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A Miniaturized Wearable Textile UWB Monopole Antenna for RF Energy Harvesting

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In this paper, a monopole Ultra-wide band (UWB) textile antenna is designed and analyzed for RF Wireless Energy Harvesting (RFEH). The intended antenna exhibits its excellent characteristics with a compact dimension of 80 × 60 mm^2. In the front plane of the proposed antenna, the microstrip line fed enneagon (nonagon) shaped patch structure has been modified by incorporating rectangular and semi-circular shaped slots. On the other hand, the bottom plane consists of a partial ground plane and a rhombus shaped parasitic radiating structure has been incorporated at the backside of the substrate to utilize the available space above the partial ground to obtain wide impedance bandwidths. Moreover, textile materials are used in this design to improve flexibility and conformability of the designed antenna. From the simulated results, the proposed antenna achieves a wide impedance bandwidth from 1.54 GHz to 12.79 GHz $S_{11} \le -10$ dB. Moreover, the maximum gain is 5.03 dB, and the peak radiation efficiency is 95 %. With merit characteristics, the proposed design can be well applied to harvest RF energy. The results show that the proposed miniaturized UWB antenna system can cover the bandwidth requirements of entire UWB systems (3.1-10.6 GHz) and also supports several wireless communication standards such as Wi-Fi (2.4-2.484 GHz, 5.15-5.35 GHz, 5.725-5.825 GHz, 5.925-7.125 GHz), 4G LTE (2.3-2.39 GHz, 2.555-2.655 GHz), Sub 6 GHz 5G FR-1 NR bands (1-6 GHz), and X-band (8-12 GHz).

Keywords: E-textile antenna, Partial ground plane, Monopole UWB, RF energy harvesting (RFEH).

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1. INTRODUCTION

With the rapid advances in wireless communication technology, low-power electronic devices are increasing exponentially. These devices are being used in a growing range of applications, including the Internet of Things (IoT), smart cities and The operating frequency of the receiving antenna, the bandwidth, the gain, the efficiency and the radiation characteristic are very important parameters that determine the amount of energy processed by the rectifier circuit of the rectenna. The RF energy available in the natural environment is extremely low (of the order of μ-Watts). The delivery of sufficient RF power can be improved by selecting a receiving antenna with high gain and multi-band/broadband characteristics [10]. UWB antennas will be used in the case of a broadband energy harvesting system. The gain of these antennas over a wide band plays a vital role for the captured RF power. Thus, the impedance matching of the antenna to the rectifier circuit plays a very essential role, because better the impedance matching, the lower the reflection losses. Ultra-wideband (UWB) technology has attracted a lot of interest due to its high data rates, low transmit power requirement (– 44.3 dBm), inherent resistance to interference, and relative immunity to multipath fading [11]. Recently, Textile antennas have been extensively studied due to their flexibility and lightweight properties.

These antennas based on the above characteristics are being considered as an attractive option for conventional antennas, which are made of rigid substrates. There is a variety of flexible materials usable in antenna design such as textile material, paper-based material, and polymer-based material. The properties of the material have an important influence on the behavior of the antenna. Textile materials could be conductive or non-conductive. The non-conductive textiles are usually used as the substrates of antennas to reduce the antenna's weight and profile when compared with the standard substrates. Textile materials are good choices to be used as the substrate because of their low dielectric permittivity, which improves the antenna impedance bandwidth by reducing the losses due to surface waves. Among various fabrics, felt, jeans, and polyester are widely used [12-13].

In this work, a single-fed modified enneagon monopole antenna with a size of 80 × 60 mm^2 based on the slot loading technique is reported for RF energy harvesting applications. The monopole antenna covers the entire UWB frequency range from 3.1 to 10.6 GHz. The antenna consists of a partial ground plane with parasitic patch, a feeder line, a modified enneagon-shaped patch to improve and cover multiple frequency bands. The proposed antenna is numerically

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analyzed and optimized using finite element software ANSYS high-frequency structural simulator (HFSS) and CST software. The rest of this article is organized as follows: Section 2 displays the design of the proposed antenna and explains the evolution of the UWB-receiving antenna, and presents a parametric analysis. Next, the simulated results and discussions are given in Section III. Finally, conclusions are drawn in Section IV.

