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Comparison of Output Voltages from Radio Frequency Energy Harvesting System with Textile Microstrip Single-Element and Array Antennas as Receiving Antennas

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Abstract: Textile antennas, critical electronic devices in radio frequency (RF) energy harvesting systems for wearable products, are increasingly preferable in recent years. In order to investigate the collection performance of RF energy harvesting system based on textile antennas, in this study, the textile microstrip single-element antenna and the textile microstrip array antenna were designed and prepared with polyester felts as the substrate. To build up a complete RF energy harvesting system, the combination of the signal generator, the power amplifier, the transmitting antenna and the above-designed textile microstrip antenna as the receiving antenna connected with the rectifier circuit was made. The results show that the maximum gain of the array antenna is 5.35 dB higher than that of the single-element antenna. The final output voltage shows the effectiveness of the RF energy harvesting system. As the input power increases or the receiving distance decreases, the output voltage increases. The highest output voltage through the single-element antenna is 39.2 mV, and the highest output voltage through the array antenna is 72.7 mV due to the higher gain of the array antenna. This study will bring more research ideas to this field.

Key words: radio frequency (RF) energy harvesting; textile; microstrip single-element antenna; microstrip array antenna; rectifier circuit
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0 Introduction

Wearable products are nowadays becoming the necessary accessories for people in daily life, and are applied in different fields such as healthcare, smart sports and entertainments[1-8]. The basic functions of wearable products are to collect, process and transmit data, and the above functions can be realized when the system has enough power. Collecting radio frequency (RF) energy in the environment and converting it into direct current (DC) power for wearable devices are less costly and more environmentally friendly than collecting and converting other energy sources[9-10]. Compared with other types of wearable devices, textile wearable devices are flexible as the basic substrate materials are textiles and could be easily conformal with garments, thus producing large varieties of smart textiles. Using textiles to make receiving antennas can better meet the requirements of wearable products and provide a wider selection of materials[11-16].

Current research on using textile antennas in the RF energy harvesting system is mainly focused on the antenna types used for the receiving antennas. Lopez-Garde et al.[17] proposed a textile-based 2×2 multilayer microstrip array antenna operating in 2.4 GHz WiFi band, and the textile antenna and the rectifier circuit were integrated for RF energy harvesting. Estrada et al.[18] introduced 4×4 and 9×9 antenna arrays and screen-printed them on cotton T-shirts for collecting RF energy between 2 GHz and 5 GHz. Liu et al.[19] also designed the RF energy harvesting system in which the textile-based spoof surface plasmon (SSP) array antenna was integrated with the garment. In the above research, the results were given with the output voltage or power value; however, the factors influencing the output voltage and how the output voltage was influenced were not discussed systematically.

In this study, the textile microstrip single-element and the textile microstrip array antennas with polyester felts as the substrate are designed. The microstrip antennas have low planar structures and are easy to be integrated into the RF energy harvesting system. They are used as the receiving antennas to connect with the rectifier circuit, and thus the RF energy harvesting system is formed. The system converts the received high-frequency current into DC voltage in the external environment. Compared with other researchers' work, the objective of this study is to compare the antenna performances as well as the final output voltages from the RF energy harvesting system, in which two types of designed textile microstrip antennas are used as receiving antennas. Additionally, through a series of discussions, the relationship between the antenna performance and the output voltage values is

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expected to be more clearly obtained. Furthermore, to investigate other influencing factors, the variations of the output voltages dependent on the distance as well as the input power are discussed.

1 Design and Experiment

1.1 Design and fabrication of microstrip antennas

Polyester felts with a relative permittivity of 1.38 and a loss tangent of 0.013 8 were used as the substrate for the antenna. Compared with other materials, polyester felts have medium relative permittivity, low dielectric loss and flat surface, and are suitable as the antenna substrate for antenna fabrication.

