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Ultra-Low Power High-Efficiency UHF-Band Wireless Energy Harvesting Circuit Design and Experiment

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Abstract

In this paper, an ultra-low power high-efficiency ultra-high frequency (UHF)-band wireless energy harvesting circuit based on the diode SMS7360 is designed and experimentally demonstrated, being operated in all released Global System for Mobile Communications (GSM) bands in China (GSM900 band: 0.87−0.96 GHz and GSM1800 band: 1.71−1.86 GHz). This UHF-band wireless energy harvesting circuit can harvest energy at 0.87−0.96 GHz and 1.71−1.86 GHz bands simultaneously in outdoor or indoor environment. The test results show that a radio-frequency (RF)-to-direct-current (DC) conversion efficiency in the range of 20%−63.2% is obtained for an available input power of −22 dBm to 1 dBm in GSM900 band and that in the range of 13.8%−55.5% is achieved for an available input power of −22 dBm to 3 dBm in GSM1800 band. The harvested RF energy is converted into DC energy and be stored in a 6.8 mF super capacitor through the energy management circuit. This super capacitor's capacity is more than 20 mJ, which can meet the demand of high-speed broadband wireless communication transceivers. This ultra-low power high-efficiency UHF-band wireless energy harvesting circuit could be used to achieve the low power wireless sensor network node (tag).

Keywords

GSM900; GSM1800; rectifier; RF energy harvesting; wireless sensor network

1 Introduction

As one of the world's top ten technologies, network sensor technology has been widely researched. The wireless sensor network (WSN) nodes were powered by the non-rechargeable battery which would severely limit the development of wireless sensor network techniques. Energy harvesting WSN (EH-WSN) utilizes energy harvesting technology to collect the available energy in the environment to power the whole system, which can effectively reduce the energy limitation of the sensor nodes.

Unlike most of the energy sources, the raido frequency (RF) energy sources are continuously available in the atmosphere environment. However, the power density of space RF sources is very low [1]. For example, when the distance from a China Mobile Communications Corporation (CMCC) GSM base station to the receiver is 60 meters, the wireless power intensity is 5.25 μW/cm^2; when the distance from a China Unicom GSM base station to the receiver is 70 meters, the wireless power intensity is 5.94 μW/cm^2 [2]. Moreover, if the antenna aperture is 50 cm^2, such wireless power that can meet the rectifying circuits is about -22 dBm.

Previous works on RF harvesting circuits focused on a single operating frequency [3], [5], [6]. When multiple RF energy sources are available, the amount of harvested energy can be increased if the system is designed to work in multiple frequency bands [4] as proposed in this paper. From theory analysis supported by simulation results and measurements, an ultra-low power (-22 dBm) high-efficiency UHF-band wireless energy harvesting circuit has been designed to work at the GSM900 and GSM1800 bands. The GSM900 entire band is from 870 MHz to 960 MHz including uplink (UL) and downlink (DL) modes. The DCS1800 is from 1710 MHz to 1880 MHz (including UL and DL modes). Finally, the harvested energy is stored in the super capacitor through the energy management circuit BQ25570.

This paper is organized as follows. Section 2 presents the state-of-the-art research progress and the rectifier impact on

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the multiband RF harvester architecture. Section 3 explains the designed rectifier in the dual-band RF harvester and presents the dual-band RF harvester simulations. Section 4 shows the dual-band RF harvester experiments and measurements. Section 5 concludes this work.