2. ANTENNA DESIGN AND DISCUSSION

2.1 Antenna Structure

The geometric topology of the proposed UWB textile antenna is depicted in Fig. 1. It employs flexible felt as the substrate with relative permittivity of $\varepsilon_r = 1.2$, loss tangent of $\tan\delta = 0.02$ and thickness of $h = 1$ mm [2]. The patch and the ground plane are made of conductive fabric which is a plain-weave polyester fiber layer with copper and nickel coated on the upper surface and a very thin adhesive layer attached to the bottom to facilitate integration on the substrate. It has a thickness of 0.09 mm, approximate conductivity of 5.55×10^5 S/m, and a very low sheet resistance of less than 0.09 Ω/sq [14]. The antenna has an overall size of 80 × 60 × 1.18 mm^3. The antenna is fed using a 50 Ω coaxial feed. With the aid of ANSYS HFSS, the dimensions of the proposed antenna are optimized. The detailed values of geometrical parameters in the final prototype are listed in Table 1.

Table 1 – Optimized antenna dimensions (unit: mm)

Parameter	Value	Parameter	Value
W_S	60	W_g	60
L_S	80	L_g	33
W_P	35.3	W_{g1}	30.73
L_P	37.2	L_{g1}	30.73
w_f	2.85	a	0.04
l_f	33.96	l_1	1
–	–	w_1	8

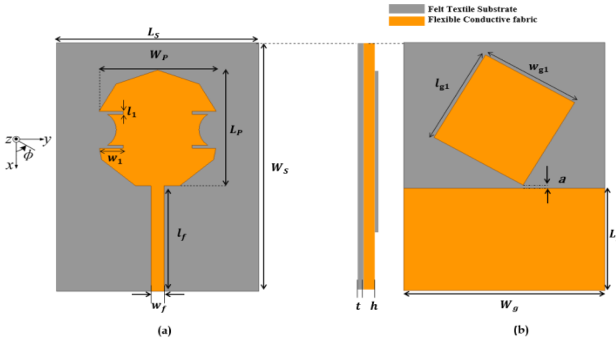

Fig. 1 – Geometry topology of the proposed antenna (a) Perspective view, (b) Top and side view

2.2 Performance Comparison of the Conventional and Proposed UWB Antenna

In this section, the performance improvements of the proposed antenna as compared to the conventional antenna is analyzed and discussed. The structural changes in the proposed UWB antenna are depicted in Fig. 2. Initially, the evolution of the UWB monopole antenna starts from designing a simple traditional rectangular patch backed with a full ground plane as shown in Fig. 2(a). The square radiator (Antenna 1) offers three narrow resonant frequencies but the prime objective of this work is to achieve multi-resonant ultra wideband operation with good impedance matching. The radiator is modified in the shape of enneagon radiator and the ground plane is adopted as a partial ground plane, which occupies a dimension of 60 × 33 mm^2 on the rear side of the substrate. Next, we added a square-shaped parasitic patch in the central position of the back side of the substrate to use the available space above the partial ground, which is advantageous to improve the impedance bandwidth performance along with an additional resonant frequency. Additionally, the circular slots are merged with rectangular slots and incorporated on the right and left edge of the patch, which disturbs the magnetic current distribution and thereby increases the operating bandwidth.

The simulated S_{11} results for the described geometries are shown in Fig. 3. To clearly understand the resonating characteristic of the monopole antenna, the simulated surface current distributions of the final design (Antenna 2) at resonant frequencies, i.e., 2.14, 4.23, 5.36, 6.73, 8.82 GHz, and 11.63 GHz, are shown in Fig. 4.

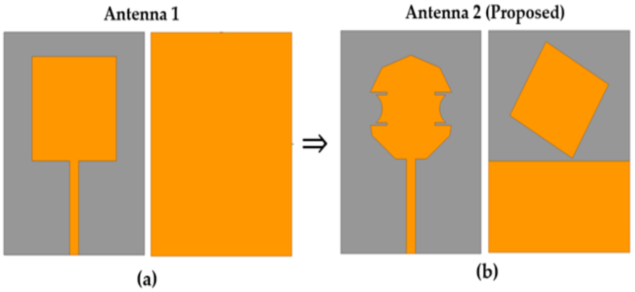

Fig. 2 – Structural modifications in antenna design (a) Antenna 1. (b) Antenna 2 (Proposed Antenna)

