Compact and Efficient Broadband Rectifier Using T-type Matching Network

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Abstract—In this letter, a multi-octave voltage doubler rectifier using a T-type matching network is demonstrated. The voltage doubler topology is used to flatten the load impedance, which makes it easier to achieve broadband impedance matching. The T-type matching network is used for the broadband input impedance matching. The design procedure of the proposed broadband rectifier is provided and discussed. For validation, a rectifier prototype is fabricated, and the performance is evaluated. The measured results exhibit Power Conversion Efficiency (PCE) of more than 50% over a frequency band of 0.2 to 3.2 GHz at 15 dBm input power and 70% from 1 to 2.7 GHz. Moreover, the peak PCE is 78.2% at 1.9 GHz when the input power is 18 dBm.

Index Terms—Wireless energy harvesting, broadband, microwave rectifier.

I. INTRODUCTION

Wireless energy harvesting (WEH) is a promising technology that can collect the environmental RF energy to power low-power sensors in Wireless Sensor Networks (WSN). It is environmentally friendly by improving energy utilization and replacing the battery. One of the main challenges of WEH is that the radiation sources usually work over a multitude of frequency bands, which makes it difficult for the rectifier to cover all these bands. To address this issue, dual-band and multiband rectifiers were proposed in the previous studies [1]-[4]. These rectifiers only can achieve high power conversion efficiency (PCE) at narrow frequency bands. If the application scenarios change, they may stop operating. Thus, it is desirable to harvest power simultaneously from many frequency bands leading to a large aggregate bandwidth requirement for the rectifier.

The key component for a broadband rectifier design is the broadband impedance matching network (IMN). In order to design the input IMN, it is necessary to get the optimum input impedance of the rectifier, and the source-pull technique was proposed to achieve this goal in [5]. After that, a broadband input IMN is a common approach to obtain broad bandwidth. To this end, some methods were proposed, including maximizing the quality factor of the input IMN [6] and the real frequency technique [7, 8]. Meanwhile, various IMN structures were proposed. Some are based on a distributed-element circuit such as branch-line coupler [9], nonuniform transmission line [10, 11], quarter-wavelength shorted stub [12], double-stub [13], coupled line [14], as well as both open and shorted stubs [15].

The others are based on the lumped-element circuit, which showed the merit of compact size [16, 17]. Although the bandwidth of the rectifiers in those works has been expanded, some frequency bands still cannot be covered. For example, the rectifiers in [5, 6, 14] cannot handle the 2.4 GHz Wi-Fi band, and the rectifier in [9] cannot cover GSM-900, GSM-1800, and UMTS-2100 Bands. On the other hand, some rectifying circuits sacrificed the circuit size to acquire the broadband performance, such as the nonuniform transmission line structure [9].

In this letter, a compact and efficient broadband rectifier using a T-type matching network for WEH is proposed. The input impedance of the voltage doubler configuration is firstly studied. It is found that the input impedance of the voltage doubler is flat and changes slowly, which is very suitable for broadband rectifier design compared with a single diode rectifier. Then the design method for the T-type input matching network is discussed. In our design, the open stub of the T-type IMN is λg/8 which is quite different from that in [18]. To validate the proposed method, a rectifier is designed and fabricated. The measured PCE of the rectifier is higher than 70% from 1 to 2.7 GHz and 50% from 0.2 to 3.2 GHz with a load of 600 Ω. Thus, most radiation sources’ working bands can be covered, including 2.4 GHz WiFi band and full 4G LTE bands using FDD mode. The overall size of the rectifier is 38 mm × 15 mm. The resultant rectifier has the merits of broad bandwidth, compact size and high efficiency.

II. DESIGN AND ANALYSIS OF THE BROADBAND RECTIFIER

![Fig. 1. Schematic of the proposed broadband rectifier.](image)

The block diagram of the proposed broadband rectifier based on the voltage doubler configuration is shown in Fig. 1. It
consists of a DC block capacitor (C₁), a T-type broadband matching network, two Schottky diodes (BAT-1503W) [19], a DC pass filtering capacitor (C₂), and a load (R₀). The voltage doubler-type configuration is chosen here not only to increase the output DC voltage but also to get more easily matched input impedance over a wide bandwidth. The T-type input matching network consists of a L₀/8 open stub (TL₂) and two transmission lines (TL₁ and TL₃). Zᵣ and θᵢ represent the characteristic impedance and electrical length of the th microstrip transmission line, respectively (i = 1, 2, 3).

A. Comparison of the impedance of the single diode rectifier and the voltage doubler

Fig. 2 shows the topologies of the single diode rectifier and the voltage doubler without the input IMN. In Fig. 2, Cₜ = 10 pF, and R₂ = 600 Ω. Both circuits in Fig. 2 were evaluated by ADS harmonic balance, and the simulated input impedance of the circuits is shown in Fig. 3. In the simulation, the input power is chosen to be 15 dBm which is close to the optimum operating point. As shown, the impedance of the voltage doubler circuit is closer to 50 Ω than that of the single diode rectifier below 3 GHz. Meanwhile, it also changes slowly, with the real part ranging between 90 and 132 Ω and the imaginary part ranging between -25 and -60 Ω from 0.2 to 3.2 GHz. For the single diode rectifier, the real part and imaginary part of the input impedance fluctuate a lot. The voltage doubler can be seen as a diode shunt connected with the single diode topology. So, the input impedance would be pulled down to a lower level. The comparison of the input impedance indicates that the voltage doubler circuit would be easier to be matched over a wide bandwidth.

