Design of a Flexible Rectangular Antenna Array with High Gain for RF Energy Harvesting and Wearable Devices

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Flexible RF electronics and antennas made from textiles are regarded as a technology that accelerates the widespread popularity of modern wearable communication devices and components. This work presents a flexible and compact 4×1 rectangular microstrip patch array antenna for radio frequency (RF) energy harvesting applications. It operates at 5 GHz and has a high gain. The proposed antenna incorporates the inset feed technique to improve impedance matching and employs a conductive fabric (E-textile) as a conductor, along with textile as a substrate. The feeding and radiating structures are designed by using stick E shield conductive textiles that possess a conductivity of 5×10^5 S/m and are 0.085 mm thick. This design relies entirely on textile materials to ensure the user's comfort, ease of production, and cost-effectiveness. The Ansys HFSS simulator, which employs the finite element method, was utilized to optimize the antenna design. Subsequently, the suggested configuration was verified using the CST MWS simulator, which utilizes the finite integration method. The study aimed to achieve high gain and robust performance from the designed antenna. The simulation results demonstrate excellent performance within the operating band, with an impedance bandwidth of 6.78% and a high gain of 14.54 dBi at 5 GHz, making it well-suited for radiofrequency (RF) energy harvesting and wearable device applications.

Keywords: E-textile (Conductive fabric), Array antenna, Gain enhancement, Radiofrequency (RF) energy harvesting.

1. INTRODUCTION

With the advancements in wireless communication technology, there has been a rapid expansion in the use of small-power electronic devices for applications including, smart cities, Internet of Things (IoT), and wireless sensor networks. Nonetheless, this has posed fresh hurdles for energy supply systems. The replacement of batteries in these small-power electronic systems is not only time-consuming but also costly. Furthermore, the incorrect removal of used piles can harm the environment. The cable charging approach is impractical for wireless sensors placed in hard-to-reach locations [1-5]. Therefore, harvesting environmental energy to supply small-power electronic devices could be a viable solution to the energy problem [6]. Researchers have explored several methods for generating electricity from various environmental energy sources like wind, vibration, solar, and electromagnetic (EM) waves. Among these techniques, RF energy harvesting stands out as it is implantable and sustainable, providing an advantage over wind, solar, and vibration energy harvesting methods [7-10]. On the other

hand, the rate of radio frequency (RF) sources in the environment has increased considerably due to advances in wireless communication systems. These sources include 5G communication base stations, wireless routers, and Internet of Things (IoT) devices, which implies that utilizing RF energy to power low-power devices is becoming more practical and achievable [11]. The rectification of RF-electromagnetic waves into direct current power is achieved by employing a rectifying antenna, commonly referred to as a rectenna, for the purpose of extracting power from RF sources. Researchers have extensively studied the rectifier and the receiver antenna in recent years. However, practical applications are limited due to the finite amount of electromagnetic energy at a unique frequency and the small DC output power generated. To overcome this challenge, multiband, broadband, or array rectennas are emerging as promising solutions to enhance power generation efficiency [12].

2. GEOMETRY OF THE SUGGESTED ANTENNA

2.1 Single-Element Antenna

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Fig. 1 illustrates the antenna design that employs an inset feed technique. The design comprises a rectangular patch loaded with vertical narrow slits printed on the substrate's top and a complete ground plane on the bottom side of the geometry. The inset feed method is employed to enhance impedance matching. In contrast to the coaxial feed antenna, the inset-fed patch antenna is preferred in this design because it conforms better to the array design and provides better polarization purity with the same realized gain. The proposed antenna design uses an adaptable substrate composed of 2 mm thickness EVA foam with dielectric constant of $\varepsilon_r = 1.17$. A conductive fabric with a thickness of 0.085 mm and a surface resistance of less than 0.009 Ω/sq is used for the radiating element and ground plane design. The optimized geometrical parameters obtained through ANSYS HFSS are shown in Table 1. The geometrical dimensions of the patch for the microstrip antenna are calculated from its operating frequency using the transmission line model equations (1) to (5) [14-15].

