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A novel dual-band RF energy harvesting circuit with power management unit for low power applications

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Abstract

In this letter, a novel dual-band RF energy harvesting circuit (EHC) with power management unit (PMU) for low power applications is proposed, that can operate BQ25504 PMU of Texas Instruments for low input power applications. The proposed RF EHC has been investigated by mathematical analysis and optimization of variable conditions, such as the number of stages and load resistance for the low input power operation. Additionally, BQ25504 is used to boost the output voltage of RF EHC and battery charging. To verify the analysis, a novel dual-band RF EHC is designed and fabricated at 0.88 and 2.44 GHz.

The measurement results show RF-DC conversion efficiency and output voltage of only dual-band RF EHC of 15% and 285 mV at −20 dBm/tone, respectively. Finally, the dual-band RF EHC connected BQ25504 achieves 3.2 V output voltage and 11% efficiency at −13 dBm/tone.

KEYWORDS

dual-band, energy harvesting, internet of thing, RF harvesting, Villard voltage multiplier

1 | INTRODUCTION

Energy harvesting techniques using such as wind, solar, vibration, heat, and electromagnetic wave are one of reasonable means to resolve limited energy sources through the use of eco-friendly energy utilization technologies. The developments of the internet of things (IoTs) and wearable devices have shown limited battery capacity to be a main restriction of performance and running time. RF energy harvesting is one of the solutions to supply DC power to devices with unused radio waves radiated in the atmosphere.

Previous works have presented several methods to enhance the output voltage and conversion efficiency of the RF energy harvesting circuit (EHC).[1–5] Reference 2 used harmonics matching circuits at the input and output ports of the Schottky diode to enhance the output voltage and conversion efficiency. References 3 and 4 also utilized dual-band RF EHC to enhance the output voltage and conversion efficiency. Compared with single band (or single-tone) signal, the dual-band (or two-tone) signals have higher peak voltage. As a result, dual-band RF EHC has higher output voltage and conversion efficiency than single band RF EHC for the same average power level. Furthermore, Ref. 5 realized RF EHC in CMOS process. This RF EHC had a good performance with small size, and was used by the inductor and low pass filter (LPF) to compensate the parasitic capacitors of the transistor and suppress harmonic signals at the output.

However, these previous works have peak performance at over 0 dBm input power. Reference 6 showed that the actual average power density of the commercial systems at the suburban level was smaller than −10 dBm. Therefore, the research of RF EHC for low input power is needed. This article addresses the low input power RF EHC with power management unit (PMU). Based on mathematical analysis and simulation, the optimized dual-band RF ECH with PMU is demonstrated.

2 | DESIGN EQUATION

As mentioned in the introduction, the two-tone signal has higher peak voltage than the single-tone signal. In the high-power region, it makes for high output voltage and conversion efficiency. Likewise, at much low power, RF EHC can operate at higher peak voltage than the threshold voltage of the diode. Therefore, the dual-band RF EHC is proper to low input power harvesting. Figure 1 shows a block diagram of the proposed novel dual-band/dual-antenna RF EHC. The proposed structure consists of a dual-band antenna, dual-band matching network, single stage Villard voltage multiplier (VVM), LPF, and load resistor R_{LOAD}. LPF is used for output voltage and conversion efficiency enhancements by suppression of the harmonic components, due to nonlinear operation of diodes in the VVM. Dual-band RF signals are rectified by the main and auxiliary RF EHCs and the reference voltage of the main RF EHC is provided from the auxiliary RF EHC to increase the output voltage and conversion efficiency.

There are many rectifying structures, such as series diode, shunt diode, and VVM. Generally, the single stage series diode and shunt diode rectifiers have relatively higher conversion efficiency at low input power compared with

