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Dual Frequency Energy Harvesting System Based on Planar Inverted F-shaped Antenna

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Abstract. With the expansion of Internet of things (IoT) scale and the extension of its application fields, node energy acquisition has become one of the constraints on the development and application of IoT technology. Wireless energy acquisition is faced with the challenge of how to enhance power conversion efficiency under low input power in the broadband range. This study aimed to improve the capability of energy collection and transmission in wireless communication, an efficient dual-frequency energy harvesting system was proposed, moreover a novel dual-frequency planar inverted-f antenna (PIFA) and its energy conversion circuit for Radio frequency (RF) energy harvesting were designed by studying the characteristics of ambient RF energy and antenna. The developed antenna is designed and manufactured for GSM 900mhz or DCS 1.8 GHz to harvest the ambient energy provided by nearby devices. It is proved that the new dual-frequency antenna still has high efficiency when the input power is less than -20 dbm, and can maximize the receiving energy. The system works with an energy conversion and storage module to convert weak signals into required voltages, the simulation and test results show that the maximum conversion efficiency of the prototype is about 65% at 920MHZ and 1.8GHz at -20 dBm input power.

Keywords: IoT, energy harvesting, planar inverted F-shaped antenna, dual frequency

1 Introduction

In recent years, with the rapid development of 5G and Internet of Things (IoT) technology, wireless sensor network nodes and wearable mobile devices have been widely used [1]. Today the limitations of IoT are the inability to provide long-term continuity of power for a mass of low-cost nodes, especially in the field where battery life is limited. How to solve the power supply has become a research hotspot. Using RF energy harvesting technology for wireless energy collection is a feasible scheme, which can convert RF power in the environment into usable DC power supply [2]. For example, tower signals are available as RF energy. But there are several challenges:

- Energy harvesting is difficult, because electromagnetic energy harvesting is slow, and energy propagation in free space is weak and unstable, resulting in voltage dynamics [3]. At the same time, the sensor's energy consumption is relatively large, and the energy demand and supply can't match each other, which leads to long sensing time interval, frequent interruption of signal processing and transmission, and it's difficult to achieve reliable information transmission.
- Weak Internet of nodes: IoT is actually a weak internet, because the reflection communication distance is very limited, only a few nodes in the network can reliably communicate with the receiver, however, most of the connections between nodes and receivers are very unreliable and show strong randomness [4].

In this wok, a novel dual-frequency planar inverted-f antenna (PIFA) and energy conversion circuit is proposed to improve the energy collection capability of wireless sensor nodes. Design of antennas with high sensitivity and wide band-width is crucial to maximize the received power. Researchers have carried out a variety of design studies in this aspect, for example, the design scheme of single band rectifier antenna is proposed [5, 6],

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different designs of antenna and rectifier are analyzed and summarized [7, 8]. An energy harvester [9] captures the low-power input RF energy in 2.4GHz, which is converted into long-term energy storage unit through rectification and voltage boost. Another rectenna with a boost converter showed the overall efficiency can achieve 50% and 80.3%, with a power density of 0.22 and 1.95W/cm2 respectively [10], Literature [11] designed a new rectifying antenna with a broadband Yagi antenna array and a dual-band rectifier to collect ambient RF power, and its output DC voltage varied between 300 m V and 400 m V.

At present, many methods to improve antenna performance have been realized. For example, using polarization diversity technology can effectively improve antenna performance [12], introducing a filter to eliminate the high-order harmonics can enhance the efficiency of converter [13].

Compared with single-band antennas, dual-band antennas extend the range of collecting RF signal frequency, and can obtain more energy from the environment. To implement the low-power RF energy harvesting function, we need to address the following challenges: firstly, to maximize the energy harvesting efficiency, a dual band network based on a planar inverted F-shaped antenna can be realized under low power consumption; secondly, achieve a favorable impedance matching between antenna and rectifier; finally, realize a superior energy conversion efficiency of the whole system.

