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Design of RF Energy Collection System

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Abstract

With the rapid growth of the population, the popularity of wireless devices has also increased, making radio frequency signals more colorful. By harnessing the potential of RF energy, we will discover their enormous potential and thus develop a new, highly viable miniature energy source. This paper mainly studies the RF micro-energy harvesting system, which collects RF energy by designing a microstrip antenna, converts it into DC voltage output through the rectifier circuit, and then raises the voltage to the available range and stores it in a capacitor through the boost module and energy management circuit, and finally controls the sensor through a single-chip microcomputer for energy transmission and data transmission and reception. This paper focuses on the design and optimization of microstrip antennas to achieve high efficiency and stability in RF energy harvesting.

Keywords

Micro-energy harvesting system, energy transmission, microstrip antenna.

1. RF Micro-Energy Harvesting System

1.1. Background of Micro-Energy Harvesting System

Micro-energy harvesting has attracted much attention as a method of reducing or eliminating the need for batteries. RF electrical energy conversion aims to convert RF energy present in external space into electrical energy, thus providing a completely new way of supplying energy without the constraints of physical factors. This technology is able to break through the limitations of traditional energy supply methods and provides a viable solution to the above problems.

A micro energy harvesting system was designed, consisting of a microstrip antenna design and an energy conversion and storage system. To improve reception gain and bandwidth, the microstrip antenna was designed using rectangular microstrip antenna theory and optimization algorithms in ADS software. The rectifier circuit in the energy conversion and storage system converts the weak RF energy collected by the microstrip antenna into high voltage, low current DC power. The boost circuit then converts the high frequency RF energy into a voltage suitable for driving subsequent electronic components. These two components together constitute an efficient energy harvesting system.

1.2. Optimization Design of Power Supply Technology

The receiving antenna plays a crucial role in converting RF signals from the surrounding space into AC electrical energy, and its performance directly impacts the magnitude of the electromagnetic power received. In the early days of mobile communication devices, monopole antennas and helical antennas were commonly used. However, they had drawbacks such as large size, integration difficulties, high costs, and vulnerability to damage, which made them less suitable for practical applications. In contrast, microstrip antennas utilize a microstrip substrate, which results in smaller dimensions and lower costs compared to the metallic materials used in traditional antennas, facilitating mass production. The fabrication process for microstrip antennas is relatively straightforward, typically accomplished through techniques

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like etching or printing. This not only keeps costs low but also ensures higher consistency and integration among antennas[1].

Based on the theoretical formulas for microstrip patch antenna design, a rectangular microstrip antenna was designed for a frequency of 2.44 GHz. The width of the microstrip antenna's feedline was calculated using the LineCalc tool within the ADS simulation software, yielding a feedline width of approximately 3.33 mm and a length of 5.00 mm. The designed microstrip antenna, as depicted in Figure 1, has specific dimensions detailed in Table 1.

Table 1 Microstrip Antenna PCB Parameters

Parameters	L(mm)	W(mm)	L1(mm)	W1(mm)
Sizes	31.75	40.27	5.00	3.33

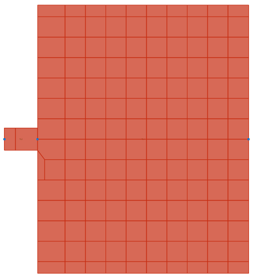

Figure 1 Microstrip Antenna Layout

Optimization of the equivalent circuit of the microstrip antenna results in a center frequency closer to 2.44 GHz, a smaller reflection coefficient at the center frequency, and a wider bandwidth.

Furthermore, within the antenna system, the power distributor is responsible for allocating the input RF power to different output ports according to a certain ratio. Microstrip array antennas can enhance reception gain, bandwidth, and other performance factors.

When selecting a power distributor type, minimizing power loss is a critical consideration, making resistive power distributors typically unsuitable. Moreover, for applications near specific frequency ranges, a first-order Wilkinson power distributor is sufficient and satisfies requirements. The first-order Wilkinson power distributor features a simple structure, lower complexity, reduced power loss, and relatively smaller size, making higher-order power distributors like second-order and third-order Wilkinson designs unnecessary. Refer to Figure 2 [3].

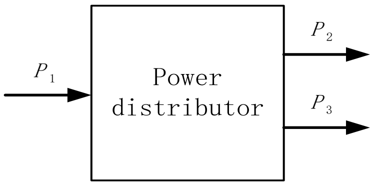

Figure 2 Power Distributor

When employing a Wilkinson power divider in high-frequency transmission, it is essential not only to ensure uniform path lengths but also to achieve proper impedance matching. The utilization of a quarter-wavelength impedance transformer can effectively facilitate impedance matching and reduce losses during energy transmission[4].