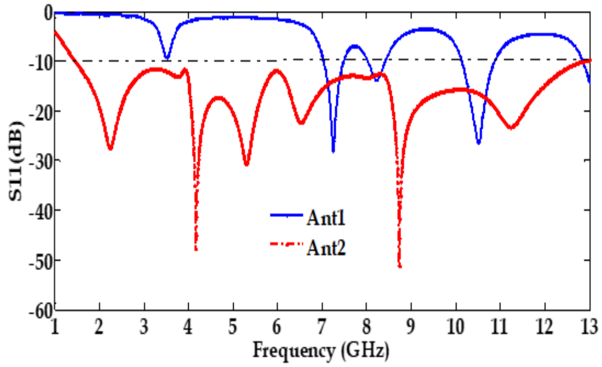

Fig. 3 – Simulated reflection coefficient characteristics of the conventional (Antenna 1) and proposed antenna (Proposed Antenna)

The geometrical dimensions of the basic patch from its operating frequency can be calculated as follows [15]:

$$W_P = \frac{C}{(2f_0)\sqrt{\frac{\varepsilon_{relative}+1}{2}}} \tag{1}$$

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

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff}+0.3\right)\left(\frac{W_P}{h}+0.264\right)}{\left(\varepsilon_{reff}+0.258\right)\left(\frac{W_P}{h}+0.8\right)} \tag{3}$$

$$L_P = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left[\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{W_P}{h}+0.264\right)}{\left(\varepsilon_{eff}+0.258\right)\left(\frac{W_P}{h}+0.8\right)}\right]. \tag{4}$$

Where, C is the velocity of light, f_0 is the resonant frequency of the monopole antenna, L_P, W_P, and ΔL are the length, width, and extended length of the radiation patch, respectively, h is the height of the substrate, ε_{reff} and ε_r are the effective and relative permittivity of a substrate, respectively.

2.3 Parametrical Studies

To examine the effect of different structural design parameters on the performance of the antenna, a systematic study is carried out. The goal of this parametric study is to identify the major influence of the design parameters to offer best performance by achieving optimal characteristic parameters. We studied the variations of two parameters, i.e., feed width W_f, length L_g of the ground plane.

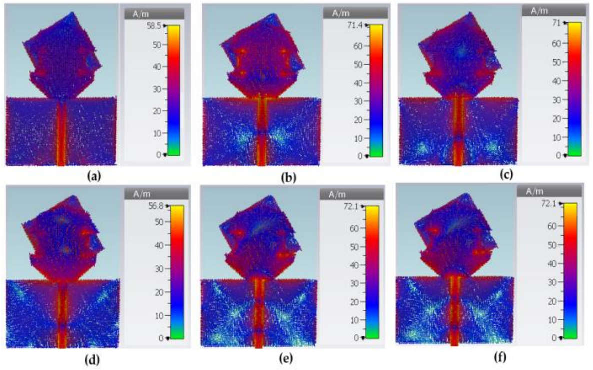

Fig. 4 – Current distribution at resonance point: (a) 2.14 GHz, (b) 4.23 GHz, (c) 5.36 GHz, (d) 6.73 GHz, (e) 8.82 GHz, (f) 11.63 GHz

The first parameter, W_f, is the width of the feed. It is clearly seen from Fig. 5 that the change in the width affects the reflection coefficients considerably. The best resonance, impedance matching and maximum operating bandwidth are obtained for the proposed dimension of W_f = 2.85 mm. In other words, the impedance matching varies significantly with the change in W_f.

As shown in Fig. 6, the length of the partial ground plane, L_g has a great influence on the impedance bandwidth as well. When, L_g = 32 mm, good matching is obtained and when L_g = 34 mm, some impedance mismatching is observed. But when L_g is set equal to 33 mm, the proposed antenna offers maximum operating bandwidth with maximum number of multi-resonant frequencies with best impedance matching. So, L_g = 33 mm is considered as the optimal design parameter.

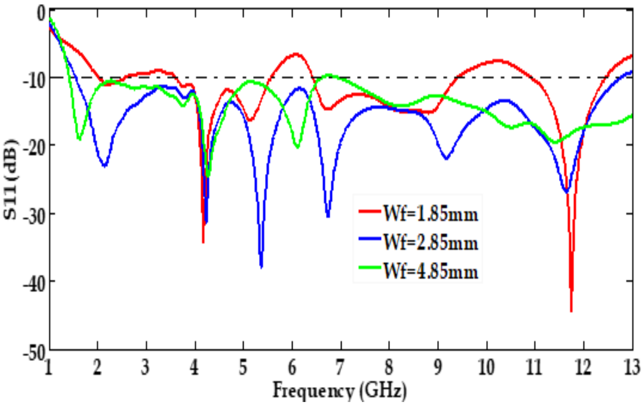

Fig. 6 – The effect of feed width W_f on S_{11} characteristics

3. RESULTS AND DISCUSSION

The performance of the proposed UWB antenna is analyzed using various parameters such as reflection coefficient (S_{11}), Voltage Standing-Wave Ratio (VSWR), radiation pattern, gain and efficiency.