2 State-of-the-Art: Rectifier Impact on Multiband RF Harvester Architecture

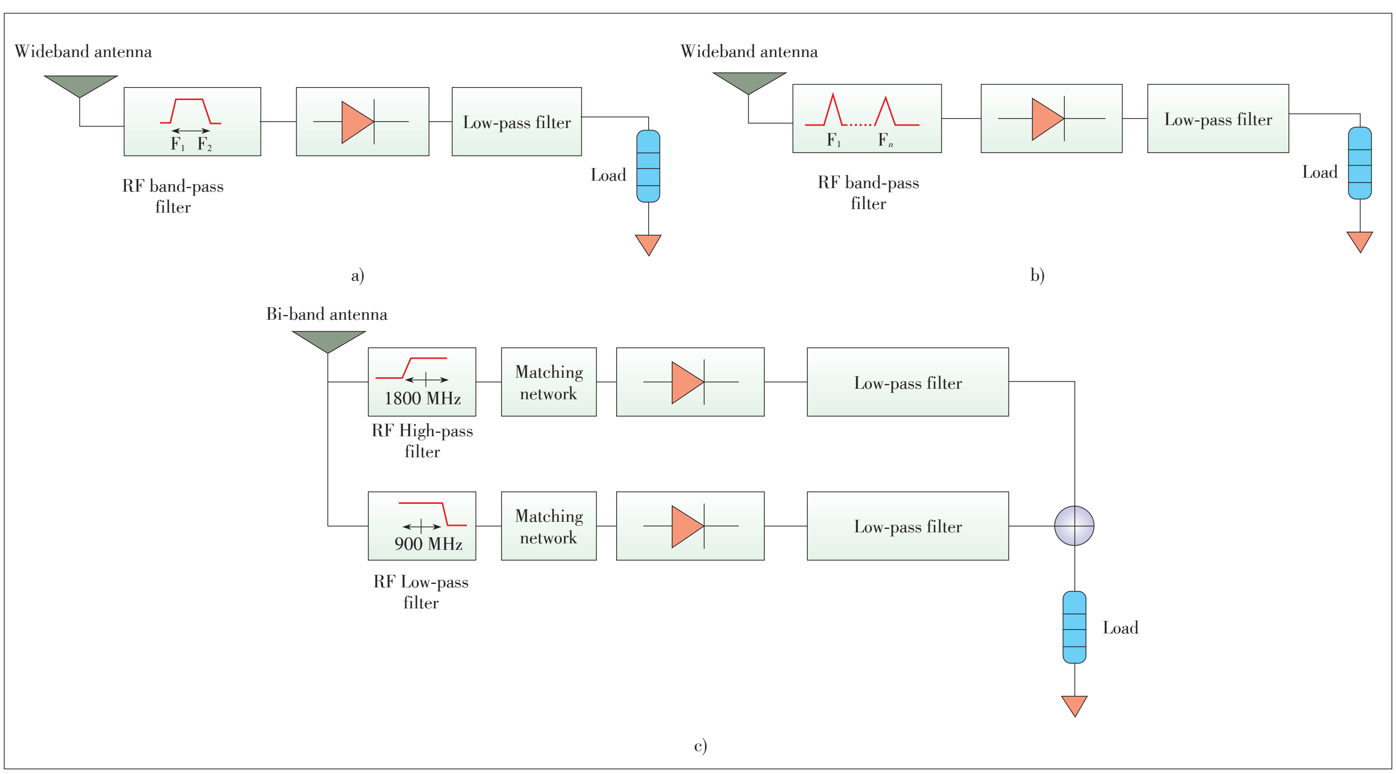
The goal of a wireless energy harvesting circuit (RF energy harvester) is to convert the RF energy received from ambient RF sources (GSM900/GSM1800 in this paper) into direct current (DC) power. A typical wireless energy harvesting circuit consists of a receiving antenna followed by an RF band-pass filter, a rectifier, a low-pass filter, and a load. Many of the previous studies are single band RF harvesting circuits [3], [5], [6] while some other studies use multi-band RF harvesting circuits [4]. However, when the operating frequency is changed from the optimal resonance frequency, a single-band harvesting circuit is not suitable to supply the sensor, since mismatching between the source and the rectifying circuits will degrade the rectification efficiency. In fact, the predominant frequencies may be different in different locations. Therefore, a multi-band energy harvesting circuit is more desirable. Some works have reported on multi-band structures [4], [7]–[13]. This type of energy harvester benefits from the accumulation of RF radiation for several frequencies and a higher amount of energy can be harvested [9].

2.1 Dual-Band RF Harvester Topology Choice

In order to harvest energy from GSM900 and GSM1800 RF bands, several RF harvester topologies should be investigated. The main difference among these topologies is the design of RF band-pass filter. The role of the RF band-pass filter is to match the antenna impedance and the conjugate impedance of the rectifier circuit. In the previous studies, there are two common topologies, as shown in **Fig. 1a** and **Fig. 1b**.

In the first topology, the RF bandpass filter covers a large bandwidth; however, its shortcoming is significant. As we all know, the rectifier circuit input impedance with the antenna impedance varies as a function of the frequency and the incident power. The impedance mismatch will undoubtedly affect the RF-to-DC conversion efficiency. As shown in Fig. 1a, the RF-to-DC conversion efficiency is 8% at 1550 MHz RF band, when the incident power is 20 dBm [11]. However, this efficiency is 15% in [8] with the same incident power and same topology, but at 300 MHz RF band. Because our harvester is designed for GSM900 and GSM1800 bands, we cannot use this topology.

For the second one, its RF band-pass filter is a multi-band band-pass filter (Fig. 1b), and many designs [6], [11], [13], [14] have used this architecture. The complexity of RF band-pass filter will affect the RF-to-DC conversion efficiency and make the circuit design more difficult. The filter components are im-



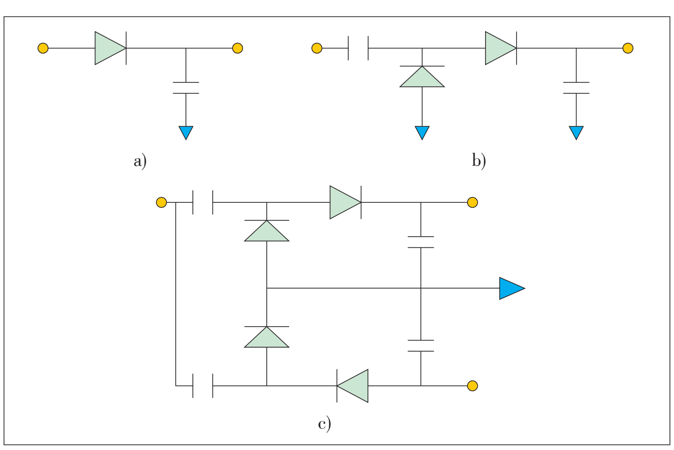
▲**Figure 1. Multi-band RF harvesters a) with only one designed broadband RF band-pass filter, b) for a multi-band band-pass circuit, and c) in the proposed architecture in this paper.**

portant for obtaining the correct adaptations between the antenna and the rectifier.

RF energy around multiple frequencies can be harvested by stacking several rectifier circuits. In this case, a structure for four bands with RF-to-DC efficiency up to 84% is proposed in [4]. Based on the similar idea, Fig. 1c illustrates the architecture proposed in this paper, which is for GSM900 and GSM1800 bands. The diplexer (a RF high-pass filter or a RF low-pass filter), the matching network, the rectifier, and the low-pass filter compose an RF branch (Fig. 1c). In this paper, we will not focus on the design of the dual-band antenna. The input of a diplexer is connected to a single access dual-band antenna, in order to match two parallel rectifiers at the dedicated frequencies. This structure is more compact. There is a matching network circuit between the diplexer and rectifier in each branch to allow the maximum energy to reach input of the rectifier to improve the RF-to-DC conversion efficiency. Finally, the rectifier branch DC output is connected to the load (one independent load for each or a shared one). Any RF signals must be blocked by a low-pass filter which is connected at the end of rectifier, so this structure only allows the DC component to pass through.