The structural schematic diagrams of receiving antennas are shown in Fig. 1. In Fig. 1(a), there are the rectangular patch and the microstrip feed line in the textile microstrip single-element antenna, and the rectangular slots with a length of x and a width of y is on both sides of the intermediate microstrip feed line to achieve the impedance matching and increase the bandwidth. The structural schematic diagram of the textile microstrip array antenna is shown in Fig. 1(b). This textile microstrip array antenna has four conductive radiant elements and one feeding network system. The optimized dimensional parameters of the textile microstrip single-element antenna and the textile microstrip array antenna as receiving antennas are listed in Tables 1 and 2, respectively.

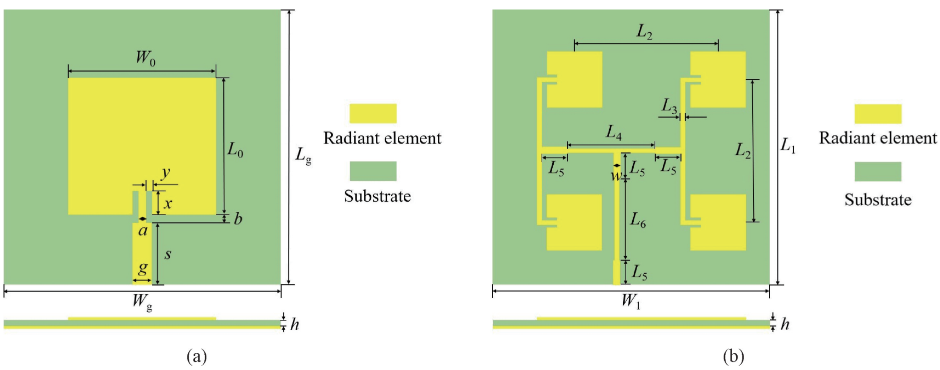


Fig. 1 Structural schematic diagrams of receiving antennas: (a) textile microstrip single-element antenna; (b) textile microstrip array antenna

Table 1 Optimized dimensional parameters of textile microstrip single-element antenna Unit: mm

Parameter	L_g	W_g	L_0	W_0	x	y	s	g	a	b	h
Value	80	80	48.7	48	10	2	24	6.3	3.6	3	3

Table 2 Optimized dimensional parameters of textile microstrip array antenna Unit: mm

Parameter	L_1	W_1	L_2	L_3	L_4	L_5	L_6	w	h
Value	250	250	122	3.6	60	30	65	7.2	3

The textile microstrip single-element antenna and the textile microstrip array antenna were prepared by the screen printing method. The final prototypes of the two textile microstrip antennas are shown in Fig. 2.

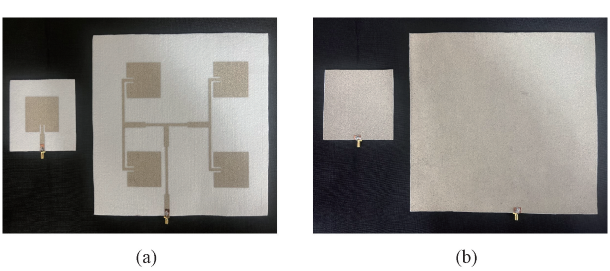


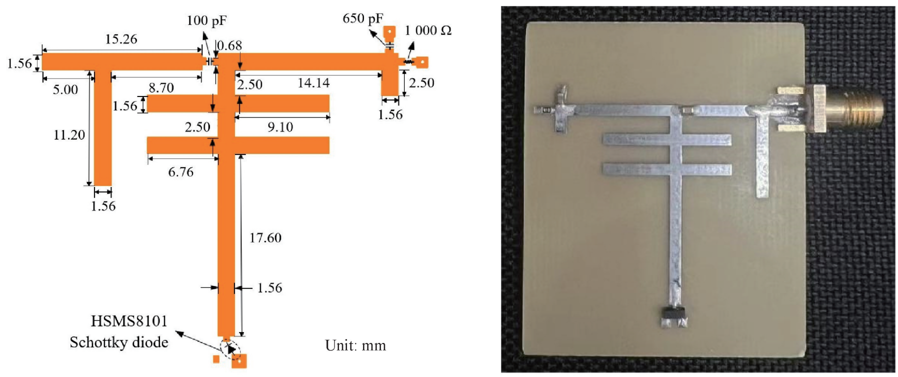
Fig. 2 Prototypes of textile microstrip antennas: (a) front side; (b) back side