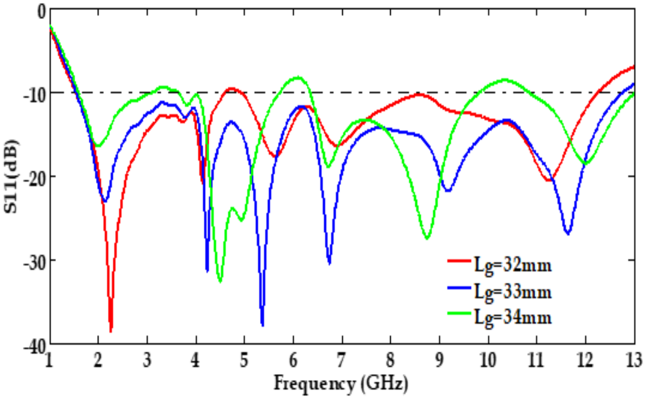

Fig. 7 – The effect of length of the ground plane L_g on S_{11} characteristics

3.1 Impedance Parameters

The reflection coefficient and VSWR characteristics of the proposed UWB antenna are analyzed with the help of HFSS and CST simulation tools. The analyzed values of S_{11} and VSWR are presented in Fig. 8 (a-b). The depicted results indicate that the proposed antenna has achieved ultra-wideband resonance characteristics with good impedance matching in the entire UWB frequency range of 1.54 to 12.79 GHz. Both the results obtained from CST and HFSS confirms the UWB operation with an identical impedance bandwidth of 11.25 GHz.

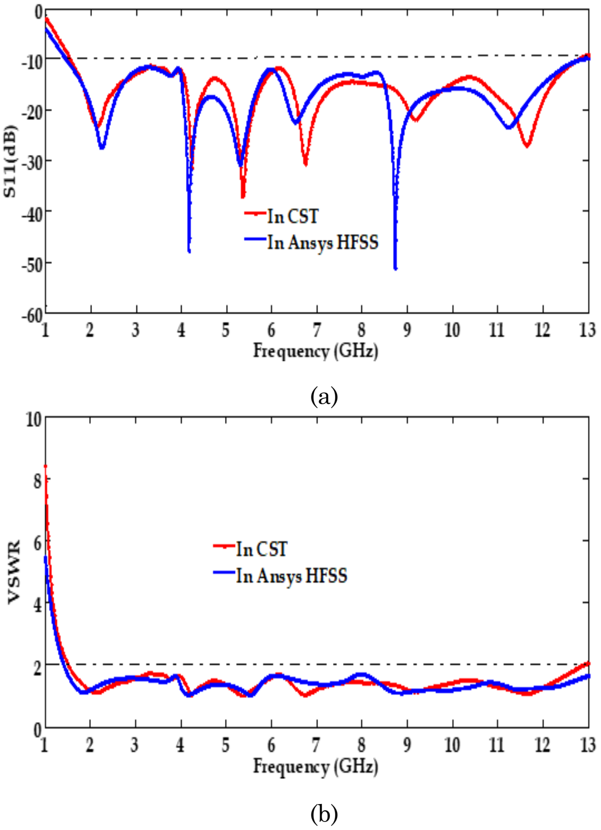

Fig. 8 – Simulated results of the proposed antenna in CST and HFSS (a) $|S_{11}|$ (b) VSWR

The slight discrepancy between the two programs may be due to the different numerical methods used by the two programs, but in general, the reported results in the two electromagnetic programs agree well with each other.

3.2 Radiation Characteristics

The radiation features of the suggested antenna are analyzed and discussed in terms of gain, radiation efficiency, total antenna efficiency and radiation patterns. The variations of gain over the entire UWB range are depicted in Fig. 9. The UWB antenna offers positive gain characteristics over the entire UWB range with an average gain of 3.775 dB and a maximum peak gain of 5.03 dB. The total antenna and radiation efficiency are compared and presented in Fig. 10.

The proposed UWB antenna is highly efficient as per the presented efficiency results. The radiation efficiency is higher than total antenna efficiency. The radiation efficiency ranges from 72 % to 96 % throughout the UWB range, as shown in Fig. 10. The radiation patterns of the proposed antenna for *E* and *H* planes at different frequencies such as 2.14, 5.36 and 11 GHz are plotted in Fig. 11. The Co and Cross pol components are compared in both the principal planes. The cross-pol parts in the radiation patterns are significantly lower than the co-pol components. The shape of the radiated fields resembles nearly omni-directional in H-plane and nearly bi-directional in E-plane.