The width of the patch is:

$$W_p = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}}, \qquad (1)$$

with f_0 as resonance frequency, c is the velocity of light, and ε_r is the dielectric constant of the substrate.

The effective permittivity of the substrate is:

$$\varepsilon_{eff} = \frac{\varepsilon_{relative}+1}{2} + \frac{\varepsilon_{relative}-1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{h}{W_P}\right)}}\right), \qquad (2)$$

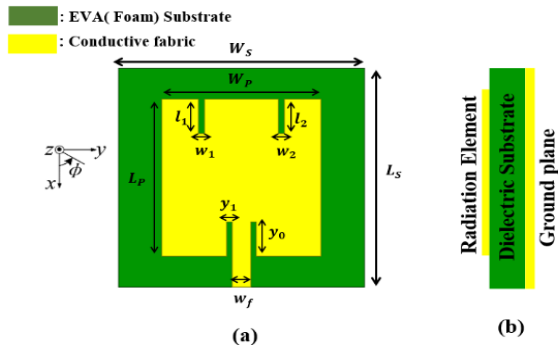The length of the radiator is then obtained from:

$$L_P = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta L, \qquad (3)$$

where ΔL is the extension of length due to the fringing field and can be calculated using:

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_P}{h}+0.264\right)}{(\varepsilon_{reff}+0.258)\left(\frac{W_P}{h}+0.8\right)}, \qquad (4)$$

The efective length of the radiator is then:

$$L_e = L_P + \Delta L, \qquad (5)$$

Fig. 1 – Geometry of suggested single element antenna. (a) Top view. (b) Side view

Table 1 – Optimized Dimensions of Single Antenna Element

Parameters	Values(mm)	Parameters	Values(mm)
W_S	35	l_f	5
L_s	40	$w_1 = w_2$	1
W_P	25	$l_1 = l_2$	5.4
L_p	26	y_0	5.5
w_f	3	y_1	0.9

2.2 Single Antenna Performance

This section introduces and analyzes the simulation results of a single antenna structure. Using the Ansys HFSS simulator, the reflection coefficient, VSWR, and radiation parameters of the antenna are studied. Fig. 2(a) shows the S_{11} of the suggested antenna, indicating resonance at 5 GHz with a bandwidth of 4.95 to 5.12 GHz for $|S_{11}| \leq -10\ dB$. VSWR is an important parameter, and Fig. 2(b) demonstrates that the antenna has better matching performance with a VSWR of less than 2 at the operating frequency. The antenna's gain and efficiency are depicted in Fig. 2(c) and Fig. 2(d), respectively, revealing a maximum gain of 6.37 dB and a maximum efficiency of 67%. The simulated E and H plane radiation pattern characteristics of the antenna are presented in Fig. 3, indicating that the antenna radiates its maximum power in the broadside direction. The accuracy of the simulation results is verified by comparing the reflection coefficients (S_{11}) and VSWR obtained from Ansys HFSS with those obtained from the CST MWS simulator. While the outcomes from both software show good agreements across a wide range of frequencies, there are slight differences noticed owing to the distinct numerical techniques employed by each software.

## 3. ANTENNA ARRAY DESIGN

3.1 Two-element Antenna Array

During the design's second phase, a two-element array was formed by employing the same single-element patches. This has been done to improve the antenna's efficiency, gain, and bandwidth. Fig. 4 displays the configuration of both the array and its feeding network. The array is excited using a parallel feed network, and the impedance of the main feed line is matched with 50 Ω, while the branch lines are matched at 100 Ω. To perform the impedance matching in the simulation, the typical transmission line formulas are used. The optimized geometrical parameters are outlined in Table 2.