2.2 Voltage Doubler Rectifier Topology Choice

There are several rectifier topologies which depend on the incident power and frequency (**Fig. 2**). Fig. 2a shows the series topology. This topology is suitable for the situations of low input power [12]–[14]. Fig. 2c is the Greinacher topology [7]. This topology has a higher output DC voltage levels. However, it has twice as many diodes as a voltage doubler (Fig. 2b) and four times more than a series rectifier. In the case of outdoor applications, the number of rectifier's diodes must be limited as the RF density power is low, thus the Greinacher rectifier is not a good candidate. The voltage doubler topology is chosen to maintain high RF-to-DC conversion efficiency at low RF input power while maximizing the output DC voltage of rectifier. The voltage doubler topology has a higher output voltage than



▲**Figure 2. Three topologies of rectifier: a) series, b) voltage doubler, and c) Greinacher.**

the series topology and helps implement cold/hot start of the subsequent DC-DC boost devices, so that it gets the sensitivity of minimum input RF power and the voltage doubler's diode number is just two. Based on these discussions, the voltage doubler topology is selected.

3 Dual-Band RF Harvester Design and Simulations

The ultra-low power high-efficiency UHF-band wireless energy harvesting circuit (**Fig. 3**) consists of five major parts: diplexer, matching networks, rectifiers, BQ25570 and its peripheral circuit diagram, and super capacitor.

3.1 Diplexer Design

The diplexer consists of a high-pass filter and a low-pass filter and is located between the antenna and the matching network. The ambient RF energy is divided into two parts, respectively located in the GSM900MHz and GSM1800MHz bands after RF energy through the diplexer. Since this novel design will not reduce the incident energy of each branch, it can improve the RF-to-DC conversion efficiency and output voltage.

This diplexer circuit is to divide the GSM900/GSM1800 signal energy collected by antenna into two branches: the 870–960 MHz output connected to the GSM900 rectifier circuit and the 1710–1860 MHz output connected to the GSM1800 RF-DC rectifier circuit. The input and output impedance of the diplexer is matched to 50 Ω.