In either Fig. 2(a) or Fig. 2(b), the left prototype is the textile microstrip single-element antenna and the right prototype is the textile microstrip array antenna. It could be clearly seen that the silver paste was printed evenly and smoothly as the conductive radiant elements on the antenna substrates. The size parameters of the feed lines and the feed network were accurate enough to ensure subsequent efficient feeding. The SMA (SubMiniature version A) connectors were soldered tightly with the microstrip feed lines of the antenna and the ground planes on the back sides.

1.2 Design and fabrication of rectifier circuit

In order to match the rectifier circuit with the antenna at the receiving end of the RF energy, the circuit simulation software advanced design system (ADS, Keysight Technologies Inc., USA) was used to simulate and design the rectifier circuit with an operating frequency of 2.45 GHz. The selected dielectric substrate was FR4 (glass fiber/epoxy resin composites) with a relative permittivity of 4.2 and a loss tangent of 0.02, and the thickness was 0.8 mm. The rectifier circuit was physically processed according to the design layout, and the tin immersion treatment was used to prevent the rectifier circuit from oxidizing. Inner and outer cores of the 50 Ω SMA connector were connected to the input terminal and ground plates of the rectifier circuit respectively by soldering.

The layout and the prototype of the rectifier circuit are shown in Fig. 3. It can be seen that the rectifier circuit is fabricated well and the necessary components are properly soldered in the rectifier circuit. The entire circuit structure includes the matching network, the harmonic suppression structure and the output filtering section. T-matching was applied in the matching part of the circuit. In the filtering part, the F-type harmonic suppression network structure was used in the rectifier circuit to suppress the second and the third harmonic waves. The output pass-through filter was used for filtering out the alternating current component, consisting of the microstrip line with the length of $\lambda/4$ and a parallel-connecting capacitor. λ is the free space wavelength.



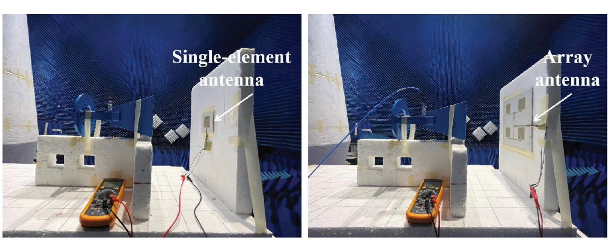
(a) (b)

Fig. 3 Structural diagrams of rectifier circuit: (a) layout; (b) prototype

1.3 Measurement and connection system

The return losses of the antennas and the rectifier circuit were tested using the vector network analyzer KC901V (KeChuang Measure Association, China). Radiation patterns and gains of the antennas were tested using the vector network analyzer Agilent N5225A (Keysight Technologies Inc., USA) in the microwave anechoic chamber.

The connection systems for the output voltage testing with textile microstrip antennas as receiving antennas are shown in Fig. 4.



(a) (b)

Fig. 4 Connection systems for output voltage testing with textile microstrip antennas as receiving antenna: (a) single-element antenna; (b) array antenna

The single-element antenna and the array antenna are connected to the connection system in the same way. In the connection system, the signal generator with the power amplifier could generate and amplify signals. Through the horn-transmitting antenna, the signal was transmitted to the designed receiving antenna which was connected with the rectifier circuit. The distances between the horn-transmitting antenna and the receiving antenna were 25, 50, 75 and 100 cm, respectively. The output voltage displayed on the multimeter would be recorded. During the testing, the input power of the signal generator was set as −10 dBm to 10 dBm with a step length of 1 dBm.