A microstrip array antenna is attracting increasing attention due to its characteristics of improving reception gain and expanding bandwidth, and it has been widely applied in various fields. To achieve greater received power in antenna design, this design adopts an array consisting of four unit patch microstrip antennas [3]. To ensure that these four unit antennas generate the same current output, it is necessary to ensure that each unit has an identical

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structure. To achieve this, three symmetrically designed power dividers are used, which helps minimize length variations and enhance the feeding signal of each unit, thereby improving overall signal transmission efficiency.

By using these symmetrically designed power dividers, a more balanced current distribution can be achieved among the unit elements of the microstrip array antenna, ensuring that they operate with similar efficiency. This design not only helps improve the performance of the antenna system but also maintains stable performance across different operating frequency bands. By reducing length variations, signal distortion and losses caused by uneven currentnt distribution can be minimized.

Energy management system design

Design of the energy management part of an RF micro-energy harvesting system, including rectifier and booster circuits

The voltage multiplier rectification circuit is capable of producing a direct current output voltage higher than the input alternating voltage. However, due to its relatively small overall power variation, the circuit's ability to deliver output current is limited, resulting in characteristics of high voltage and low current. Given that the collected energy from the patch microstrip antenna is relatively small, leading to lower voltages, achieving the required specifications with a Cockcroft-Walton voltage multiplier rectification circuit becomes challenging. Therefore, in this design, two sets of polarity-opposite voltage multiplier rectification circuits are combined to form a quadruple rectification circuit, meeting the necessary voltage requirements. The voltage multiplier rectification circuit is illustrated in Figure 3. The final output voltage is twice that of the Cockcroft-Walton voltage multiplier rectification circuit, i.e., four times the input voltage [6].

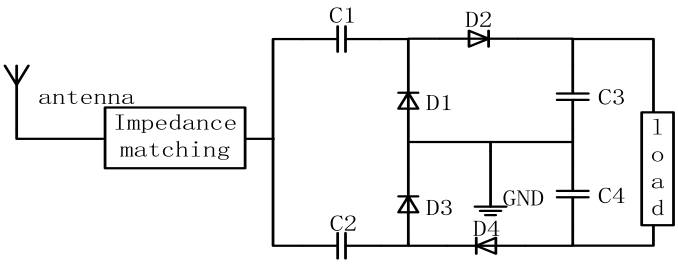

Figure 3 Quadruple Voltage Rectification Circuit

In the rectification circuit, the choice of rectifying diodes significantly influences the overall rectification efficiency. Schottky Barrier Diodes (SBDs) are commonly used rectifying diodes due to their advantages, including high switching frequency, low forward voltage drop, low threshold voltage, and fast reverse recovery time. Based on the diagram of the quadruple voltage multiplier rectification circuit, we selected HSMS286C as the rectifying diode for this design. With an input signal frequency of 2.45 GHz, its sensitivity can reach -56 dBm, and it operates with a mere 5 μA current. Therefore, the HSMS286C diode perfectly meets the design requirements of the RF energy harvesting system.

Booster circuits play an important role in RF micro energy collection systems, requiring not only rated voltage but also a certain amount of current to ensure sufficient power output. BQ25570, as an ultra low power energy collection power management chip with boost and buck converters, can continuously collect energy at a cold start voltage as low as 100mV; The typical current value of its fully operational static operation is only 488nA, and the battery current in the energy-saving mode is lower than 5nA. It supports a peak output current of 110mA with a typical value, and can be programmed to adjust the output within the range of 1.3-5.5V; The maximum energy conversion efficiency can reach 93%, as shown in Figure 4.

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Figure 4 Physical diagram of BQ25570 module

2. Simulation analysis

Through simulation and analysis by ADS software, we verified the hardware improvements of the system such as antenna feeder, power divider, rectifier-doubler circuit composed of Schoendienst diode, and the joint system, and evaluated the system's performance indexes as well as the energy harvesting efficiency. Finally, the analysis of the resultant data shows that after the RF energy harvesting system in this paper, the energy harvesting efficiency has been greatly improved, and the scheme has certain practicality and effectiveness.

In terms of optimizing the equivalent circuit of microstrip antennas, the OPTIM and GOAL of ADS software are utilized. The matching optimization principle diagram is shown in Figure 5. TL1 is an optimized microstrip line, with a length L of approximately 1.75mm and a width W of approximately 3.33mm; TL2 is an optimized microstrip terminal opening route, with a length L of approximately 2.72mm and a width W of approximately 3.33mm. The T-shaped microstrip line patch (MTEE) is used as the connecting wire for the microstrip antenna. According to its size requirements, its W1, W2, and W3 are all set to 3.33mm.

