A Novel High-Sensitivity Broadband Rectifier for Ambient RF Energy Harvesting

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Abstract. In this paper, a novel high-sensitivity broadband rectifier is proposed aiming at ambient radio frequency (RF) energy harvesting. Traditionally, voltage doubling rectifying circuit is used to design high-sensitivity rectifier. But when the input power is lower, the rectifying efficiency is significantly reduced. Therefore, an improved parallel half-wave rectifying circuit is proposed in this article which can convert RF energy in the whole period. And the proposed rectifying circuit can work better in lower power environment and has a higher efficiency level. Besides, the impedance match is also important component of rectifier. Due to the nonlinearity and complexity of rectifying circuit, achieving wideband matching network is a challenge. Thus, a design approach of broadband impedance circuit is given in this study. Combining with the proposed high-sensitivity rectifying circuit, a high-sensitivity wideband rectifier can be generated, when the input power is –15 dBm, –20 dBm, –25 dBm, the efficiency is 43%, 32%, 20%, respectively. Finally, a second-order wideband rectifier with high sensitivity is realized, and the range of bandwidth can cover four main frequency bands of GSM 900 MHz, GSM 1800 MHz, UMTS 2100 MHz, WLAN 2400 MHz. To verify the validity, the rectifier is fabricated and measured, and the measurement has a good agreement with simulation results.

Keywords
High-sensitivity, broadband rectifier, RF energy harvesting

1. Introduction

As the development of Internet, there are existing many wireless sensor nodes around environment. How to supply power to these sensor nodes, is the main problem facing now. Traditionally, the battery is regarded as power supply for nodes, but the operating cost of this method is much higher and it is not convenient to replace the battery in some dangerous or remote place. As the rapid growth of communication industry, the RF energy around environ-
energy harvesting is generated, and the six-band rectifier is achieved by using improved impedance matching circuit with three paralleling branches. But the efficiency is still lower. As for wideband rectifier [14–19], it can harvest more energy in a wide range of frequency band, but it is always challenging. In [16], a novel ultrawideband rectenna is presented by using hybrid resistance compression technology to improve the impedance matching performance over a wide frequency range, which has high rectifying efficiency from 450 MHz to 900 MHz. In [17], an impedance matching network with additional quarter wavelength shorting was designed to achieve broadband impedance matching of the rectifier. The efficiency is above 50% when the input power is in the range of 3–15 dBm. In [18], a new broadband rectenna for ambient energy harvesting is realized, and a novel two-branch impedance matching circuit is introduced to enhance the characteristic of bandwidth and efficiency. When the input power is –10 dBm, the efficiency can reach 55%. But the rectifying efficiency is still a little lower at a relatively lower ambient input power level.

Therefore, this paper presents an improved parallel half-wave rectifying circuit which has higher rectifying efficiency at lower input power level. Basing on the proposed high-sensitivity rectifying circuit, a design method of broadband impedance circuit is also presented. In conclusion, a high-sensitivity broadband rectifier can be achieved by combining the high-sensitivity rectifying circuit with wideband impedance matching circuit. Firstly, this article generates a high-sensitivity broadband rectifier operating form 1.9 GHz to 2.5 GHz. Then, a dual-band rectifier working at GSM 900 and GSM 1800 is introduced. Finally, basing on the above two rectifiers, a new rectifier topology is proposed, which can cover four major frequency bands of GSM 900 MHz, GSM 1800 MHz, UMTS 2100 MHz and WLAN 2400 MHz.

2. Rectifier Design and Analysis

2.1 High-Sensitivity Rectifying Circuit

Usually, the voltage doubling rectifying circuit is utilized to design high-sensitivity rectifier at low input power level. But the rectifying efficiency is not enough for ambient RF energy harvesting, hence, this paper proposes an improved parallel half-wave rectifying circuit which has higher efficiency under low power. The rectifying circuit is presented in Fig. 1.