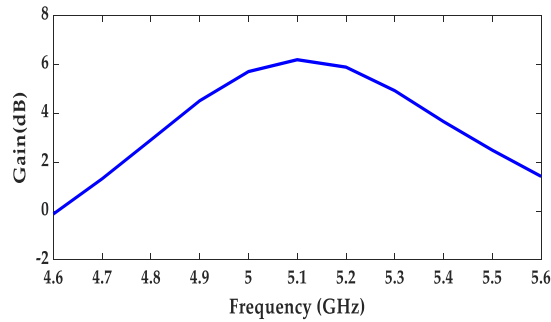**Table 2** – Optimized Dimensions of Two Antenna Element

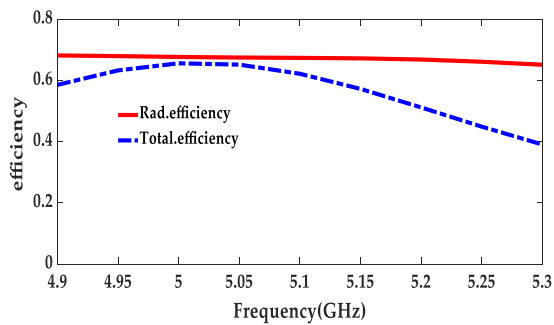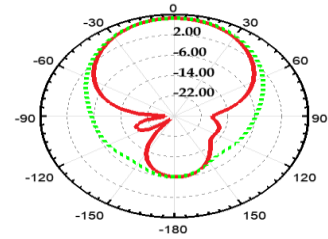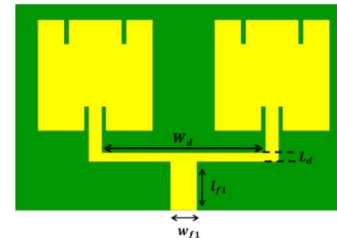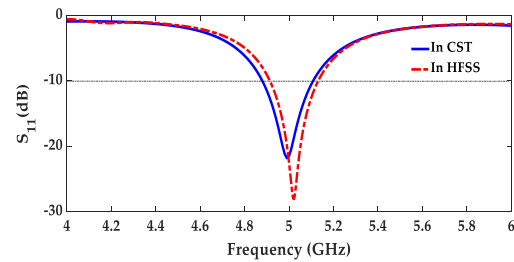| Parameters	Values(mm)
W_S	75
L_s	47
W_d	37
L_d	1.5
W_{f1}	6
L_{f1}	11
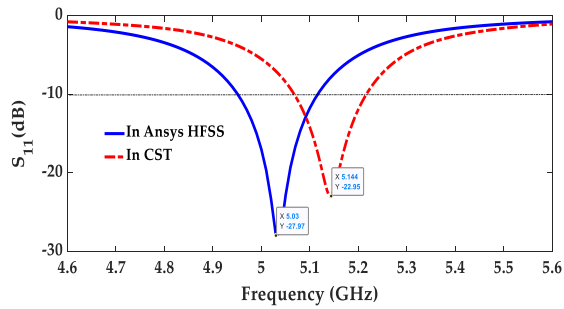
(a)
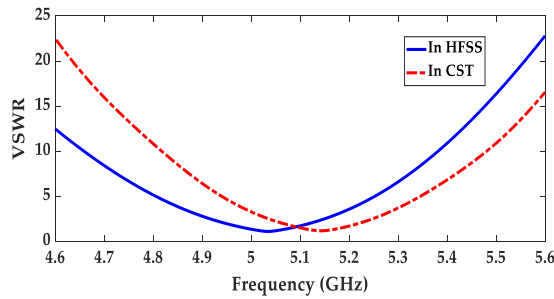
(b)

(c)

(d)

Fig 2 – Performance parameters of suggested single antenna (a) S_{11} (b) VSWR, (c) Gain, (d) and Efficiency
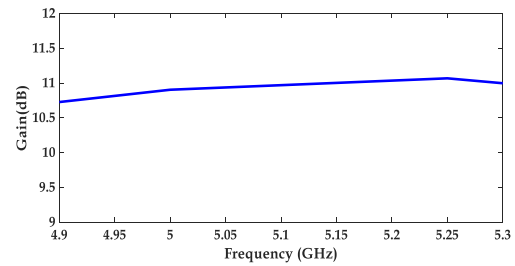

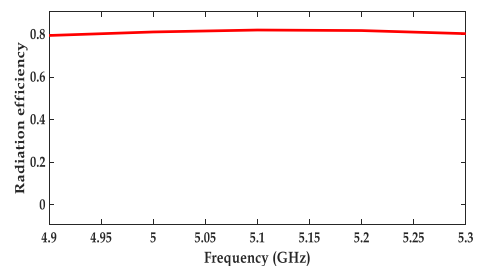**Fig. 3** – Radiation patterns plot of the single antenna at 5 GHz