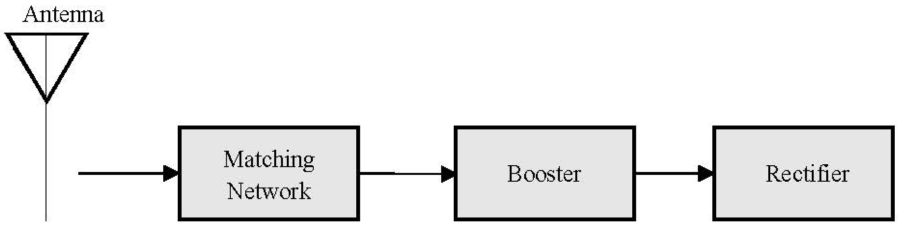


Fig. 1. RF Energy harvesting system

The basic block diagram of a RF energy harvesting system is shown in Fig. 1. The matching network we designed is composed of some inductance and capacitance elements, which ensures maximum transmission capacity from the antenna to the booster. The booster is a switching boost circuit used to drive the rectifier. The incident power through rectifier and converted to a DC signal. The energy storage module uses the charging circuit to store the excess energy. In summary, the contributions of this research are as follows:

(1) An antenna system in the operating frequency bands of 920 MHz and 1.8 GHz is proposed. The circuit consists of common off-the-shelf components, such as zero bias Schottky diode hsss-2822, which is low cost and easy to implement. This circuit can work at the input power less than -20dBm, solve the problem of energy supply in the radio frequency circuit.

(2) We conduct strict performance evaluation, and compare the design solutions from simulations. In order to make the system conversion efficiency increases, the antenna size, impedance matching and rectifier circuit repeated simulation is carried out.

(3) We propose the use of dual-band planar inverted F-shaped antenna, which can significantly increase the energy collection. The simulation results show that the scheme is feasible under the condition of dual band antenna constraints.

The rest of this work is arranged as follows. In Section II, we make an exposition of the related work, The Section III introduces the design of RF energy harvesting system, including dual band antenna and rectifier circuit. The planar inverted F-shaped antenna simulation results are presented in Section IV. We also conduct the performance evaluation of the circuit in Section IV. Section V summarizes the study and proposes future work.

2 Related Work

Energy harvesting has been a focus of the research community for the past few decades. Researchers have studied options for converting various forms of energy into electricity [14] and have developed various technologies to utilize sustainable energy from different sources [15], which include water power, wind power, solar energy, etc. [16]. However, these energy sources are affected by the requirements of environmental climate and natural operating conditions, resulting in an unsustainable supply [17, 18].

In recent years, wireless energy transmission, which collects RF energy from the environment, has attracted the attention of researchers. The technology mainly realizes the receiving and transmission of energy through the rectifier antenna, which can transmit the widely distributed electromagnetic wave energy in the daily living environment to the place where other energy (such as solar energy, thermal energy, vibration energy) cannot be transmitted. Recently, the power density of environmental electromagnetic signals is expanding due to the expansion of mobile cellular networks and applications supporting Wi-Fi [19-21]. Currently, properly managed collected energy has been applied on low-power devices and low-power sensor nodes [22-25].

The research of RF energy harvesting system mainly focuses on two aspects. One is to improve the sensitivity [26], that is, to reduce the minimum input power available. The other is to improve the efficiency of energy conversion. In order to improve the energy conversion efficiency of the system, in addition to improving the structure of the components, it is necessary to carry out the maximum power transmission among the components.

Due to the influence of digital broadcasting and cellular mobile communication, electromagnetic environment is considered to be an important environment for extracting RF energy. Ambient RF energy is available at different operating frequencies and energy densities. Wireless power transmission mechanisms are primarily divided into near- or far-field systems. Frequency identification technology is standardized for six frequency ranges, as presented in the Table 1, which show that the design of the global universal and compatible with a variety of frequency band antenna for reducing the cost is very meaningful [27]. Most far-field wireless energy collection work is in the UHF band between 862C928 MHz for RFID-based sensors. For the current work we used the UHF frequencies and MW 1.8 GHz range to achieve radio frequency energy harvesting.

Table 1. Radio frequency operation

Frequency	Typical operation range
LF,135KHz	Near Field
HF,13.56MHz	Near Field
UHF,920MHz	Near/Far Field
MW,1.8GHz	Far Field
MW,2.4GHz	Far Field
MW,5.8GHz	Far Field

The antenna aims to transmit the maximum energy in and out of the tag chip. This work has realized and optimized the dual-band low-input power energy acquisition system, which is small in size and easy to install, and contributes to the popularization of wearable devices.

3 RF Energy Harvesting System

3.1 Antenna Design

The basic structure of planar inverted F-shaped antenna (PIFA) is shown in Fig. 2. which consists of four parts, the ground plane, the radiation unit, the short circuit metal sheet and the coaxial feeder line. The ground plane can be used as a reflector at the same time radiation element is parallel to the sheet metal ground plane. With short circuit metal plate is connected with the radiation element and the ground plane. The coaxial feed using two concentric cylinders, used for signal transmission channel. PIFA is seen as a derivative of linear inverted F antenna (IFA). For IFA antennas, both the radiation unit and ground wire are thin wires. Replacing the thin wires of IFA with metal sheets of a certain width can reduce the input impedance and increase the bandwidth, thus forming IPFA.