In Fig. 1(a), the improved rectifying circuit consists of series inductance \( L_0 \), shunt capacitor \( C_0 \), shunt diode \( D_1 \) (SMS 7630-079) and series capacitor \( C_1 \). The load resistance is chosen as 2700 \( \Omega \), \( L_0 = 10.7 \) nH, \( C_0 = 1000 \) nF, \( C_1 = 520 \) nF. \( Z_1 \) and \( Z_2 \) are the input impedance from A to Path 1 and Path 2, respectively. Comparing with voltage doubling rectifying circuit, the improved rectifying circuit uses one diode only, which consumes lesser energy when the input power is lower. The fundamental theory is as follows:

When the first positive half period of signal comes, the diode \( D_1 \) is cut-off, the signal reaches the \( V_{out} \) port through Path 1. When the first minus half period comes, the diode is turn on. Because the impedance value from A to Path 1 is more than the impedance value from A to Path 2, the signal is preferring to getting through Path 2, and the energy is stored in capacitor \( C_1 \). When the second positive half period comes, the diode is cut-off, the energy lying in the first minus half period and the second positive half period reaches the \( V_{out} \) port together through Path 1. In a word, the improved rectifying circuit can also operate at the whole period. Table 1 demonstrates the impedance value of \( Z_1 \) and \( Z_2 \) when the input power is –20 dBm.

In order to verify this idea, an improved rectifying circuit and a voltage doubling rectifying circuit are designed, and the comparing result is given in Fig. 2 at –20 dBm input power level.

In Fig. 2, the result shows that the return losses between voltage doubling and improved rectifying circuit are nearly same, and even the return loss of voltage doubler is even better comparing with the improved rectifying circuit, but the efficiency of improved rectifying circuit is much higher than voltage doubler. Hence, the improved rectifying circuit has higher efficiency at a low ambient power level.

<table>
<thead>
<tr>
<th>( f ) (GHz)</th>
<th>( Z_1 )</th>
<th>( Z_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>1.258E3/–82.341</td>
<td>77.144/–42.252</td>
</tr>
<tr>
<td>1.9</td>
<td>681.733/–85.440</td>
<td>73.482/–27.490</td>
</tr>
<tr>
<td>2.0</td>
<td>467.785/–86.495</td>
<td>76.264/–13.325</td>
</tr>
<tr>
<td>2.1</td>
<td>355.061/–86.960</td>
<td>83.806/–1.571</td>
</tr>
<tr>
<td>2.2</td>
<td>284.511/–87.152</td>
<td>96.035/7.362</td>
</tr>
<tr>
<td>2.3</td>
<td>235.369/–87.171</td>
<td>114.105/13.618</td>
</tr>
<tr>
<td>2.4</td>
<td>198.394/–87.042</td>
<td>139.163/16.974</td>
</tr>
<tr>
<td>2.5</td>
<td>168.772/–86.747</td>
<td>173.683/17.134</td>
</tr>
</tbody>
</table>

Tab. 1. The \( Z_1 \) and \( Z_2 \) change with frequency (unit: \( \Omega \)).
2.2 Wideband Impedance Matching Circuit

Due to the nonlinearity and complexity of the rectifying circuit, an impedance matching circuit is required to connect the front-end antenna with back-end rectifying circuit. In this text, a design method of wideband impedance matching circuit is introduced, and combining with the above high-sensitivity rectifying circuit, a novel high-sensitivity broadband rectifier can be achieved. Firstly, a second order dual-frequency matching technology for complex impedances is introduced [20], and the structure diagram is displayed in Fig. 3 where Z1 and Z2 are the characteristic impedance, $\theta_1$ and $\theta_2$ are electrical length, $Z_0$ is source impedance, $Z_L$ is load impedance, $Z_{in}$ and $Z_{L2}$ are input impedance.

According to the theory of transmission line, the input impedance can be expressed:

$$Z_m = Z_1 + jZ_t \tan (\theta_1),$$

$$Z_{L2} = Z_2 + jZ_t \tan (\theta_2).$$

In order to maximize the transfer of energy, a conjugacy relation can be written:

$$Z_m = Z_0 = R_0 - jX_0.$$

Combining with (3), equation (1) can be written as:

$$Z_{L2} = Z_2 + jZ_t \tan (\theta_2).$$

Because $Z_L = R_L + jX_L$, combining equation (2) with (4):

$$Z^2_2 \frac{R_2 + jX_2 + jZ_t \tan (\theta_2)}{Z^2_2 + j(R_2 + X_2) \tan (\theta_2)} = Z_2 + j(R_2 + jX_2) \tan (\theta_2).$$

Expanding equation (5) and separating the real part and imaginary part:

$$\left(R_2 Z_2^2 - R_0 Z_0^2 \right) \tan (\theta_2) = Z_2 Z_0 (R_2 - R_0) + [Z_2 \tan (\theta_2)] \times (R_0 X_2 - R_2 X_0),$$

$$Z_2 Z_0^2 \tan (\theta_2) = Z_2 Z_0 \tan (\theta_2) = Z_0 Z_2 \tan (\theta_2).$$