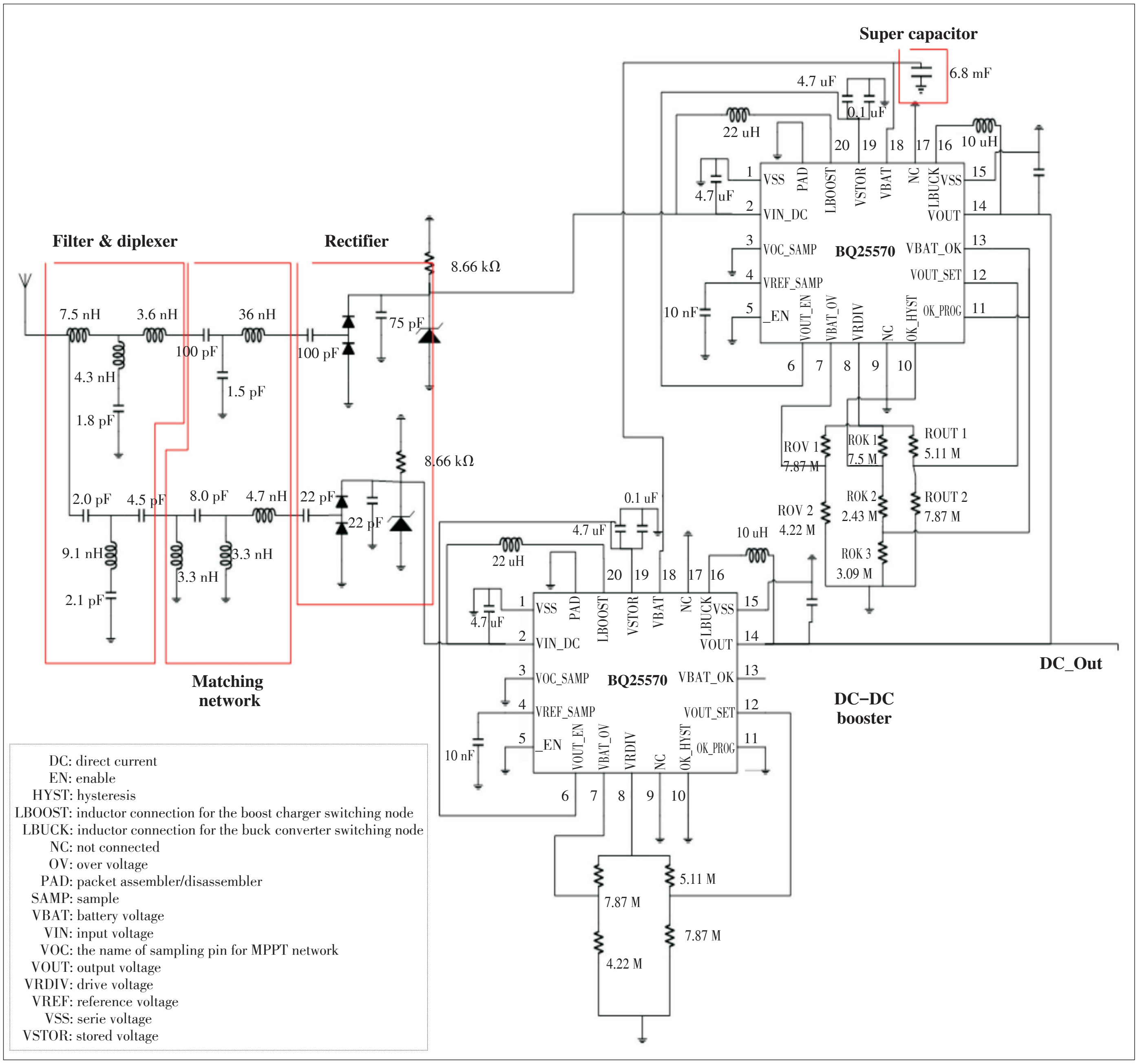
3.2 Diplexer Simulation Setup in ADS

The diplexer was simulated using the Advanced Design System (ADS) software from Agilent Technologies.

The return loss of the diplexer circuit's RF input port is larger than 18 dB in the 100–3000 MHz band, larger than 22 dB in the GSM900 band, and larger than 18 dB in the GSM1800 band. Furthermore, the return loss of the RF output port (GSM900 band) is larger than 20 dB, while the insertion loss of the input port and the RF output port (GSM900 band) is less than 0.3 dB. The return loss of the RF output port (GSM1800 band) is larger than 17 dB, while the insertion loss of the input port and the RF output port (GSM1800 band) is less than 0.3 dB. Finally, the minimum isolation between RF GSM900 output port and GSM1800 output port is greater than 8 dB (1100–1500 MHz).

3.3 Matching Network Design

We next focus on the design of the matching network. Thanks to the maximum power transfer theory, the highest power can be transferred to the load if the source and load complex impedances are complex conjugates. This is achieved by means of an impedance matching network placed between the diplexer and the rectifier. Whenever a source or a load has a reactive component, the adaptation depends on the frequency



▲**Figure 3. Wireless energy harvesting circuit schematic diagram.**

for which it is designed. The most frequently used matching networks are the L-type, the Π-type and the T-type networks [14]. With the aid of ADS, we get the T-type matching network for GSM900 and the Π-type matching network for GSM1800, and the specific parameters are shown in Fig. 3.

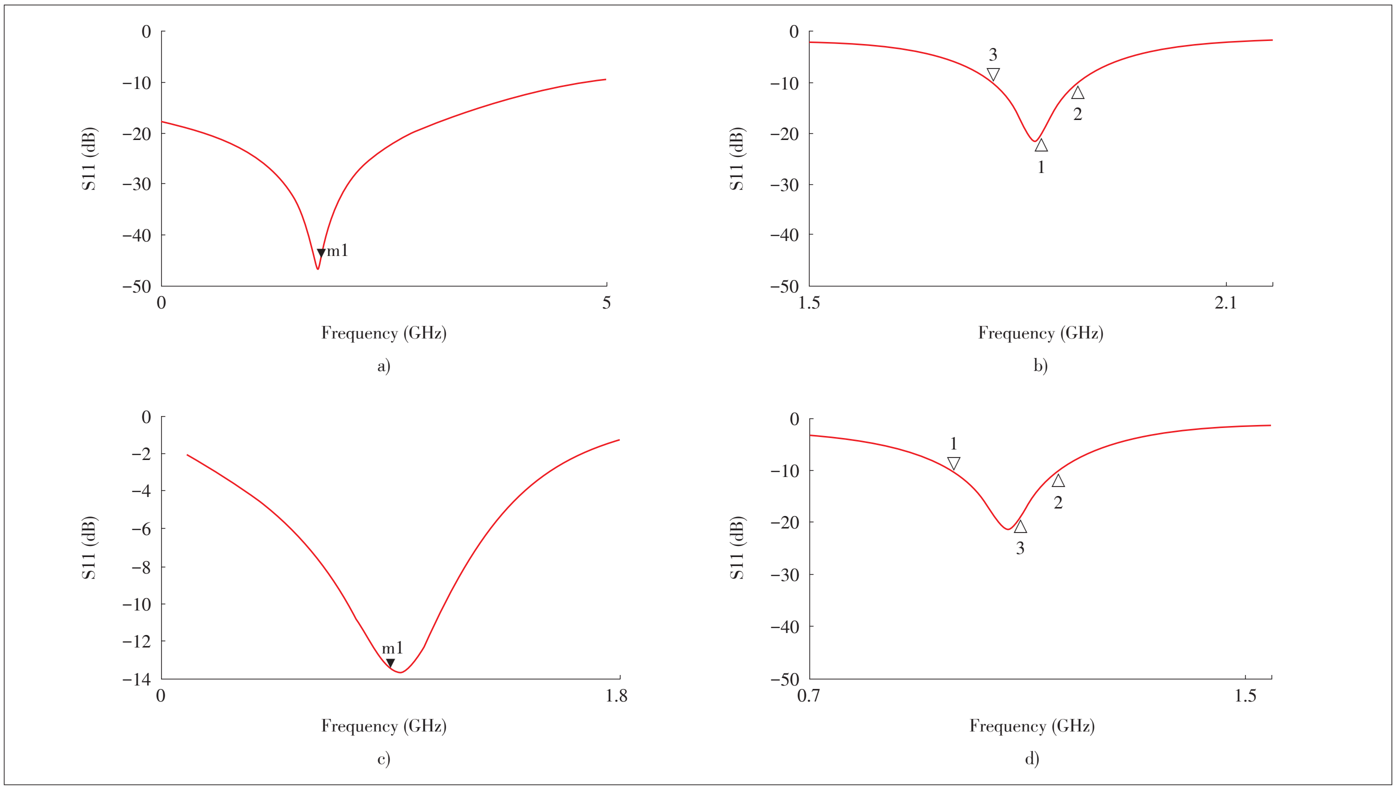
3.4 Matching Network Simulation Setup in ADS

These matching networks were simulated by ADS and the simulation results are shown in **Fig. 4**.