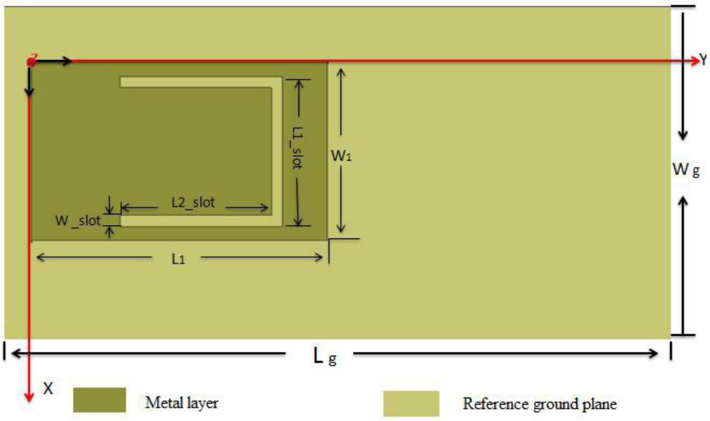


Fig. 2. Antenna structure

Design of the PIFA antenna operates at GSM 920MHz or DCS 1.8GHz band. The material of the ground plane, the radiation metal sheet and the short circuit metal piece are all metal copper. The resonant frequency of PIFA antenna is closely related to the width L_1, the length of L_2, the width of the short circuit metal sheet W and the height of the radiation sheet metal H. The resonant frequency can be calculated by the down mode (1) and (2) for short circuit metal sheet of W with arbitrary width.

$$f_r = r * f_1 + (1-r) f_2,\ L_1 \le L_2, \tag{1}$$

$$f_r = r^k f_1 + (1-r^k) f_2,\ L_1 > L_2. \tag{2}$$

In the formula,

$$r = \frac{W}{L_1}, \tag{3}$$

$$k = \frac{L_1}{L_2}, \tag{4}$$

$$f_1 = \frac{c}{4(H+L_2)}, \tag{5}$$

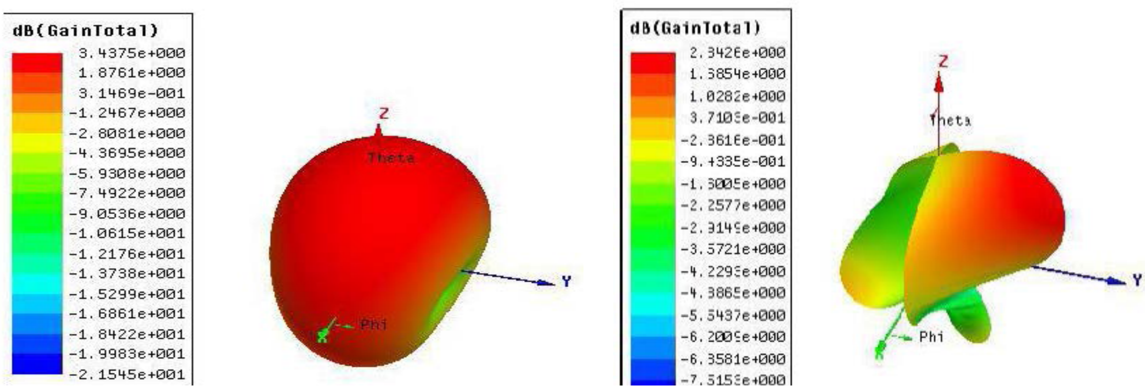
$$f_2 = \frac{c}{4(H+L_2+L_1-W)}. \tag{6}$$

U shaped slot of the PIFA antenna radiation to change the original current path, the formation of two relatively independent current loop, so as to achieve the dual band PIFA antenna work. In the U-shaped slot length L_1, width W_1 of the rectangular metal sheet as a radiation element 1, produce low-frequency resonant frequency f_1, length L_2, width W_2 rectangular pieces of metal as a radiation element 2, resulting in high frequency resonant frequency f_2. According to the formula, the low frequency resonance frequency and the high frequency resonance frequency can be estimated as (7) and (8)