2 Results and Discussion

2.1 Return losses of textile microstrip antennas

The return losses of textile microstrip antennas are shown in Fig. 5.

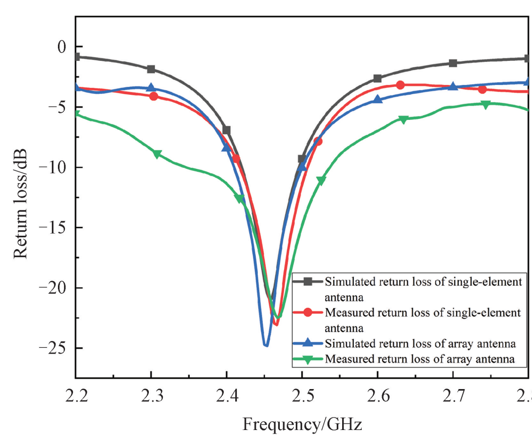


Fig. 5 Return losses of textile microstrip antennas

On the whole, the measured results of both antennas are in good agreement with their simulated results. For the textile microstrip single-element antenna, the measured return loss is −23.05 dB with a bandwidth of 3.26%. The textile microstrip array antenna has a measured return loss of −22. 36 dB with a bandwidth of 7. 38%. The measured resonant frequencies of two antennas have a very small shift to the simulated values, which may be related to a little inaccuracy in measurement or in the fabrication process. However, the antennas still work at the determined frequency range.

2. 2 Radiation patterns of textile microstrip antennas

Figure 6 shows the radiation patterns of two textile microstrip antennas. It can be seen that the front lobes are much larger than the back lobes due to this special type of the antenna structure. As there are radiation patches on the front sides and reflective ground planes on the back sides, the electromagnetic waves would superpose in the far field in the front direction. The final gain results show that the measured gains in the E-plane and the H-plane of the textile microstrip array antenna are 5. 35 and 4. 43 dB higher than those of the textile microstrip single-element antenna, respectively, due to more radiant elements in the array antenna design.

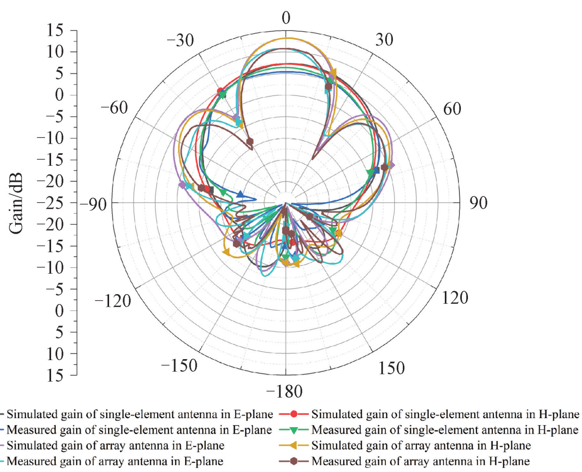


Fig. 6 Radiation patterns of textile microstrip antennas

2. 3 Return losses of rectifier circuit

The comparison of simulated and measured return losses is shown in Fig. 7. The two values are almost consistent at a working frequency range of 2. 40 to 2. 48 GHz. At the resonant frequency of 2. 44 GHz, the measured return loss is − 19. 34 dB, meeting the requirement of lower than −10 dB for proper operation of the rectifier circuit. However, the alsolute value of measured return loss is lower than that of the simulated one, which might be due to the loss generated by the transmission line in the rectifier circuit or the small shift of the real dielectric property from the simulated value.