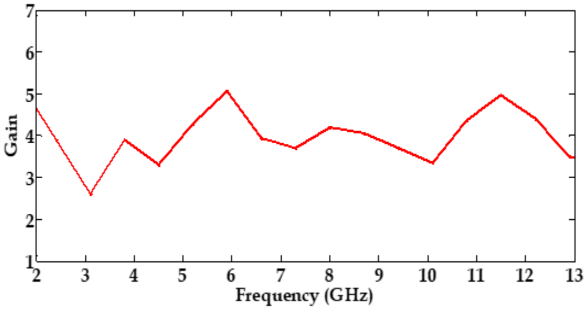

Fig. 9 – Gain variations of the UWB antenna

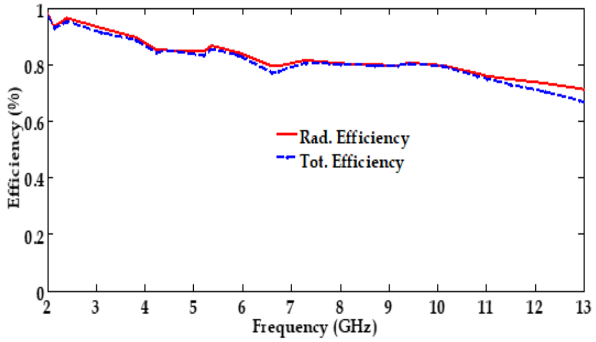

Fig. 10 – Radiation and total efficiency plot

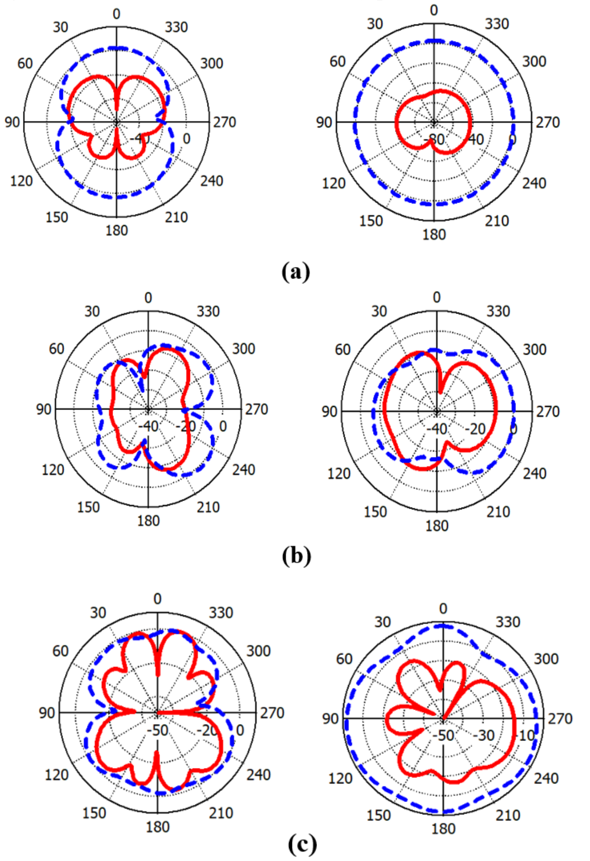

Fig. 11 – Simulated Radiation characteristics on *E*-plane and *H*-plane at: (a) 2.14 GHz, (b) 5.36 GHz, (c) 11 GHz

4. INFLUENCE OF THE HUMAN BODY ON THE PERFORMANCE OF THE PROPOSED UWB TEXTILE ANTENNA

The performance of the UWB antenna has been analyzed by considering the effect of the human body. The human body can be considered as lossy, dispersive, and inhomogeneous nature of human tissues. Therefore, to evaluate the effect of human tissues on the textile antenna performance, we carried out simulations using a simplified three-layer phantom model as shown in Fig. 1. It is composed of a 1.7 mm thick skin layer, 8 mm thick fat layer, and a 10 mm thick muscle layer. To save the computation time and clarify the illustration, the human model is simplified with a total size of 130 × 120 × 19.7 mm^3, which can enable the distance between the antenna and outer edge of the phantom to be greater than a quarter wavelength at the operating band. In addition, considering the actual wearing situation, the spacer polyester fabric (ε_r = 1.4, tan δ = 0.007) material with a thickness of d_i = 0.2 mm is placed between the antenna and phantom.