$$f_1 = \frac{c}{4(H + L_1 + W_1)}, \tag{7}$$

$$f_2 = \frac{c}{4(H + L_2 + W_2)}. \tag{8}$$

In this work, the ground plane is located at the bottom, its length and width are 60mm and 120mm respectively. The radiation metal sheet is located at the top, the sum of length and width is about a quarter of the working wavelength, respectively, taking 55mm and 32mm. In order to allow the PIFA antenna to have enough bandwidth, the antenna height is 10mm. The radiation on sheet metal width is 2mm of U-shaped slot to implement dual-band work with W_slot and the width is L1_slot = 25mm and the length is L2_slot = 52mm. PIFA is used to transmit the signal energy of the feeder mode is coaxial feeder, coaxial feeder by the inner core radius of R_1 and the outer ring radius of R_2 two cylinder, R_1 = 0.25mm, R_2 = 0.59mm. Radiation metal sheet and the connection between the ground plane filled the lower dielectric constant Rohacell RF foam, the relative dielectric constant is 1.06 and the loss tangent is 0.005. The three-dimensional simulated radiation pattern of the proposed antenna at 920 MHz and 1.8 GHZ is shown in Fig. 3(a) and Fig. 3(b).



(a) 920MHz (b) 1.8GHz

Fig. 3. Three-dimensional simulation of the antenna

3.2 Impedance Matching Network

In order to acquire better transmission power of dual-band collector, an impedance matching network can be inserted between the antenna and the rectifier. The impedance matching network is a passive network. When the input impedance of the antenna matches that of the rectifier, the antenna achieves the maximum RF power capture and transmission. Since the antenna impedance is a function of frequency, and the input impedance of the rectifier circuit is a function of frequency and incident power, this work uses advanced design system (ADS) to design and optimize a dual-branch impedance matching circuit that meets the requirements of the index. Using high frequency structure simulator (HFSS) software, the initial design of -20 dBm input power is carried out under the conditions of 920 GHz, 41-4jat1.8 GHz and input impedance of 31-12.5j, as shown in Fig. 4.

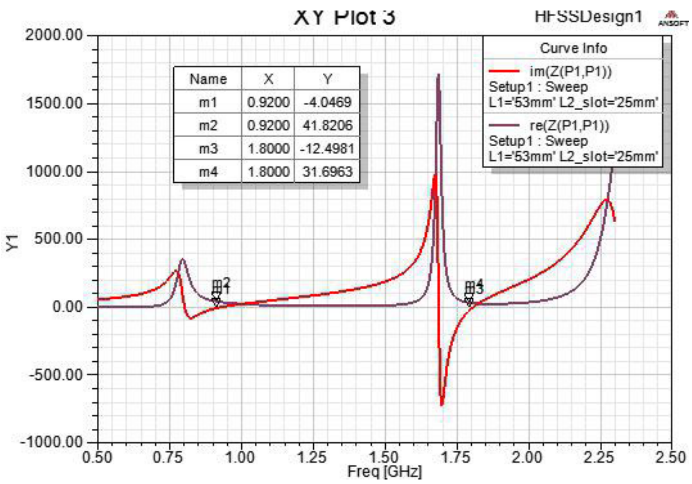


Fig. 4. Antenna input impedance

An ideal match was achieved by using microstrip dual branch tuning matching method, which has been showed in Fig. 5. the parameters of the matching network were optimized by using precise electromagnetic tuning method. After optimizing the results as shown in Fig. 7(a) and Fig. 7(b), The voltage standing wave ratio of the rectifier with the studied power is less than 1.2 in the two central frequency bands.

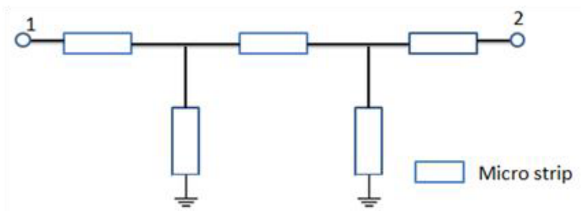


Fig. 5. The matching network model

3.3 Booster Circuit

Since the RF signal power received by the PIFA in this work is -20dBm, meaning that the maximum voltage amplitude of the AC signal is less than 50mv, which is far less than the diode threshold, so a booster circuit is needed to drive the rectifier. Boost converter is a kind of switching boost circuit, usually using a capacitor and a diode, the capacitor stores the charge, the diode prevents the current from pouring, when the frequency is high, the circuit voltage is the circuit input voltage plus the voltage on the capacitor, play a role in boosting the voltage. The basic circuit diagram is shown in Fig. 6. The output voltage is decided by