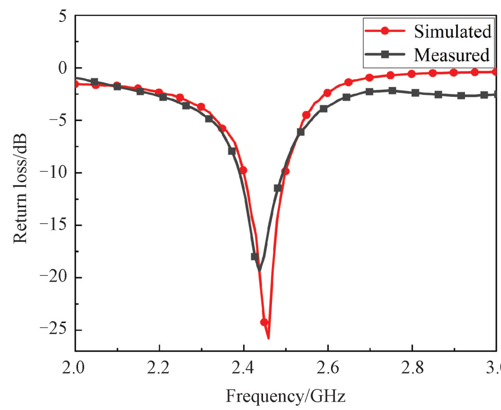


Fig. 7 Return losses of rectifier circuit

2. 4 Output voltage variations of RF energy harvesting systems

When the operating range of the signal generator as well as the application range of the receiving distance was considered, the input power and the receiving distance were properly chosen in testing the output voltage. The output voltages through the textile microstrip single-element antenna and the textile microstrip array antenna at different receiving distances are shown in Fig. 8.

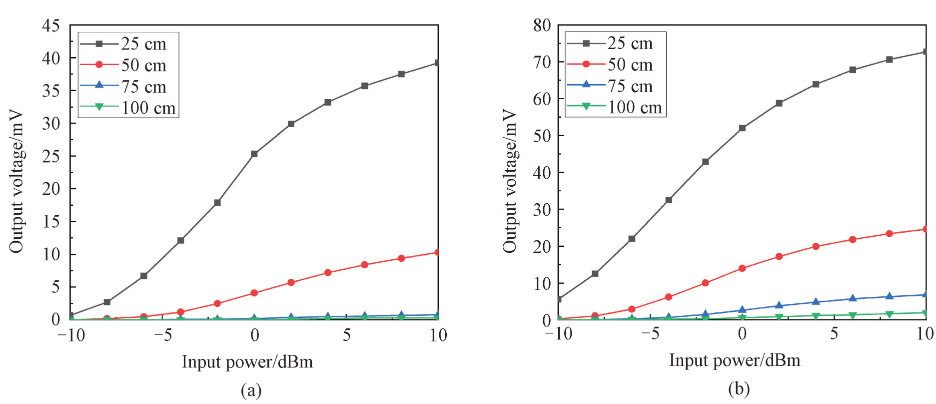


Fig. 8 Output voltage dependence on input power at different receiving distances through antennas: (a) textile microstrip single-element antenna; (b) textile microstrip array antenna

It can be seen that through the two types of antennas, the output voltage increases as the input power increases. It can be also seen that the output voltage sharply decreases when the receiving distance increases. For the single-element antenna, when the receiving distance is 25 cm and the input power is 10 dBm, the output voltage has the highest value of 39. 2 mV; when the receiving distance is 50 cm, the maximum output voltage is only 10.3 mV. Therefore, the receiving distance significantly influences the output voltage and thus setting a proper receiving distance is of great importance. As the array antenna has a higher gain than the single-element antenna, the output voltage through the array antenna is higher than that through the single-element antenna, and the highest value achieves 72.7 mV when the receiving distance is 25 cm and the input power is 10 dBm. The above results follow the Friis transmission equation law. When the transmitting antenna has constant power, the higher the gain of the receiving antenna is, the higher the receiving power it receives from the transmitting antenna. Accordingly, more high-frequency alternating current electromagnetic wave signal would be converted into the DC output through the rectifier circuit, so the final output voltage through the textile microstrip array antenna is higher than that through the textile microstrip single-element antenna.

2.5 Output voltage comparison

Table 3 lists the comparison of output voltage of RF energy harvesting systems. Compared with others' work, this work has a relatively good output voltage value and shows the effectiveness of RF energy harvesting system design. Compared to Refs. [21−23], this work uses a flexible material polyester felt as an antenna substrate which is easier to be conformal with garments and meets the requirements of wearable products. In addition, when the designed frequencies, the antenna types and the receiving distances between the receiving antenna and the transmitting antenna are different, the output voltage will show different values.

The above designed RF energy harvesting system based on textile microstrip antennas has much potential in the application of providing energy for the low-power system, such as Bluetooth transmission module systems and temperature-humidity sensor module systems. Additionally, when the receiving distance is too long, the output voltage will be much lower and the antenna cannot be applied to provide power. The longest receiving distance at which the output voltage can be still valid will be discussed in the future.