To meet equation (6) at $f_1$ and $f_2$, the following equations can be obtained where the $l_1$ and $l_2$ are the physical length of microstrip line $Z1$ and $Z2$, $f_2 = m f_1$, $m > 1$, $\beta = 2 \pi / \lambda_i$.

$$\left(R_2 Z_2^2 - R_0 Z_0^2 \right) \tan (\beta l_1) \tan (\beta l_2) = Z_2 Z_0 (R_2 - R_0) + [Z_2 \tan (\beta l_2)] \times (R_0 X_2 - R_2 X_0),$$

$$Z_2 Z_0^2 \tan (\beta l_1) = Z_2 Z_0 \tan (\beta l_1) = Z_0 Z_2 \tan (\beta l_2).$$

From (7), we can know that equations have four variables of $Z_1$, $Z_2$, $\beta_1$, $\beta_2$, and $R_0$, $R_L$, $X_0$, $X_L$, $m$ are known. But equation (7) is nonlinear, it can’t get the analytical solution well unless $X_0 = 0$, $X_1 = 0$ [19–21]. Of course,
an approximate numerical solution can be realized, as follows:

Basing on [21], the initial values can be obtained:

\[ I_{1s} = I_{2s} = \frac{\lambda_1}{2(1 + m)}, \quad (8.a) \]

\[ Z_{1s} = \sqrt{\frac{R_0(R_L - R_0)}{2\tan^2\left(\frac{\pi}{1+m}\right)} + \frac{R_0(R_L - R_0)}{2\tan^2\left(\frac{\pi}{1+m}\right)}} + R_0^2R_L, \quad (8.b) \]

\[ Z_{2s} = \frac{R_1R_0}{Z_{1s}}. \quad (8.c) \]

Supposing \( Z_{L2} \) has a conjugate relation between \( f_1 \) and \( f_2 \):

\[ Z_{L2} / f_1 = \text{conj}(Z_{L2} / f_2) = R_{L2} + jX_{L2} \quad (9) \]

where the \( \text{conj}(\cdot) \) is conjugate function.

Combining with (9), the other equations can be deduced from (7). Referring to [22–25], we can obtain:

\[ Z_1 = \sqrt{R_0R_{L1} + \frac{X_0^2R_{L1} - X_{L1}^2R_0}{R_0 - R_{L1}}}, \quad (10.a) \]

\[ Z_2 = \sqrt{R_1R_{L1} + \frac{X_1^2R_{L1} - X_{L1}^2R_1}{R_1 - R_{L1}}}, \quad (10.b) \]

\[ \tan(\beta l_1) = \frac{Z_1(R_0 - R_{L1})}{R_0X_{L1} - R_{L1}X_0}, \quad (10.c) \]

\[ \tan(\beta l_2) = \frac{Z_2(R_{L2} - R_1)}{R_1X_{L1} + R_{L2}X_{L1}}, \quad (10.d) \]

\[ \tan(m\beta l_1) = \frac{Z_1(R_{L1} - R_0)}{R_0X_{L1} + R_{L1}X_0}, \quad (10.e) \]

\[ \tan(m\beta l_2) = \frac{Z_2(R_{L2} - R_1)}{R_1X_{L1} + R_{L1}X_{L1}}. \quad (10.f) \]

Considering \( Z_1 > 0, \ Z_2 > 0 \), equation (10) can be simplified to two nonlinear equations:

\[ m \arctan \left[ \frac{Z_1(R_0 - R_{L1})}{R_0X_{L1} - R_{L1}X_0} \right] = \arctan \left[ \frac{Z_1(R_{L1} - R_0)}{R_0X_{L1} + R_{L1}X_0} \right] + \pi, \quad (11.a) \]

\[ m \arctan \left[ \frac{Z_2(R_{L2} - R_1)}{R_{L2}X_{L1} + R_1X_{L1}} \right] = \arctan \left[ \frac{Z_2(R_1 - R_{L2})}{R_{L2}X_{L1} - R_1X_{L1}} \right] + \pi, \quad (11.b) \]

where \( Z_1 \) and \( Z_2 \) can be expressed by \( R_{L1} \) and \( X_{L1} \), equations (11) only have two variables. The solution of (11) is similar to (7). Firstly, basing on (8) and (2), the initial values of \( R_{L1}, X_{L1} \) can be obtained. Secondly, put the initial values of \( R_{L1}, X_{L1} \) into (10), the initial values of \( Z_1, Z_2 \) can be gained. Then, put the initial values of \( Z_1, Z_2 \) into (11), the values of \( R_{L1}, X_{L1} \) can be realized. Finally, combining with (10), we can get the values of \( Z_1, Z_2, \beta l_1, \beta l_2 \). So far, the microstrip line parameter can be determined.