$$V_{out} = \frac{1}{R}\sqrt{\frac{L}{C}}V_S. \quad (9)$$

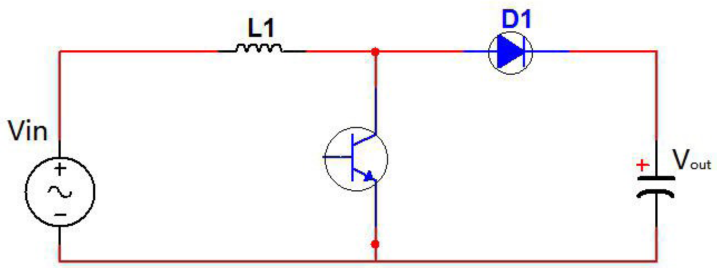
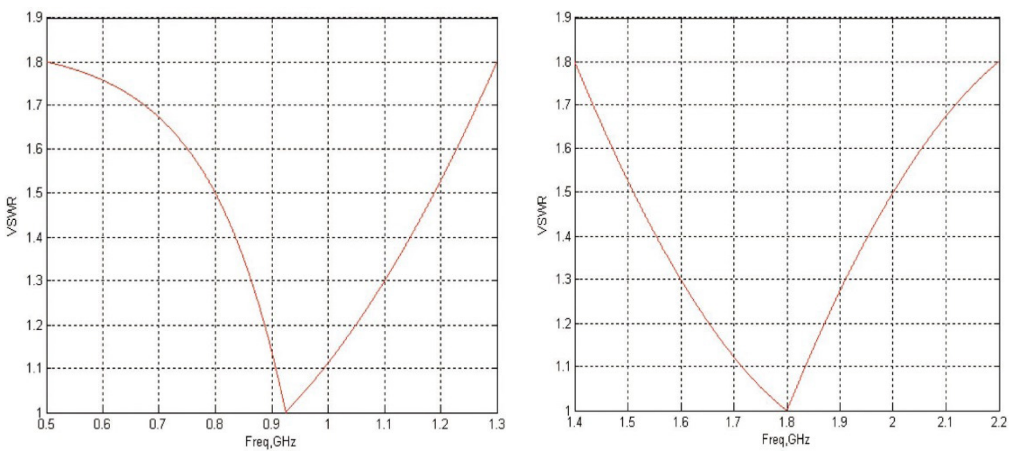


Fig. 6. The simple booster circuit diagram

When all the components are in ideal condition, the circuit will reach its highest output voltage at the resonant frequency [28]. According to formula, the boosted voltage amplitude increases with the increase of inductance and decreases with the increase of capacitance. With constant inductance, smaller capacitance brings higher output voltage at a higher resonant frequency. Assuming that the transistor has not worked for a long time, all the components are in an ideal state, the capacitor voltage is equal to the input voltage. In the charging process, the transistor conduction and use the wire instead, then, the input voltage flow through the inductor. Since the input is a direct current, the current on the inductor increases linearly at a certain ratio, which is related to the size of the inductor. With the increase of the inductor current, some energy is stored in the inductor. The function of the diode is to prevent the capacitance to ground discharge. In the discharge process, the transistor cut-off, due to the inductor current retention characteristics, flow through the inductor current will not be immediately changed to 0, but the slow change from the charge to 0. The original circuit has been disconnected, so the inductance can only be discharged through a new circuit, that is, the inductance of the capacitor to start charging, the capacitance at both ends of the voltage rise, the output voltage is higher than the input voltage.



(a) 920 MHz (b) 1.8 GH

Fig. 7. Voltage Standing Wave Ratio (VSWR) of the antenna

3.4 Rectifier

Rectifier is a device that converts alternating current (AC) into direct current (DC), and then gets stable direct current supply load after filtering. One of its main functions is to provide charging voltage to the battery as a charger, so the rectifier circuit is an important part of the RF energy harvesting system. Designing a rectifier with low power consumption and high-power sensitivity can effectively improve the conversion efficiency of RF-to-DC. The rectifier circuit proposed in this work is based on Villard voltage multiplier invented by Heinrich Greinacher, and the basic circuit diagram is shown in Fig. 8.

