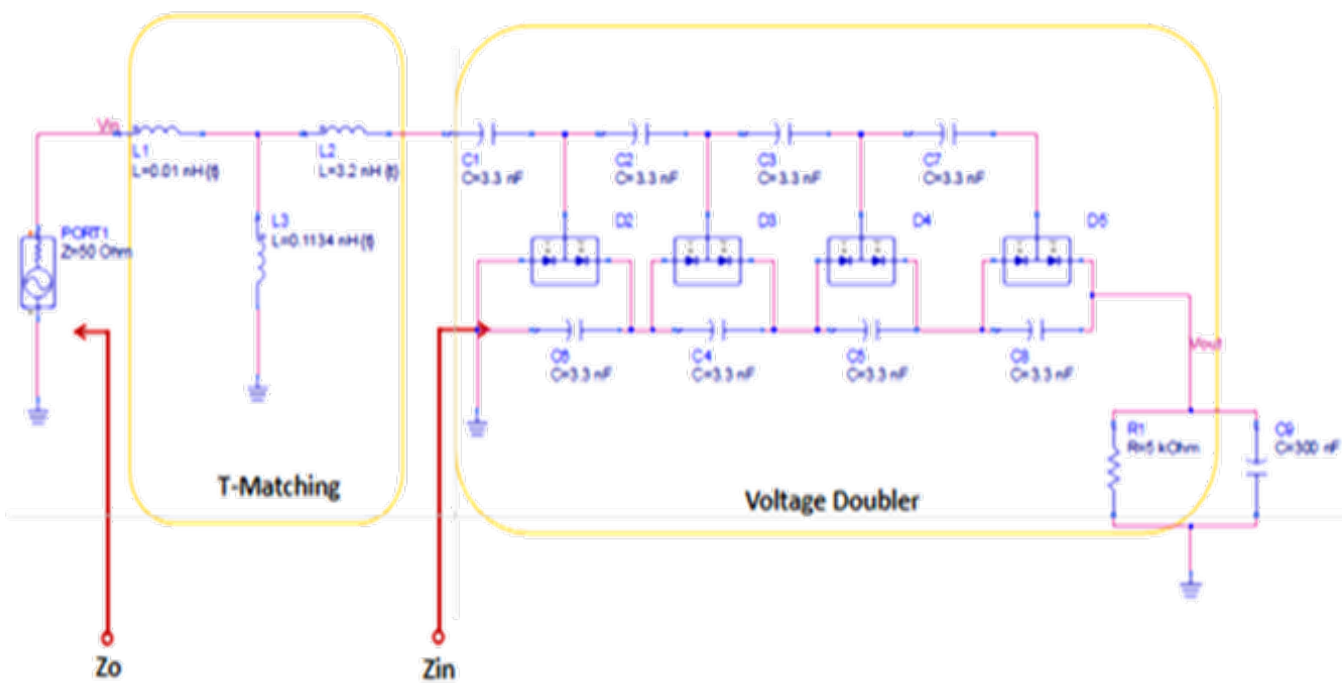

Fig. 3. Schematic diagram of the harvester

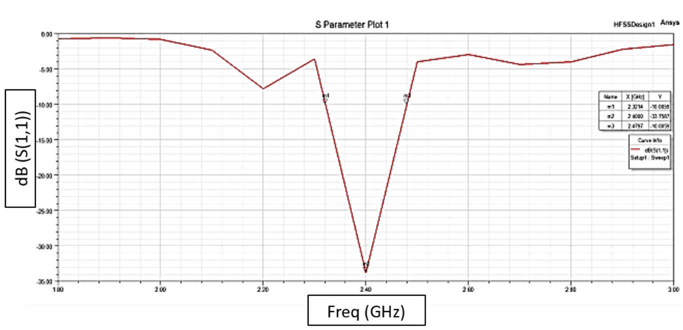

Fig. 4. S-parameter plot of the antenna

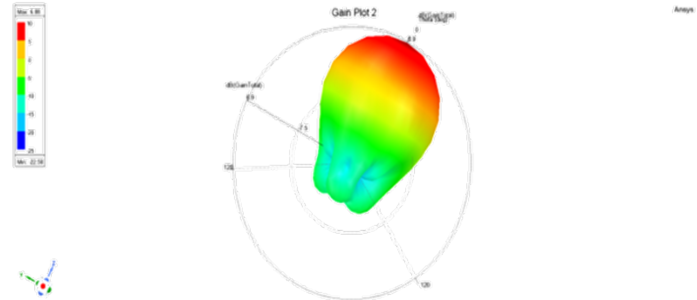

Fig. 6. Radiation pattern of the antenna array

III. Results and Discussion

Fig. 4 depicts the S-parameter plot of the antenna obtained using Ansys HFSS. The S-parameter, specifically S11, measures the reflection or return loss of the antenna. It indicates how well the antenna is matched to the transmission line or source. In the plot, the return loss for the resonating frequency of 2.4 GHz is shown as -33.7587 dB. It indicates a significant reduction in the power reflected from the antenna. In practical terms, this means that the antenna is highly efficient at converting the received RF energy into useful radiation at the resonating frequency of 2.4 GHz. The S11 value below -10 dB is considered desirable for effective antenna performance. This threshold indicates that the majority of the incident power is being radiated by the antenna, while only a minimal amount is being reflected. Therefore, the S11 value of -33.7587 dB obtained for the 2.4 GHz resonating frequency demonstrates that the antenna is operating optimally within this range and is highly effective in terms of power conversion and radiation efficiency.