Based on the simulation results, the return loss (S11) of the GSM1800 matching network and that of the GSM900 matching network are larger than 13 dB in the GSM900/GSM1800 band.

3.5 Dual-Band RF Harvester Design

In order to obtain higher rectification efficiency from low power incident RF sources, we choose one-stage voltage doubler rectifier circuits. The overall design of the dual-band RF harvester is shown in Fig. 3. At the end of the rectifier in the figure, a Zener diode is connected parallel to limit the voltage for protecting the follow-up circuit. Finally, the end of the circuit is an 8.66 kΩ load. We must point out that the resistance is only required under the test environment and it is not includ-



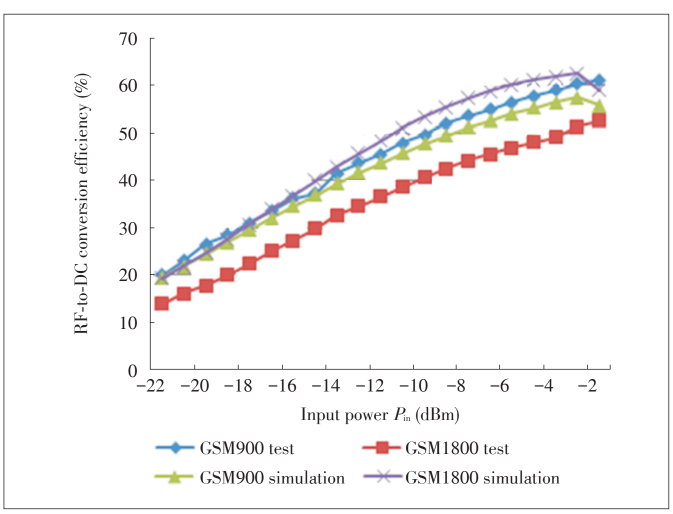
▲Figure 4. a) The simulation results of GSM1800 matching network; b) the test results of GSM1800 matching network; c) the simulation results of GSM900 matching network; d) the test results of GSM900 matching network.

ed in the actual tag.

3.6 Dual-Band RF Harvester Simulation Setup in ADS

The dual-band RF harvester was simulated by the ADS. In the cases of different incident power levels with the same frequency and different frequencies with the same incident power, the RF-to-DC conversion efficiency was simulated (**Fig. 5**).

Based on the simulation results, when the RF incident power is greater than - 14 dBm, the DC output voltage of GSM900MHz rectifier circuit in the 850–950 MHz bandwidth is greater than 0.365 V, and the efficiency is higher than 39%. This voltage meets energy management circuit BQ25570's cold start condition. The DC output voltage of GSM1800MHz rectifier circuit in the 1800–1860 MHz bandwidth is greater than 0.370 V, and the efficiency is higher than 40%. This voltage also meets energy management circuit BQ25570's cold start condition.



▲Figure 5. The RF-to-DC conversion efficiency of the GSM900/GSM1800 branch varies with the input power.

3.7 DC-DC Boost and Energy Management Circuit

The DC-DC boost and energy management circuit use two BQ25570s as core components, and the input ports are connected to the output of GSM900 rectifier circuit and the output of GSM1800 rectifier circuit, respectively. The output is the power supply for other chips. These two BQ25570s' pin VBATs are connected in parallel to a 6.8 mF super capacitor.

To prevent rechargeable batteries from being exposed to excessive charging voltages and to prevent overcharging a capacitive storage element, the over-voltage (*VBAT_OV*) threshold level can be set based on (1) using two external resistors (R_{OV1}, R_{OV2}), where *VBIAS*=1.21 V.

$$VBAT\_OV = \frac{3}{2} VBIAS\left(1 + \frac{R_{ov2}}{R_{ov1}}\right). \quad (1)$$

Battery voltage within operating range (VBAT_OK Output) can be set based on (2) and (3) through external three resistors (R_{OK1}, R_{OK2}, R_{OK3}).

$$VBAT\_OK\_PROG = VBIAS\left(1 + \frac{R_{OK2}}{R_{OK1}}\right), \tag{2}$$

$$VBAT\_OK\_HYST = VBIAS\left(1 + \frac{R_{OK1} + R_{OK2}}{R_{OK1}}\right). \tag{3}$$

The OUT regulation voltage (V_{OUT}) is then given by (4):

$$V_{OUT} = VBIAS\left(\frac{R_{OUT2} + R_{OUT1}}{R_{OUT1}}\right). \tag{4}$$

The V_{OUT} output pin can be used directly as the supply voltage for other chips without the aid of low dropout regulator (LDO).

4 Dual-Band RF Harvester Experiments and Measurements

To validate the approach described in the previous section, the following experiments were performed.

4.1 Diplexer Measurements

The diplexer was tested using the vector network analyzer. The diplexer has three ports, one input port and two output ports. We used a vector network analyzer and a 50 Ω load to experiment.