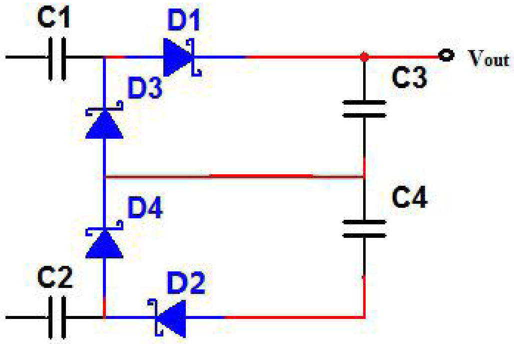


Fig. 8. A basic schematic of a villard voltage multiplier

Rectifier part is the use of Schottky diode rectifier. Schottky rectifier with only a carrier transfer charge, without the accumulation of excess minority carrier on the outside of barrier. Therefore, there is no charge storage problem, make switching characteristics obtained show improvement. The reverse recovery time can shorten to less than 10 ns. It's a reverse pressure value is low, generally less than 100V. So, it is suitable to work in low voltage and high current situation. By using the characteristics of low voltage drop, the efficiency of low voltage and high current rectifier circuit can be improved.

The rectifier is a single stage voltage multiplier that uses the Avago HSMS-2822 RF detector diodes. The turn-on voltage of HSMS-2822 is 340mv, which is suitable for low power circuit. In the selection of the diode is considered when there are three parameters: the higher the saturation current, the lower the capacitance of the lower series resistance (ESR). A higher saturation current will have a higher forward current, which is good for the drive circuit. Low series resistance will reduce power consumption [29]. There are two branches, and each branch has two diodes. The output of each diode can be used as a partial bias voltage of the latter diode, which reduces the whole RF power consumption. The full wave rectifier mechanism is adopted to improve the power sensitivity and achieve good power processing capability.

When the voltage is in positive half cycle, the series diode D1 rectifies and the capacitor C1 charges to store energy. When the voltage is negative half cycle the wave is rectified by the parallel diode D2, and the capacitor C2 stored energy. The energy in C2 can be added to C1, so the voltage across C1 is about twice the peak voltage in a single series diode configuration. The rectifier breakdown voltage is aggrandized, so the conversion efficiency of the theoretical maximum rectifier is also improved. In addition, D1's offset voltage is provided by using part of D2's rectifier wave, thereby reducing the input RF power requirement.

4 Experiment Results

This section illustrates the implementation and experimental of the whole energy harvesting system. Firstly, we describe the whole process of the design of various parts of the antenna. Then, we have optimized the parameters of the planar inverted F antenna and the performance of the system. Finally, we evaluated the overall energy conversion efficiency.

4.1 The Design of the Antenna

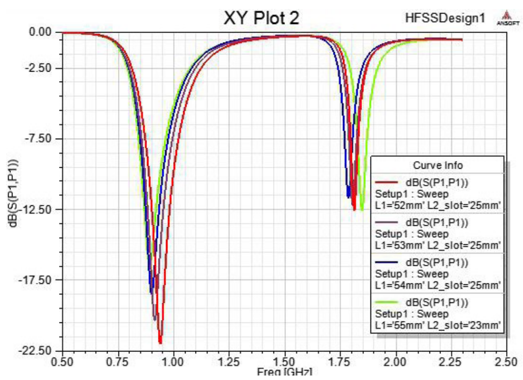
Design of the PIFA works in the GSM 900 MHz and DCS 1800 GHz. For GSM 900 MHz band, the uplink frequency range is 880 MHz915 MHz, the downlink frequency range is 925 MHz-960 MHz, so the center frequency is 920 MHz For DCS 1.8 GHz, the uplink frequency range is 1.71 GHz-1.78 GHz, the downlink frequency range is 1.80 GHz-1.88 GHz, so the center operating frequency is 1800 MHz The whole antenna structure is divided into five parts, which are the ground plane, the radiation metal sheet, the short circuit metal sheet, the coaxial feeder and the foam support. Creating a PIFA antenna simulation model in HFSS, in order to facilitate the analysis of influence of structural parameters on the antenna performance, we need to define a series of variables to represent the antenna structure, some parameters as illustrated in Table 2.

Table 2. Parameters of the antenna

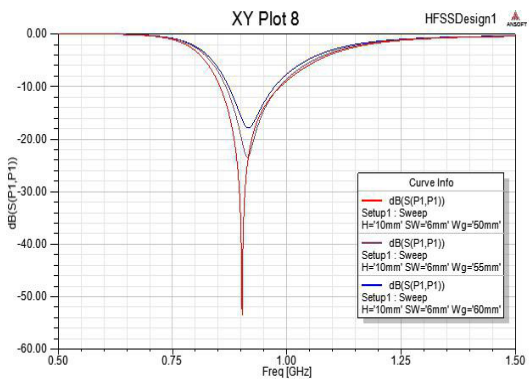
Variable	Variable name	Initial value
Antenna Height	H	10mm
Radiation Metal Sheet Length	L1	55mm
Radiation Metal Sheet Width	W1	32mm
Ground Plane Length	Lg	120mm
Ground Plane Width	Wg	60mm
Width of Short Metal Sheet	SW	6mm
Inner Radius of Coaxial Feeder	R1	0.25mm
Outer Radius of Coaxial Feeder	R2	0.59mm
U-shaped Slot Width	L1slot	27mm
U-shaped Slot Length	L2slot	23mm