Fig. 5 displays the voltage standing wave ratio (VSWR) characteristics of the 2x2 inset-fed microstrip patch antenna obtained using Ansys HFSS. The VSWR for the resonating frequency of 2.4 GHz is measured to be 1.0419. A low VSWR value indicates that a negligible amount of power is reflected in the source, implying efficient power transfer from the antenna. The VSWR is also utilized as a measure of the antenna's bandwidth, known as the impedance bandwidth.

The impedance bandwidth is determined by the frequency range where the VSWR meets the specified criteria. In this case, a commonly used criterion is a 2:1 VSWR, which defines the operating bandwidth as the range of frequencies where the VSWR remains below 2. Therefore, the antenna's operating bandwidth is selected from the frequencies within this range. Additionally, the statement mentions that the antenna has a bandwidth of 53 MHz, indicating the frequency span over which the antenna exhibits acceptable VSWR characteristics.

Together, the VSWR analysis presented in Fig. 5 confirms the antenna's ability to effectively match the impedance and transfer power at the resonating frequency of 2.4 GHz with minimal reflections. The measured VSWR of 1.0419 and the specified bandwidth of 53 MHz contribute to the antenna's performance and suitability for RF energy harvesting applications.

Fig. 6 illustrates the 3D polar plot of the microstrip patch antenna, providing insights into its radiation characteristics. The plot reveals that the antenna's gain is measured at 4.87 dBi, 6.88 dB, or 36.88 dBm. the gain of the microstrip patch antenna is reported as 4.87 dBi, 6.88 dB, or 36.88 dBm. The "dBi" unit indicates the gain relative to an ideal isotropic

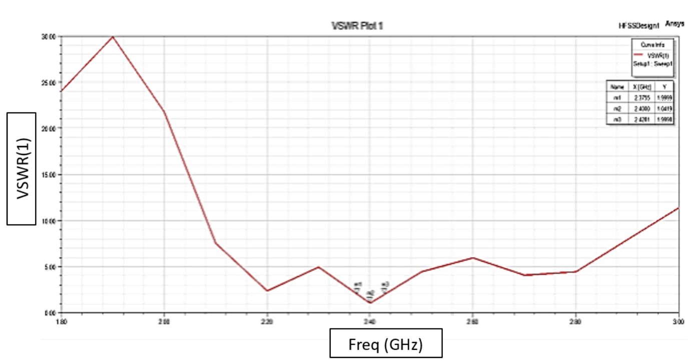

Fig. 5. Voltage standing wave ratio (VSWR) characteristics of the 2x2 inset-fed microstrip patch antenna

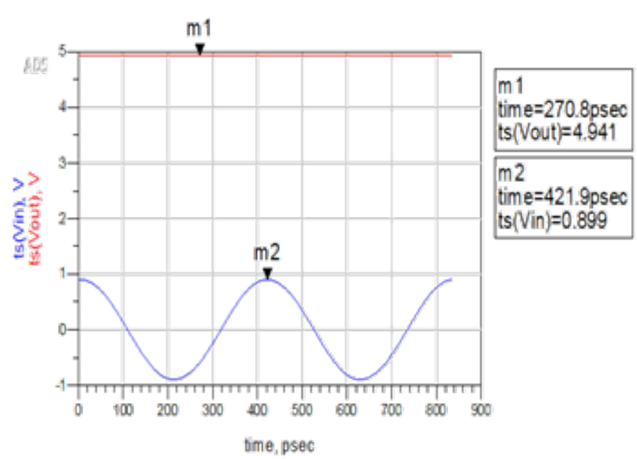

Fig. 7. Voltage output of the RF energy harvester

radiator, while ”dB” and ”dBm” represent gain referenced to a specific power level. These gain values signify the antenna’s ability to focus and radiate energy in a particular direction, indicating its directivity and efficiency.

Fig. 7 displays the results of the DC output voltage achieved using the RF energy harvester system. The system comprises a microstrip patch inset-fed antenna, a T-matching impedance circuit, a four-stage voltage doubler rectifying circuit, and a load. The simulation and measurement results indicate that the output voltage is 4.941 V when the input is 0.899 V at a frequency of 2.4 GHz, as depicted in the figure.

IV. Conclusion

The RF energy harvesting system developed in this project consists of a 2x2 inset-fed microstrip patch antenna array, a Tmatching impedance network, and a voltage doubler rectifying circuit coupled to a load. The antenna array, comprising four identical patches on an FR-4 substrate, utilizes the inset-fed technique to maximize energy reception from the surroundings, operating within the 2.38 to 2.43 GHz frequency range that covers the widely used 2.4 GHz Wi-Fi band. With a peak gain of 4.87 dBi and a VSWR of 1.04, the antenna array proves to be suitable for RF energy harvesting applications. Additionally, a single-band rectifier circuit, operating at 2.4 GHz, incorporates a four-stage voltage doubler to ensure the output voltage meets the desired level. The input impedance of the rectifier circuit is matched to the 50 Ω RF source using a T-matching impedance network consisting of three inductors with carefully chosen values to optimize circuit efficiency. Furthermore, the load impedance of 5 kΩ is determined as the optimal value for maximum efficiency. Importing the S-parameter file of the microstrip patch antenna array into the circuit, the measured output voltage at 2.4 GHz frequency is found to be 4.941 V with an input of 0.899 V. This demonstrates the successful design of an RF energy harvesting system utilizing the 2x2 inset-fed microstrip patch antenna array, capable of converting the 2.4 GHz radio frequency from the Wi-Fi band into a 5V DC voltage, making it suitable for charging low-power devices like smartphones.

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