The return loss of the diplexer circuit's RF input port is larger than 7 dB in the 600–24,000 MHz band, larger than 34 dB in the GSM900 band, and larger than 16 dB in the GSM1800 band. Furthermore, the return loss of the RF output port (GSM900 band) is larger than 5 dB, while the insertion loss of the input port and the RF output port (GSM900 band) is less than 0.7 dB. The return loss of the RF output port (GSM1800 band) is larger than 20 dB, while the insertion loss of the input port and the RF output port (GSM1800 band) is less than 0.8 dB. Finally, the minimum isolation between RF GSM900 output port and GSM1800 output port is greater than 16 dB (1100–1500 MHz). The comparisons between simulations and test results indicate that these test results can validate the simulation values.

4.2 Matching Network Measurements

The matching network was tested using the same vector network analyzer. The front end of the matching network was connected to the vector network analyzer, and the back end of the matching network was connected to the rectifier circuit and the load. Therefore, S11 represents the degree of matching. Fig. 4 shows the test results.

Based on the test results, S11 of the GSM1800 matching network and that of the GSM900 matching network are larger than 13 dB in the GSM900/GSM1800 band.

4.3 Dual-Band RF-DC Rectifier Circuit Measurements

Then, we tested the ultra-low power high-efficiency UHF-band wireless energy harvesting circuit's RF-to-DC conversion efficiency. The test contained three parts: a) The GSM900 branch test, b) the GSM1800 branch test, and c) the GSM900+GSM1800 combined test.

First of all, we tested the RF-to-DC conversion efficiency of the GSM900 branch. The test system is built as shown in **Fig. 6b**. We connected the signal source directly to the input port of the GSM900's matching circuit, and then used the multimeter to observe the voltage on the load which was connected at the end of the GSM900 branch to calculate the RF-to-DC conversion efficiency.

In the GSM900 branch rectifier circuit, it could be seen that the RF-to-DC conversion efficiency reached 40.5% when the input power was −14 dBm, and the voltage across the load was 375 mV. This voltage meets BQ25570's cold start condition. In the case that the input power was 1 dBm, the RF-to-DC conversion efficiency reached 63.2%, while in the case that the low input power was −22 dBm, the RF-to-DC conversion efficiency reached 20%. Fig. 5 shows that the RF-to-DC conversion efficiency of the GSM900 branch varies with different input power.

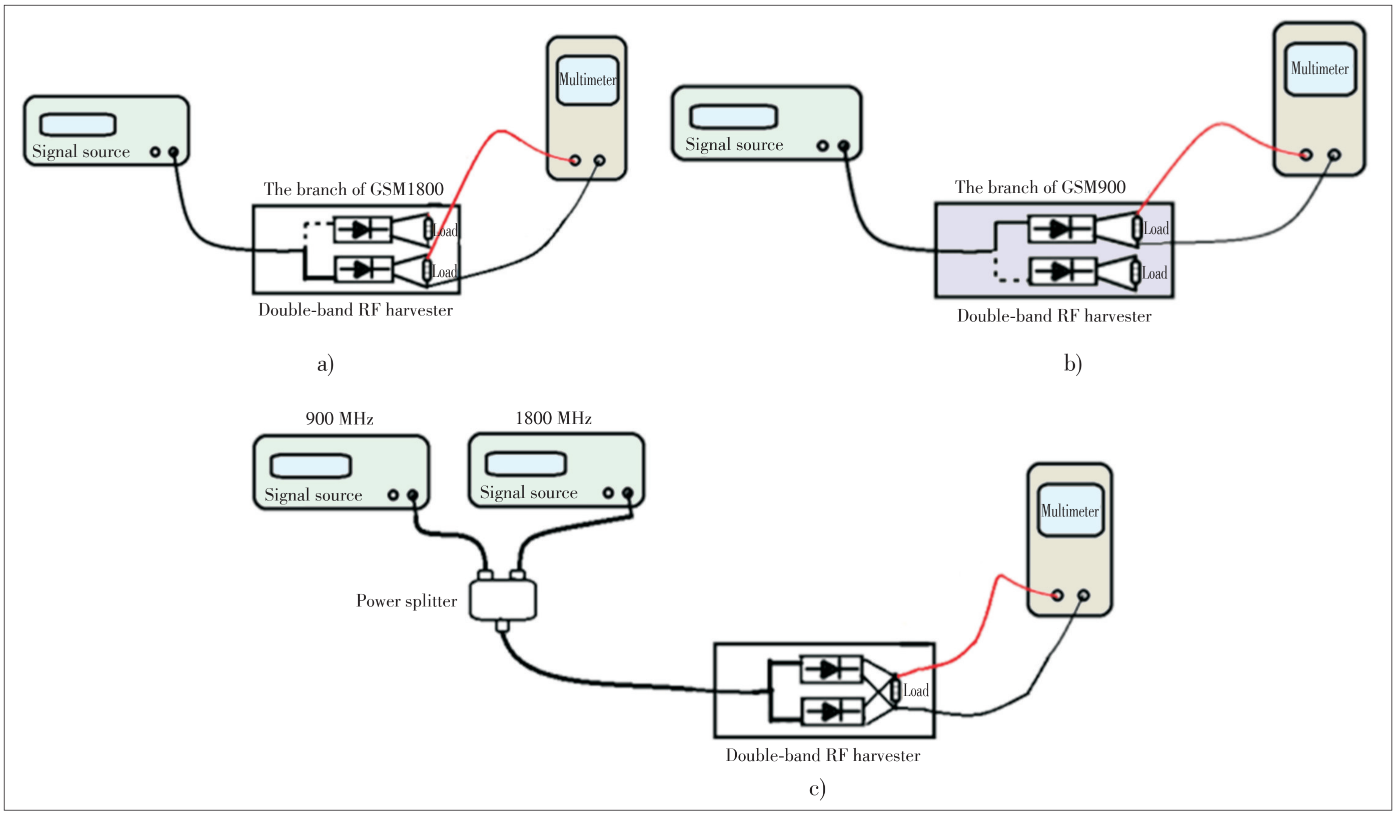
The RF-to-DC conversion efficiency of the GSM900 branch varies with the frequency of the GSM900 band. When the frequency is 880 MHz, the RF-to-DC conversion efficiency of GSM900 is the highest which reaches to 41%.