But the dual-band technology only achieves the impedance match at \( f_1 \) and \( f_2 \), therefore, optimization and adjustment are required. In this paper, the resonant inductance and impedance translation unit (ITU) are introduced to let the real part of \( Z_0 \) remain stable and let imaginary part of \( Z_0 \) remain odd-symmetrical about center frequency \( f_0 \) in an expected band, then, a wideband match can be realized by choosing two suitable frequencies of \( f_1 \) and \( f_2 \). The structure diagram is shown in Fig. 4 where \( L1 \) is the resonant inductance, \( D \) is the Schottky diode, \( Z_L \) is the input impedance of the rectifying circuit.

The resonant inductance is introduced to let the intrinsic resonant frequency of the diode move to low frequency, and choosing suitable inductance value by sweeping parameter. The sweeping results are given in Fig. 5.

From Fig. 5, it is shown that when the inductance value is \( 51 \) nH, the real part and imaginary part of \( Z_L \) change gently in target bands. Usually, the resonant inductance is transformed into a short stub and there is a relationship as follows [26]:

\[ I = \frac{11.81L}{Z_0\sqrt{\varepsilon_r}} \quad (12) \]

where \( L \) is the inductance value (unit: nH), and \( l \) is the physical length of microstrip line (unit: inch).

The ITU is utilized to make the real part of \( Z_0 \) remain stable and make the imaginary part of \( Z_0 \) remain odd-symmetrical about the center frequency. The transformed result is demonstrated in Fig. 6.

In Fig. 6, it is shown that the real part is stable and the imaginary part is odd-symmetrical about 2.2 GHz from 1.8 GHz to 2.6 GHz. Two frequencies of \( f_1 \) and \( f_2 \) can be chosen, then, a wideband impedance match can be achieved by coupling between passbands.
2.3 High-Sensitivity Broadband Rectifier

Combining with the above high-sensitivity rectifying circuit and broadband impedance matching circuit, a high-sensitivity broadband rectifier can be achieved. To verify this approach, the high-sensitivity broadband rectifier is simulated and implemented on a 1.575 mm-thick Rogers RO5880 substrate which has a loss tangent of 0.0009 and relative dielectric constant $\varepsilon_r$ of 2.2. According to previous section, the parameter values of $Z_1$, $Z_2$, $\beta_{l1}$, $\beta_{l2}$ can be calculated as follows:

Firstly, some parameter values can be determined: $f_1 = 2.0$ GHz, $f_2 = 2.4$ GHz, $f_0 = 2.2$ GHz, $m = 2.4/2 = 1.2$, $\lambda_1 = 109.2$ mm. Usually, in front of the rectifier, a receiving antenna is utilized to harvest ambient RF energy, therefore, $Z_0 = 50$ $\Omega$, $R_0 = 50$, $X_0 = 0$. The $Z_L$ can be ensured by choosing several impedance points from 1.9 GHz to 2.5 GHz. From Fig. 6, we can know that these impedance values are $40.3 - j79$, $34.7 - j51.3$, $31.6 - j28.7$, $30.6 - j9$, $30.9 + j10.7$, $31.8 + j31.1$, $35.6 + j55.8$, respectively, and the average value is $33.6 - j10.1$, therefore, $R_L = 33.6$, $X_L = -10.1$.

Combining with (2) and (8), $Z_{l2} = 34.7 + j10.6$, the initial values of $R_{l2}$, $X_{l2}$ are 34.7 and 10.6, respectively. Put the initial values of $R_{l2}$ and $X_{l2}$ into (10), get initial values of $Z_1$, $Z_2$, $\beta_{l1}$, $\beta_{l2}$ can be calculated as:

Finally, put the values of $R_{l2}$ and $X_{l2}$ into (10), considering errors and differences, the parameter values can be calculated as: $Z_1 = 34.9$ $\Omega$, $Z_2 = 38.7$ $\Omega$, $\theta_1 = 247$ deg, $\theta_2 = 89.75$ deg.

In a word, the initial parameters of impedance matching circuit can be obtained according to the above calculation. Combining with the proposed high-sensitivity rectifying circuit, a high-sensitivity broadband rectifier is simulated and optimized in Advanced Design System. The final results are given in Fig. 7.