Table 3 Comparison of output voltage from RF energy harvesting systems

Reference	Receiving antenna	Design frequency/GHz	Output voltage/mV
[20]	Ultra-high frequency radio frequency identification tag antenna	0.915	3.003
[21]	Microstrip circularly polarized antenna	2.4	26
[22]	Microstrip patch antenna	2.45	72
[23]	Coplanar waveguide-fed monopole patch antenna	2.45	97
This work	Textile microstrip array antenna	2.45	72.7

3 Conclusions

The RF energy harvesting system including the textile microstrip antenna and the rectifier circuit was designed and prepared in this study. Both the textile microstrip single-element antenna and textile microstrip array antenna have the return losses lower than −10 dB at the working frequency range, and the array antenna has 5.35 and 4.43 dB higher gains than the single-element antenna in the E-plane and the H-plane. The minimum return loss of the rectifier circuit is −19.34 dB at a working frequency range of 2.40 to 2.48 GHz. The final output voltage from the RF energy harvesting system with the textile microstrip antennas as the receiving antennas shows the effectiveness of this RF energy harvesting system design. When the input power increases or the receiving distance decreases, the output voltage increases. The highest output voltage through the single-element antenna is 39.2 mV, and the highest output voltage through the array antenna is 72.7 mV. The above content will lead to more research ideas in this area, and better design as well as realization methods will be expected in the future.

References

[1] HOU Z C, LIU X H, TIAN M W, et al. Smart fibers and textiles for emerging clothe-based wearable electronics: materials, fabrications and applications[J]. *Journal of Materials Chemistry A*, 2023, 11(33): 17336-17372.

[2] KHADKA B, LEE B, KIM K T. Drug delivery systems for personal healthcare by smart wearable patch system[J]. *Biomolecules*, 2023, 13(6): 929.

[3] LUO J, MAO A H, ZENG Z W. Sensor-based smart clothing for women's menopause transition monitoring[J]. *Sensors*, 2020, 20(4): 1093.

[4] WANG W, YU A F, ZHAI J Y, et al. Recent progress of functional fiber and textile triboelectric nanogenerators: towards electricity power generation and intelligent sensing [J].

Advanced Fiber Materials, 2021, 3(6): 394-412.

[5] AMIT M, CHUKOSKIE L, SKALSKY A J, et al. Flexible pressure sensors for objective assessment of motor disorders[J]. *Advanced Functional Materials*, 2020, 30(20): 1905241.

[6] KAN C W, LAM Y L. Future trend in wearable electronics in the textile industry[J]. *Applied Sciences*, 2021, 11(9): 3914.

[7] WANG C L, WANG X. Monitoring muscle fatigue based on characteristics of muscle thickness measured by fabric strain sensors[J]. *Journal of Donghua University (English Edition)*, 2024, 41(1): 15-20.

[8] LIU L, HUI P X, LIU F, et al. Highly sensitive strain sensor with aligned fibrous base and patterned biphasic metal sensing layer[J]. *Journal of Donghua University (English Edition)*, 2024, 41(1): 1-7.

[9] DOLEZ P I. Energy harvesting materials and structures for smart textile applications: recent progress and path forward[J]. *Sensors*, 2021, 21(18): 6297.

[10] CUI H R, JIAO J H, YANG W, et al. High-efficiency rectifier for wireless energy harvesting based on double branch structure[J]. *Journal of Donghua University (English Edition)*, 2023, 40(4): 438-445.

[11] IBRAHIM H H, SINGH M J, AL-BAWRI S S, et al. Radio frequency energy harvesting technologies: a comprehensive review on designing, methodologies, and potential applications[J]. *Sensors*, 2022, 22(11): 4144.

[12] ULLAH M A, KESHAVARZ R, ABOLHASAN M, et al. A review on antenna technologies for ambient RF energy harvesting and wireless power transfer: designs, challenges and applications[J]. *IEEE Access*, 2022, 10: 17231-17267.