Fig. 4 – Geometry of suggested two element antenna

(a)

(b)

(c)

Fig. 5 – Two-element antenna array results (a) Reflection coefficient, (b) gain, and (c) radiation efficiency

3.2 Performance of Two Elements Antenna Array

In this part, we examine and discuss the simulation results in terms of S_{11}, realized gain, and efficiency for the two-element array antenna. Fig. 5(a) depicts the reflection coefficient of the two-element antenna, which resonates around the 5 GHz frequency band with better impedance matching and improved bandwidth compared to the single-element antenna. The gain and radiation efficiency are illustrated in Fig. 5 (b) and (c), respectively, and indicate that a two-element array provides slightly better gain and radiation efficiency than a single element. The polar radiation pattern of the two-element antenna array at 5 GHz is displayed in Fig. 6.
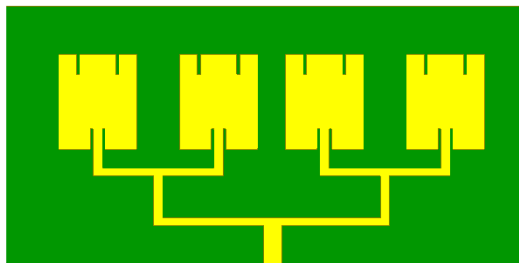
3.3 Four Elements Antenna Array

During the last stage of antenna design, a four-element array is produced by employing same unique-element patches with a single port. The configuration of this antenna array, consisting of four elements is displayed in Fig. 7. Fig. 8(a) shows its S_{11} parameter performance. As can be observed, the antenna has a wider bandwidth compared to the two-element antenna and resonates in the 5 GHz range with good impedance matching. The simulated results of the realized gain and efficiency of the 4-element array antenna are depicted in Figs. 8(b)-(c). It is evident from Fig. 8(a) that the 1×4 array antenna yields a high realized gain of approximately 14.45 dB at the operating frequency with a radiation efficiency of 82%, indicating the impact of increasing the radiating elements. The polar radiation pattern of the two-element antenna array at 5 GHz is demonstrated in Fig. 9.
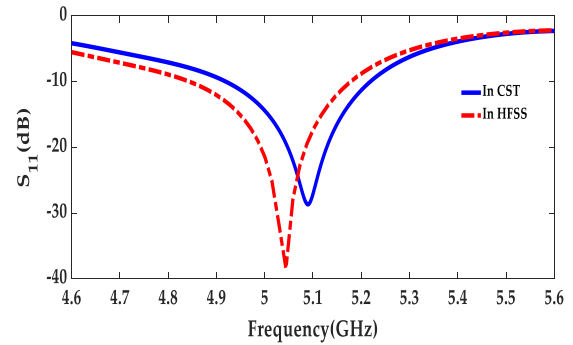
A comparison between the single-element, 2-element array, and 4-element array antenna is summarized in Table 3.
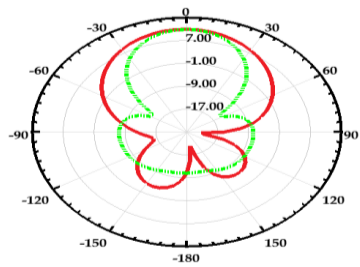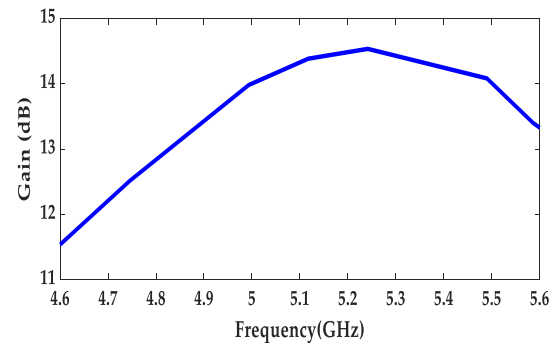

Fig. 6 – Radiation patterns at 5 GHz.