Then, we tested the RF-to-DC conversion efficiency of the GSM1800 branch. The test system is built as shown in **Fig. 6a**. We connected the signal source directly to the input port of the GSM1800's matching circuit, and then used the multimeter to observe the voltage on the load which was connected at the end of the GSM1800 branch to calculate the RF-to-DC conversion efficiency.

Based on the test results, on the GSM1800 branch rectifier circuit, when the input power was -14 dBm, the RF-to-DC conversion efficiency reached 32.6%, and the voltage across the load was 335.7 mV. This voltage meets BQ25570's cold start condition. When the input power was 3 dBm, the RF-to-DC conversion efficiency reached 55.5%, and when the input power is -22 dBm, the RF-to-DC conversion efficiency reached 13.8%. Fig. 5 shows the RF-to-DC conversion efficiency of the GSM1800 branch varies with different input power.

The RF-to-DC conversion efficiency of the GSM1800 branch varies also with the frequency of the GSM1800 band, in the case that the input power is -14 dBm. When the frequency is 1770 MHz, the RF-to-DC conversion efficiency of GSM1800is the highest that reaches to 33.3%.

Finally, we tested the RF-to-DC conversion efficiency of the combined GSM900 and GSM1800 branches. The test system is



▲**Figure 6. a) The test system of GSM1800, b) the test system of GSM900, and c) the test system of GSM900+GSM1800.**

built as shown in Fig. 6c. We connected two signal sources and a power splitter to the input port of the diplexer, and then used the multimeter to observe the voltage on load.

Based on test results, in the case that both two input powers are -14 dBm (Double -14 dBm input powers equal to -11 dBm), the RF-to-DC conversion efficiency reaches 29.5%, due to the insertion loss of the diplexer. The voltage across the load is 451 mV, and this voltage meets BQ25570's cold start condition. In the case that the input power is 0 dBm, the RF-to-DC conversion efficiency reaches 42.7%, and in the case that the input power is -22 dBm, the RF-to-DC conversion efficiency reaches 11.7%.

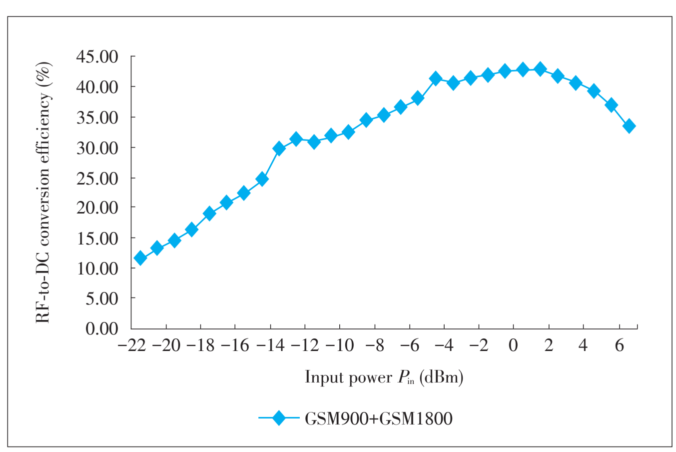
Fig. 7 shows the RF-to-DC conversion efficiency of the combined GSM1800 and GSM900 branches varies with the changes of the input power.

The test results of RF-to-DC conversion efficiency of GSM900/GSM1800 which varies with the input power are basically the same as the simulation results with small difference. In the branch of GSM900 and that of GSM1800, the average difference between test results and simulation results is only 1.7% and 11.4% respectively. The test results of RF-to-DC conversion efficiency GSM900/GSM1800 which varies with frequency are also basically the same as the simulation results with small difference. In the branch of GSM900 and that of GSM1800, the average difference between test results and simulation results is only 5.46% and 11.46% respectively. The average difference of the branch of GSM1800 is large, but it is still in the acceptable range.

4.4 Analysis of Cold and Hot Start of BQ25570 Chip

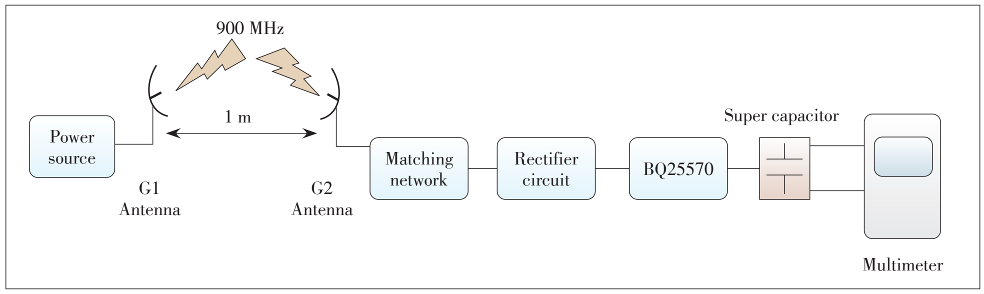
The DC-DC boost and energy management circuits used two BQ25570 as core components, and the input were connected to the output of GSM900 rectifier circuit and the output of GSM1800 rectifier circuit respectively.