In Fig. 7, when the input power is $-20$ dBm, the operating bandwidth of rectifier is 1.9 GHz–2.5 GHz and the rectifying efficiency is better than 32%. The layout structure is presented in Fig. 8 and Tab. 2 demonstrates the physical parameter values. Comparing with previous works, the rectifier has higher rectifying efficiency; there is a comparison in Tab. 3.
span of four bands is much larger, it is impractical to design a rectifier operating at 800–2450 MHz. In order to get more energy, this article designs a parallel impedance matching network, and the upper half part is used to harvest the RF energy of 800–960 MHz and 1790–1880 MHz, the lower half part is utilized to harvest the energy of 2100–2170 MHz and 2380–2450 MHz. The impedance matching network of lower half part can use the above matching circuit of 1.9–2.5 GHz, therefore, an impedance matching circuit working at 800–960 MHz and 1790–1880 MHz is required. According to the dual-band matching technology, a dual-band rectifier operating at 900 MHz and 1800 MHz is designed. The design process is similar to the aforementioned rectifier, and the design results are given in Fig. 9.

In Fig. 9, it’s shown that when the input power is –20 dBm, the rectifier operates at 900 MHz and 1800 MHz, and the efficiency is better than 32%.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Input power (dBm)</th>
<th>Operating frequency (GHz)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10]</td>
<td>–15</td>
<td>2.1, 2.45</td>
<td>6%, 16%</td>
</tr>
<tr>
<td>[12]</td>
<td>–20</td>
<td>0.55, 0.75, 0.9</td>
<td>30%, 28%, 32%</td>
</tr>
<tr>
<td>[13]</td>
<td>–20</td>
<td>0.915, 1.8</td>
<td>20%, 20%</td>
</tr>
<tr>
<td>[16]</td>
<td>–20</td>
<td>1.8–2.5</td>
<td>26%</td>
</tr>
<tr>
<td>[17]</td>
<td>–20</td>
<td>0.9, 1.8, 2.05, 2.6</td>
<td>23%, 13%, 11%, 8%</td>
</tr>
<tr>
<td>This work</td>
<td>–20</td>
<td>1.9–2.5</td>
<td>32%</td>
</tr>
</tbody>
</table>

Tab. 3. Comparison between the high-sensitivity broadband rectifier and previous works.

Basing on Sec. 1, there are four main frequency bands around environment: 800–960 MHz, 1790–1880 MHz, 2100–2170 MHz, 2380–2450 MHz. Because the frequency
Combining with the above two rectifiers, a novel topological structure of rectifier is presented in Fig. 10. To verify the structure, the rectifier is simulated and implemented on a 1.575 mm-thick Rogers RO5880 substrate which has a loss tangent of 0.0009 and relative dielectric constant $\varepsilon_r$ of 2.2. The design results are given in Fig. 11, and Figure 12 displays the layout structure, the physical parameter is also presented in Tab. 4.

In Fig. 11, it is shown that when the input power is $-20$ dBm, the rectifier has a high rectifying efficiency about 30% which can cover four major bands of GSM 900 MHz, GSM 1800 MHz, UMTS 2100 MHz, WLAN 2400 MHz.

### 3. Measurement and Analysis

To verify the validity, the rectifier has been fabricated and tested as shown in Fig. 13 and Fig. 14, respectively. Before the test is done, it is necessary to solder the single SMS7630-079, GCM2165C2A561JA16 and GCM21A7U2E102JX01.

In Fig. 14, it is shown that when the input power is $-20$ dBm, the resonant frequency is offset, and the return loss and rectifying efficiency become worse clearly. It is due to the package inductance of diode and the parasitic inductance of soldering electronic elements, which causes the resonant frequency to shift to low frequency. Similarly, the S parameter gets worse because of machining error, soldering SMA, the parasitic resistance of electronic components, which leads to the decline of rectifying efficiency. But it is acceptable in general and the measured efficiency can reach about 20% in four target bands.

### 4. Conclusion

In this letter, a high-sensitivity rectifying circuit is proposed which has higher efficiency in lower power level comparing with traditional voltage doubling circuit. To verify the idea, analysis and comparison are given by a design example, the results show that the improved circuit is better. At the same time, aiming at the target bands, this paper also designs a wideband impedance matching network. Combining with the proposed high-sensitivity rectifying circuit, a high-sensitivity broadband rectifier can be achieved. Comparing with previous works, the rectifier has higher rectifying efficiency under the same lower input power.

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References


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