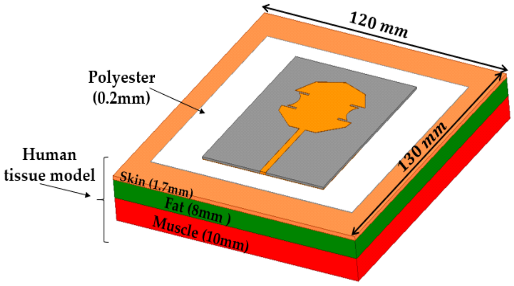

Fig. 12 – Schematic of the three-layer human tissue model

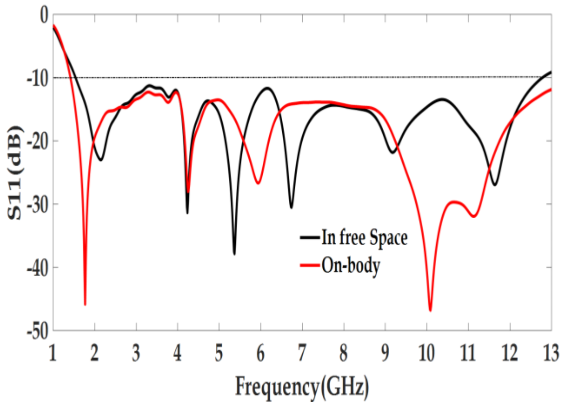

Fig. 13 – S_{11} variations due to human body effect

To exhibit the merit performance, the proposed antenna is simulated in free space and on phantom, as shown in Fig. 4. It can be seen that the influence of human phantom on impedance matching is almost negligible.

5. 5CONCLUSION

In this work, a novel design of a low-profile UWB textile antenna covers the entire UWB range for energy harvesting applications has been presented. The proposed antenna exhibits a good impedance matching in the entire UWB frequency range from 1.54 GHz to 12.79 GHz covering the entire UWB spectrum (3.1 to 10.6 GHz). The simulated results obtained by CST and HFSS EM solvers show a good correlation between them. The designed antenna exhibits – 10 dB impedance bandwidth from 1.54 to 12.79 GHz with a fractional bandwidth (FBW) of 157.01 %. Also, it provides a peak realized gain of 5.03 dBi, and radiation efficiency of 96 % within the UWB operating band. The proposed directional UWB antenna provides tremendous features, such as compact size, simple structure, good gain, efficiency, wide bandwidth coverage and directionality offering good adaptability for practical applications.

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Мініатюрна переносна текстильна UWB монопольна антена для реєстрації радіочастотної енергії

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У цій статті розроблена монопольна надширокодіапазонна (UWB) текстильна антена розмірами 80 × 60 мм^2. Параметри антени проаналізовані для радіочастотного бездротового збирання енергії (RFEH). У передній площині пропонованої антени мікросмужкова лінія була модифікована шляхом включення прямокутних і напівкруглих прорізів. З іншого боку, нижня площина складається з часткової заземленої площини, а паразитна випромінювальна структура у формі ромба була включена на задній стороні підкладки, щоб використовувати доступний простір над частковою заземленням для отримання широких смуг пропускання імпедансу. Крім того, у цій конструкції використовуються текстильні матеріали для покращення гнучкості та зручності розробленої антени. Зі змодельованих результатів запропонована антена має широку смугу пропускання від 1,54 ГГц до 12,79 ГГц S11 $\leq$- 10 дБ. Крім того, максимальне підсилення становить 5,03 дБ, а пікова ефективність випромінювання - 95 %. Запропоновану конструкцію можна застосовувати для збирання радіочастотної енергії. Результати показують, що запропонована мініатюрна система UWB-антени може покривати вимоги до пропускної здатності цілих систем UWB (3,1-10,6 ГГц), а також підтримує кілька стандартів бездротового зв’язку, таких як Wi-Fi (2,4-2,484 ГГц, 5,15-5,35 ГГц, 5,725- 5,825 ГГц, 5,925–7,125 ГГц), 4G LTE (2,3–2,39 ГГц, 2,555–2,655 ГГц), діапазони Sub 6 ГГц 5G FR-1 NR (1–6 ГГц) і діапазон X (8–12 ГГц).

Ключові слова: Антена на основі провідного текстильного матеріалу, Частково заземлена площина, Монополь UWB, Реєстрація радіочастотної енергії (RFEH).