4.2 Optimized the Parameters of the PIFA

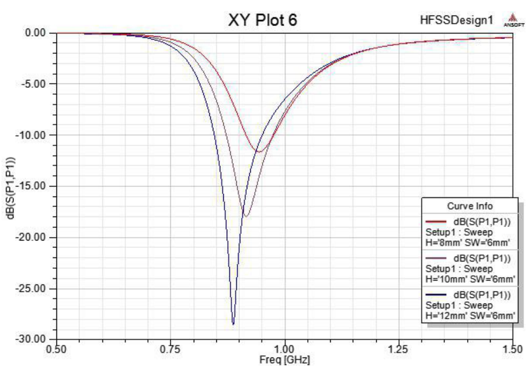
Simulation results of the performance parameters of the PIFA are viewed after the data processing is completed. The operating frequency and bandwidth are important parameters, and the effect of the height, the width of the short circuit and the size of the ground plane is analyzed by means of the Fig. 9(a) to Fig. 9(d).



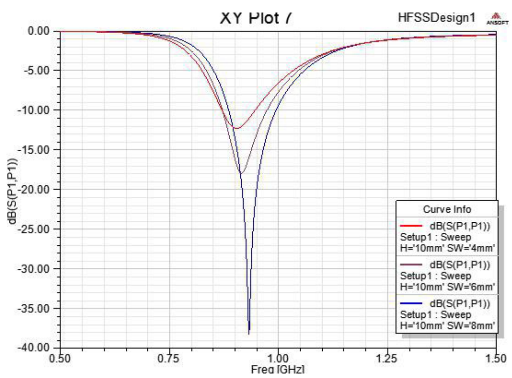
(a) Optimization of short circuit metal sheet width SW