![Fig. 2. Rectifier circuit topologies, (a) single diode rectifier, and (b) voltage doubler.](image)

First, a series transmission line TL₁ transforms the impedance so that the impedance at 0.2 and 3.2 GHz are complex conjugate, as shown in Fig. 4 (b). At the lowest working frequency of 0.2 GHz, the matching circuit is much smaller than the wavelength. So, it only changes the input impedance a little. The characteristic impedance and length of TL₁ can be found by solving the equation

\[ Z_{\text{in}}(fₚ) = \left[ Z_{\text{in}}(fₚ) \right] ', \]

with

\[ Z_{\text{in}}(f) = Z_{i}(f) + jZ_{i}(f)\tan\theta_i(f) \]

where, fₚ = 0.2 GHz, fₚ = 3.2 GHz. And we can get Z₁ = 115 Ω and θ₁ = 80° at 3.2 GHz.

Then, a shunt open stub TL₂ with a length of λₒ/8 at fₚ transforms the impedance at fₚ to the impedance at f₁, and the locus constructs a circle as shown in Fig. 4 (c). Thus, most of the locus is inside the VSWR = 2 circle. The electrical length of TL₂ is about 3° @ f₁ which can be neglected. Thus, the admittance of the open stub at f₁ is given by

\[ Y_{\text{stub}}(f₁) \approx 0. \]

It indicates that the open shunt stub has little effect on the impedance at low frequencies. At fₛ, the admittance of the open stub is

\[ Y_{\text{stub}}(fₛ) = jY_2. \]

According to the requirement Zₐ₁(Zₐ₁(fₛ)) = Zₐ₂(Zₐ₂(fₛ)), we can get

\[ Y_{\text{in}}(fₛ) = Y_{\text{in}}(fₚ) + jY_2. \]

Combining Equations (1) and (5), characteristic admittance of TL₂ can be obtained by

\[ Y_2 = 2B. \]

where B is the susceptance of Yₐ₁(fₛ). Thus, we can calculate Z₂ = 100 Ω.

![Fig. 4. Impedance locus over 0.2-3.2 GHz at different input power levels, (a) Zᵣ, (b) Zₐ₁, (c) Zₐ₂, and (d) Zᵣ.](image)
In the final step, a series transmission line TL3 rotates the impedance locus clockwise. The characteristic impedance and length of TL3 are deliberately tuned to get the optimum values which guarantee that a long and continuous impedance locus is inside the VSWR = 2 circle. We can get Z3 = 80 Ω and θ3 = 60° @ f2. The DC block capacitor C1 allows the RF signal to pass and has little influence on the rectifier’s high-frequency performance. Fig. 4(d) shows the input impedance of the final circuit.

III. IMPLEMENTATION AND MEASUREMENT RESULTS

To verify the design concept, the proposed broadband rectifier is fabricated and measured. The substrate employed in the design is 0.8 mm F4B (relative dielectric constant = 2.6, and loss tangent = 0.002). Two Infineon BAT15-03W Schottky diodes were used, and the package parasitic was considered in the design process. In addition, the values of the DC blocking capacitor and the DC pass capacitor with the 0603 package from ATC are 39 and 10 pF, respectively. The output load R2 is 600 Ω. Fig. 5 shows the layout and photograph of the fabricated rectifier. The dimensions of the rectifier are 38 mm × 15 mm.

The simulated and measured |S11| and PCE versus frequency with four different input power levels are plotted in Fig. 6. As shown, both the measured and the simulated results are in good agreement, except that the higher edge of the measured PCE is slightly lower than that of the simulated one. This may result from the parasitic of the capacitors. At 15 dBm input power, the measured |S11| is better than -10 dBm from 1 to 3.2 GHz, while the measured PCE is higher than 70 % from 1 to 2.7 GHz, featuring a fractional bandwidth of 91.9 %. Moreover, the measured PCE is over 50 % from 0.2 to 3.2 GHz at the same input power. When the input power level reduces to 0 dBm, the measured PCE remains over 30 % from 1.1 to 2.8 GHz.

18 dBm. At 3.2 GHz, the measured PCE gets its maximum value of 53.7 % when the input power is 17 dBm. The measured PCE is slightly lower than the simulated one. The discrepancy is due to deviations of the diode parameters between the simulated model and the actual device at high frequencies. Fig. 7(b) shows measured PCE changing with the load at 1.9 and 3.2 GHz when the input power is 10 and 15 dBm. It can be seen that the peak PCE ranges from 600 to 800 Ω at different frequencies and input power levels.

The performance comparison of the proposed rectifier and the previous works featuring broadband design in the literature are listed in Table I. As observed, the rectifier has a much broader bandwidth than the previous works for both 50 % PCE and 70 % PCE bandwidth. Moreover, our design also exhibits the smallest circuit size of 38 mm × 15 mm. The lowest working frequency in this work is 0.2 GHz which is much lower than that of the previous works. The maximum PCE is also comparable with that in those designs.

![Fig. 6. Simulated and measured |S11| and PCE versus frequency at different input power, (a) |S11|, (b) PCE.](image_url)

![Fig. 7. Simulation and measurements, (a) Simulated and measured PCE and output voltage versus input power, (b) Measured PCE versus R2.](image_url)

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<th>Table I: COMPARISON BETWEEN THE PROPOSED RECTIFIER AND THE REFERENCES</th>
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IV. CONCLUSION

A broadband microwave rectifier using a T-type matching network has been proposed, and a design methodology of the IMN is discussed. For validation, a rectifier with PCE higher than 70 % from 1 to 2.7 GHz has been implemented. Measured results show that PCE remains over 50 % with a broad band of 0.2-3.2 GHz. The rectifier shows the merits of compact size, broad bandwidth, and high efficiency, which can potentially be applied in arbitrary RF energy harvesting scenarios.
REFERENCES