The BQ25570 device is specifically designed to efficiently extract microwatts (μW) to milliwatts (mW) of power generated



▲**Figure 7. The RF-to-DC conversion efficiency of GSM900+GSM1800 varies with the input power.**

from a variety of high output impedance DC sources. The boost charger can effectively extract power from low voltage output harvesters, such as our dual-band RF-DC rectifier circuit. The outputting voltages of harvesters go down to VIN(DC) (100 mV minimum), so it can be hot start. When starting from the voltage of the super capacitor < 100 mV, the cold start circuit needs at least VIN(CS), 330 mV typical to charge.



▲Figure 8. The prototype photograph of the test system.

The BQ25570 chip's DC input impedance is 8.66 kΩ which was simulated at the end of the rectifier circuit. Based on the test results of the rectifier circuit, in the case that the input power is greater than or equal to -14 dBm, the output of the GSM900/GSM1800 rectifier circuit can provide a voltage greater than 330 mV (GSM900: 375mV and GSM1800: 335mV) to cold and hot start BQ25570 chip.

4.5 Wireless Energy Charging Experiments

In order to verify the wireless charging performance of double-band RF harvester, we organized this wireless energy charging experiment. We used the method of wireless charging to charge the super capacitor on the dual-band RF harvester. The experimental system is built as shown in **Fig. 8**.

We used the R2000 reader as the power source, and connected the coaxial cable to the R2000 reader and transmitter antenna. The transmit power of R2000 reader was 30 dBm, and the gain of the transmitter antenna was 12 dBic. The receiving antenna which gain was 8 dBic was one meter away from transmitter antenna. As the reader was sending GSM900 band signal, we used the GSM900 branch rectifier circuit to charge the super capacitor. Due to the insertion loss, the diplexer was abandoned. Finally, we used the multimeter to observe the voltage in the super capacitor.

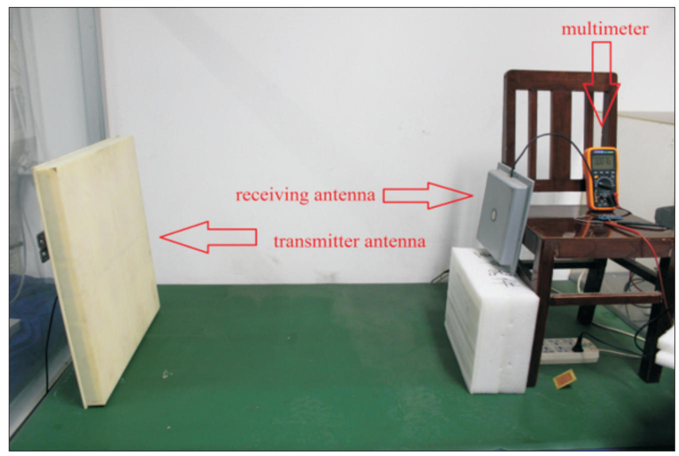
According to the Friss formula (electromagnetic wave propagation), we can calculate the power intensity at the front end of the rectifier circuit as follows.

$$Pe = P_1 + G_1 + G_2 + G_3 + 10\lg\left(\frac{\lambda}{4\pi r_1}\right)^2, \tag{5}$$

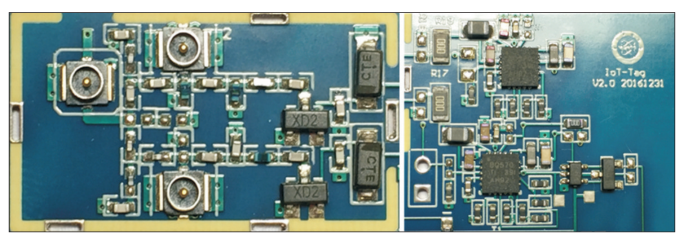
where Pe is the power intensity at the front end of the rectifier circuit, P_1 is the transmit power of R2000 reader, G_1 is gain of the transmitter antenna, G_2 is gain of the receiving antenna, G_3 is the loss of pipelines (-2 dB), r_1 is distance between two antennas, and f is 900 MHz, which is used to calculate the wavelength λ. According to this formula, the Pe is 16.47 dBm.

The experimental system is built as shown in **Figs. 9** and **10**.

Based on the test results, the super capacitor was filled to the set voltage value 4.2 V in 24 seconds. This wireless energy charging experiment proves that our UHF-band wireless energy harvesting circuit can harvest wirelessly GSM900 energy and charge for supercapacitor.



▲Figure 9. The prototype photograph of the test system.



▲Figure 10. The prototype photograph of the dual-band RF harvester.

5 Conclusions

An ultra-low power high-efficiency UHF-band wireless energy harvesting circuit was designed for harvesting RF energy in the GSM900 and GSM1800 bands. This harvester features an RF-to-DC conversion efficiency in the range of 20%–63.2% for an available input power of −22 dBm to 1 dBm in the GSM900 band, and that in the range of 13.8%–55.5% for an available input power of −22 dBm to 3 dBm in the GSM1800 band. This harvester can charge the super capacitor through the energy management circuit BQ25570 in case of the input power greater than or equal to -14 dBm. Through the wireless energy charging experiments, we confirmed that this harvester could use just 24 seconds to fill the super capacitor. This ultra-low power high-efficiency UHF-band wireless energy harvesting circuit has wide application prospect. For example, it can power small sensor systems, such as the wireless sensor network (WSN) nodes.

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