(b) Optimization of ground plane size Wg



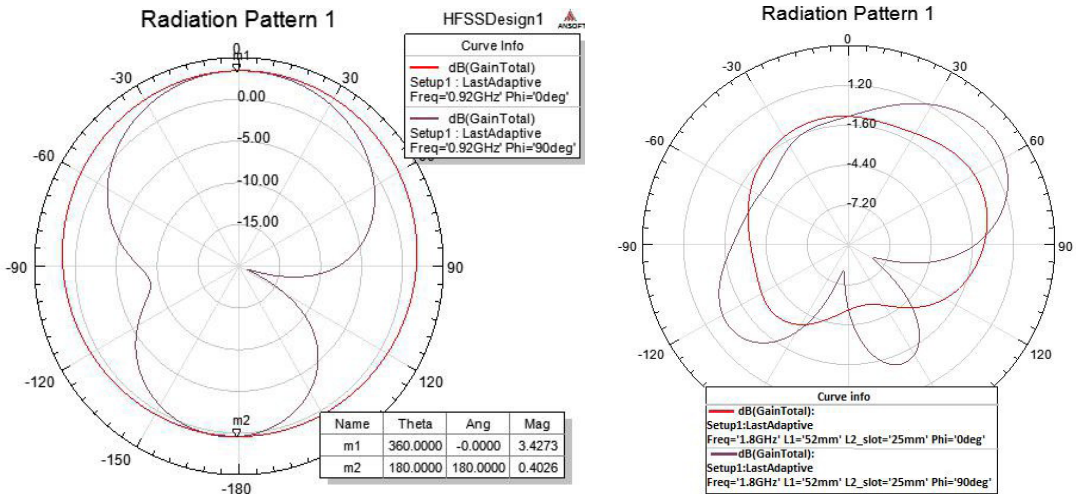
(c) Optimization of antenna height H



(d) Optimization of radiation patch and U-shaped slot length L1 and L2 slot

Fig. 9. Antenna optimization

From the generated S11 image, we can know that when the short circuit metal sheet in the 4mm-6mm changes, with the increase of SW, the frequency of the antenna is higher, the grounding metal sheet and the bandwidth are wider. The Fig. 10(b) can be drawn the width of ground plane change on the antenna resonant frequency has almost no effect, but will significantly affect the bandwidth when the ground plane width decreases, the bandwidth decreases gradually, the comprehensive consideration in order to obtain larger bandwidth Wg = 55mm. As is shown in the Fig.10(c), the results from the parametric scanning analysis can be seen, H values are 8mm,10mm and 12mm, corresponding to relative bandwidth is 6.4%, 11.0% and 11.8%. With the height increasing, the operating frequency is gradually reduced, and the bandwidth is gradually increased. To improve the low resonance point, reduce the length of the radiating patch, and increase the length of the U-shaped groove at the same time to reduce the high resonance point. Finally, we choose the parameters are SW = 6mm, Wg = 60mm, H = 12mm, L1 = 52mm and L2slot = 25mm. After optimizing the antenna parameters, the gain of the antenna 920 MHz and 1.8 GHz band isshown in Fig. 10(a) and Fig. 10(b).



(a) 920MHz

(b) 1.8GHz Band

Fig. 10. The directional gain of antenna

4.3 The Overall Energy Conversion Efficiency

By optimizing the framework, it is expected to achieve the maximum efficiency of the energy harvesting module in the -25 dBm to 0 dBm range. Due to the large number of multipath reflections in the environment, the available energy at any given point in the surroundings cannot be accurately predicted by the free space (Friis) model. The efficiency of conversion is defined in [30] as

$$\eta_c = \frac{OutputPower}{IncidentPower - ReflectedRFPower}. \tag{10}$$

Whereas, the overall efficiency is given by

$$\eta_0 = \frac{DC\ OutputPower}{IncidentRFPower}. \tag{11}$$

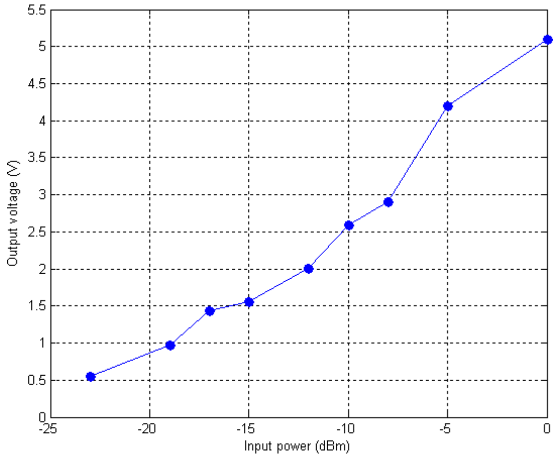


Fig. 11. Performance results

The ratio of the DC output power to the net RF input power is called the conversion efficiency. Impedance matching, reflection coefficient and rectifying effect are the key elements that affect the total efficiency. The circuit is simulated by ADS software and the results of performance are shown in Fig. 11. Since our goal is to calculate steady-state solutions for nonlinear circuits, we use the frequency-domain approach in this work.

In order to verify the performance of this research method, the conversion efficiency is compared with that of the four existing energy harvesters, which all work in dual-band or multi-band, and the detailed information is shown in Table 3. It can be seen that the method proposed in this paper has the highest maximum conversion efficiency.

Table 3. Comparison of relater work

Ref.	Frequency (GHz)	Maximum conversion efficiency %	Type of received wave
[9]	Dual-band, 1.8, 2.2	50	MW
[31]	Multiband, 0.9,1.75,2.15,2.45	16	CW
[32]	Dual-band, 0.915,2.45	35	CW
[33]	Dual-band, 0.915,2.45	56.2	CW
This work	Dual-band, 0.920,1.8	65	MW

5 Conclusions and Prospects

This work presents an efficient dual-frequency energy harvesting system for environmental wireless energy harvesting. A wideband rectifier circuit with a novel impedance matching circuit is designed, which can match the surrounding RF signals at a low power density. Use a full - wave rectifier circuit to enhance the power sensitivity. A planar inverted F-shaped antenna designed can effectively improve the receiving ability of the antenna. The simulation and experimental results show that the maximum conversion efficiency of the prototype can reach 65% when the input power of 920 MHZ and 1.8 GHz is -20 dBm.

At present, there are few researches on wireless energy harvesters in broadband or 5G millimeter-wave rectenna system, and the module for obtaining RF energy in millimeter wave has not been built yet. In the future, the RF energy harvesting technology in millimeter wave will be studied, and the miniaturization and integration of rectifying antenna will be realized, so as to promote the application of RF energy acquisition system in mobile portable devices.

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