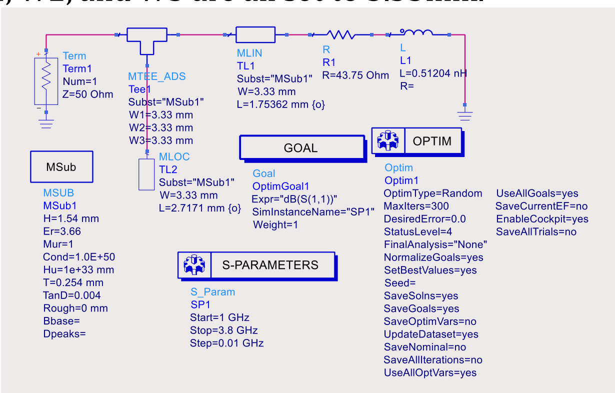

Figure 5 Schematic diagram of simulation optimization

Through the simulation of the microstrip antenna schematic above, the calculated parameters of the microstrip antenna have been well optimized. Based on the optimization results of the schematic diagram, its parameters are placed in the layout simulation. The optimized layout is shown in Figure 6.

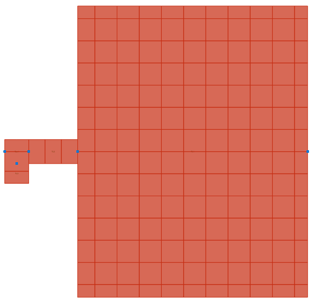
Figure 6 optimized layout

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The four-unit Wilkinson power dividers were interconnected with the designed microstrip antenna, and continuous simulation optimizations were performed on the interconnection diagram of these two components. This iterative process aimed to determine the size and parameters of the antenna array, ensuring its optimal performance. Since Wilkinson power dividers involve the use of isolation resistors, layout simulation within the ADS software was not feasible. Therefore, a combined simulation involving both schematic and layout designs in ADS was used to debug the microstrip antenna system. Figure 7 illustrates the schematic representation of the combined simulation antenna system within the ADS environment.

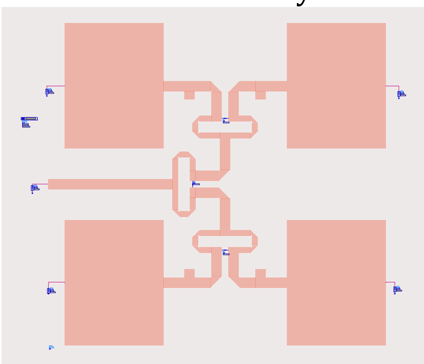

Figure 7 Schematic diagram of ADS joint simulation antenna system

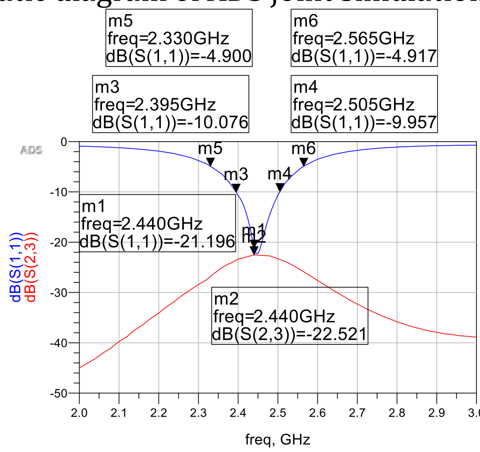

Figure 8 ADS Joint Simulation S Parameter Curve

Figure 8 shows that at point m1, the central frequency of the antenna system is approximately 2.44 GHz. At this frequency, the S11 parameter (reflection coefficient) of the system is -21.20 dB, which meets the design requirements. A reflection coefficient of -10 dB corresponds to a 10% energy transmission loss, while a reflection coefficient of -5 dB corresponds to a 32% energy transmission loss. Points m3 and m4 indicate that the microstrip antenna system has a bandwidth of about 0.11 GHz for a 10% energy transmission loss, and a bandwidth of approximately 235 MHz for a 32% energy transmission loss. This shows that the S11 parameter effectively meets the design requirements and maintains a certain level of bandwidth while ensuring a specific reflection coefficient. Regarding the S23 parameter (isolation), point m2 on the graph indicates that it is -25.52 dB at a frequency of 2.44 GHz, indicating favorable isolation characteristics.

3. Summary

The text first analyzes the current research status of micro-energy harvesting systems, conducts research on radio frequency (RF) energy harvesting, and identifies key technologies influencing RF energy harvesting. Based on this, it examines the potential for improvement in RF energy harvesting and energy conversion efficiency. By using microstrip antennas as energy receiving devices and employing techniques such as impedance matching, rectification circuits,

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and voltage boosting modules, RF signals are converted into usable electrical energy. Through simulation and experimental verification, this system has achieved favorable results in energy harvesting.

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