[13] NWALIKE E D, IBRAHIM K A, CRAWLEY F, et al. Harnessing energy for wearables: a review of radio frequency energy harvesting technologies[J]. *Energies*, 2023, 16(15): 5711.

[14] VITAL D, GAIRE P W, BHARDWAJ S, et al. An ergonomic wireless charging system for integration with daily life activities[J]. *IEEE Transactions on Microwave Theory and Techniques*, 2021, 69(1): 947-954.

[15] YAN J S, YAO L, WANG N. The optimized design and performance of textile slotted microstrip antenna[J]. *Journal of Donghua University (Natural Science)*, 2020, 46(5): 727-732. (in Chinese)

[16] WAGIH M, HILTON G S, WEDDELL A S, et al. Millimeter-wave power transmission for compact and large-area wearable IoT devices based on a higher order mode wearable antenna [J]. *IEEE Internet of Things Journal*, 2022, 9(7): 5229-5239.

[17] LOPEZ-GARDE J M, DEL-RIO-RUIZ R, LEGARDA J, et al. 2 × 2 textile rectenna array with electromagnetically coupled microstrip patch antennas in the 2.4 GHz WiFi band[J]. *Electronics*, 2021, 10(12): 1447.

[18] ESTRADA J A, KWIATKOWSKI E, LÓPEZ-YELA A, et al. RF-harvesting tightly coupled rectenna array tee-shirt with greater than octave bandwidth[J]. *IEEE Transactions on Microwave Theory and Techniques*, 2020, 68(9): 3908-3919.

[19] LIU Z, LI Z P, LI J X, et al. A body-wide RF energy harvester based on textile surface plasmonic antenna array for wearable wireless power transmission[J]. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 2023, 70(4): 1470-1474.

[20] ZHENG C, HU J Y, JIANG J H. Effect of fabric structure on the performance of screen-printed ultra-high frequency radio frequency identification tag antenna for wireless radio frequency energy harvesting[J]. *Journal of Industrial Textiles*, 2022, 52: 152808372211096.

[21] ZHANG S P, XU Z Q, SUN Y T, et al. Microstrip circularly polarized rectifier antenna for collecting 2.4 GHz RF energy[J]. *Journal of Magnetic Materials and Devices*, 2020, 51(4): 46-49. (in Chinese)

[22] LINH NGUYEN X V, GERGES T, DUCHAMP J M, et al. Stereolithography-based rectenna for wireless energy harvesting[C]//2021 IEEE 34th International System-on-Chip Conference (SOCC). New York: IEEE, 2021: 34-39.

[23] KOOHESTANI M, TISSIER J, LATRACH M. A miniaturized printed rectenna for wireless RF energy harvesting around 2.45 GHz[J]. *AEU-International Journal of Electronics and Communications*, 2020, 127: 153478.

以纺织微带单元及阵列天线为接收天线的射频能量收集系统输出电压比较研究

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摘 要：近些年，纺织天线作为可穿戴产品射频能量收集系统中的重要电子设备，越来越受到青睐。为研究基于纺织天线的射频能量收集系统的收集性能，该研究设计并制备了以涤纶毡为基底的纺织微带单元天线和纺织微带阵列天线。为了建立一个完整的射频能量收集系统，将信号发生器、功率放大器、发射天线和所设计的纺织微带天线（作为接收天线）与整流电路连接。研究结果表明，阵列天线的最大增益比单元天线高 5. 35 dB。最终的输出电压显示了射频能量收集系统的有效性。随着输入功率的增加、接收距离的减小，输出电压增加。通过单元天线的最高输出电压为 39. 2 mV，通过阵列天线的最高输出电压为 72. 7 mV，这是由于阵列天线的增益较高。这项研究将为该领域带来更多的研究思路。

关键词：射频能量收集；纺织品；微带单元天线；微带阵列天线；整流电路