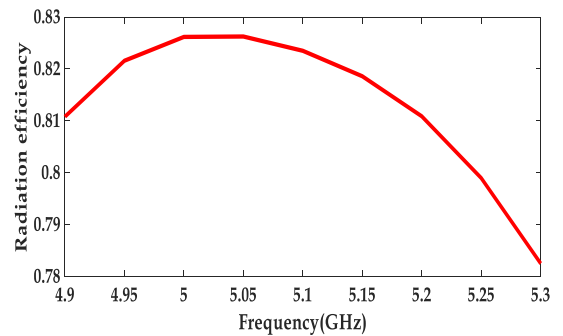**Fig. 7** – The prescribed structure of the four-element
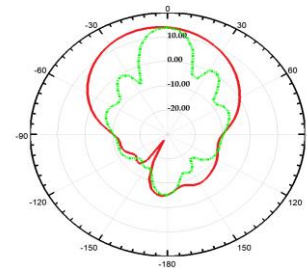

(a)

(b)

(c)

Fig. 8 – Proposed four-element antenna array (a) S_{11}, (b) gain, (d) and efficiency

Fig. 9 – Radiation patterns of the 4 elements array antenna at 5 GHz

Table 3 – A Comparative Study of Single, 2-Element, and 4-Element Arrays

Characteristics of the antenna	Single element	Two-element array	Four-element array
Frequency	5.09	5.02	5.09
Size	40×35	75×46	170×67
Return loss (dB)	–23.84	–28	–28
Bandwidth (MHz)	170	220	300
Efficiency	67%	81%	82%

4. CONCLUSION

In this study, we introduce a new, high-gain, low-profile, and flexible microstrip array antenna for RF energy harvesting applications operating at 5 GHz. The proposed antenna design is based on a single-element antenna and utilizes a simple structure to achieve low side lobes and high gain. Simulated results for the four-element antenna show an impedance bandwidth of 300 MHz with VSWR less than 2, and antenna gain of 6-9 dBi and efficiency of 82%, respectively. The antenna design has been numerically tested using two different programs, CST and HFSS, and the results demonstrate that the suggested antenna is adapted for RF energy harvesting and portable applications. The proposed antenna is expected to have potential applications in various RF energy harvesting systems and portable devices due to its flexibility, low cost, low feed network loss, and robust performance.

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Дизайн гнучкої прямокутної антенної решітки з високим коефіцієнтом посилення для збору радіочастотної енергії та переносних пристроїв

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Гнучка радіочастотна електроніка та антени, виготовлені з текстилю, вважаються технологією, яка прискорює широку популярність сучасних переносних комунікаційних пристроїв і компонентів. У даній статті представлено гнучку та компактну прямокутну мікросмужкову антенну решітку 4×1 для застосування радіочастотної (РЧ) енергії. Вона працює на частоті 5 ГГц і має високий коефіцієнт підсилення. Запропонована антена включає в себе техніку вставного живлення для покращення узгодження імпедансу та використовує

провідну тканину (Е-текстиль) як провідник разом із текстилем як підкладку. Живильні та випромінювальні структури розроблені з використанням електропровідних текстильних матеріалів типу Stick E shield, які мають провідність 5×10^5 С/м і мають товщину 0,085 мм. Цей дизайн повністю покладається на текстильні матеріали для забезпечення комфорту користувача, простоти виробництва та економічної ефективності. Симулятор Ansys HFSS, який використовує метод кінцевих елементів, був використаний для оптимізації конструкції антени. Запропонована конфігурація була перевірена за допомогою симулятора CST MWS, який використовує метод кінцевої інтеграції. Дослідження мало на меті досягти високого підсилення та надійних характеристик розробленої антени. Результати моделювання демонструють чудову продуктивність у робочому діапазоні з шириною смуги опору 6,78 % і високим коефіцієнтом підсилення 14,54 дБл на 5 ГГц, що робить його добре придатним для збору радіочастотної енергії та додатків мобільних пристроїв.

Ключові слова: Е-текстиль (провідна тканина), Антенна решітка, Підсилення сигналу, Радіочастотна енергія (RF).