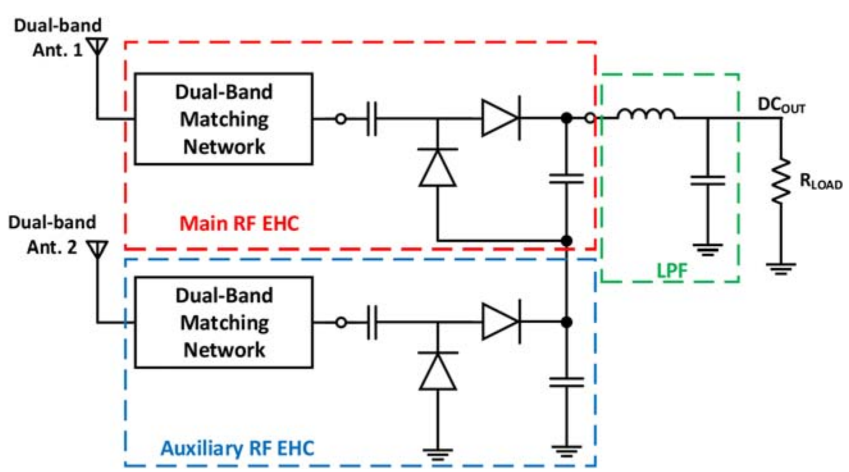

FIGURE 1 Proposed dual-band/dual-antenna RF energy harvesting circuit. [Color figure can be viewed at wileyonlinelibrary.com]

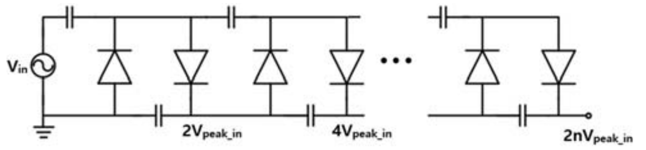

FIGURE 2 Circuit of an *n*-stage Villard voltage multiplier

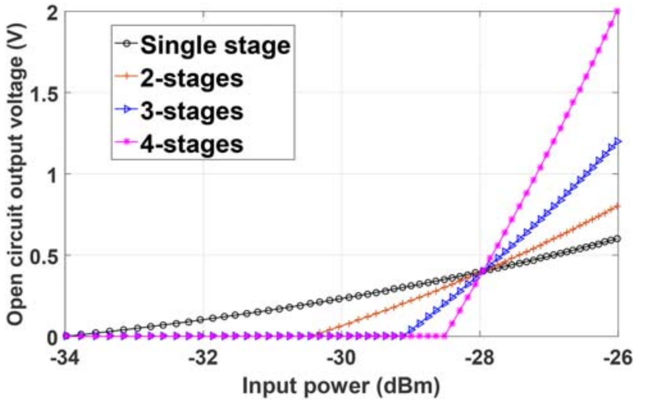

FIGURE 3 Simulation results of open circuited VVM output voltage according to number of stages. [Color figure can be viewed at wileyonlinelibrary.com]

single stage VVM, because only one diode is used for rectifying. However, the VVM can generate higher output voltage than the others, because of full wave rectifying and voltage multiplication. The series and shunt diode rectifiers can only rectify half wave signals. If the output voltage is not sufficient even though the conversion efficiency is high, the desired circuit cannot operate. Therefore, proposed structure used VVM to get enough output voltage at low input power. Figure 2 shows an *n*-stage VVM structure. In the ideal case, the output voltage is $2nV_{peak\_in}$, where V_{peak_in} is a peak voltage of input RF signal (V_s). However, actual diodes cause voltage loss due to threshold voltage, turn-on resistance, and parasitic resistance. Therefore, the output voltage of single stage VVM with lossy components is expressed as:

$$V_{out\_1st} = 2\left(V_{peak\_in} - V_{loss}\right), \quad (1)$$

where V_{loss} is overall voltage loss of diode, respectively. In the same way, the second stage and *n*th stage output voltages can also be expressed as

$$V_{out\_2nd} = 2\left(V_{out\_1st} - V_{loss}\right) = 4V_{peak\_in} - 6V_{loss}, \quad (2)$$

$$V_{out\_n} = 2nV_{peak\_in} - \left(2^{n+1} - 2\right)V_{loss}. \quad (3)$$

The conversion efficiency η is expressed as:

$$\eta = 100 \times P_{RF}/P_{DC}, \quad (4)$$

where P_{RF} and P_{DC} are the input RF power and converted output DC power, respectively.

3 | SIMULATION AND MEASUREMENT RESULTS

For an experimental validation, the dual-band/dual-antenna RF EHC is designed at 880 MHz and 2.44 GHz. To enhance the performance at low input power, HSMS-2852 Schottky barrier diodes were used, due to the ultra-low threshold voltage (150 mV), low series resistance (25 Ω), and low junction capacitance (0.18 pF). For sufficient conversion efficiency and proper operation at the low power level, the PMU consists of BQ25504 of Texas Instrument with evaluation module to boost the output voltage of the proposed dual-band RF EHC and charge the battery. The BQ25504 device is specifically designed to efficiently acquire and manage the μW to mW of power generated from a variety of DC sources. The BQ25504 can operate with V_{IN} as low as 330 mV; and once started, can continue to harvest energy down to $V_{IN} = 80$

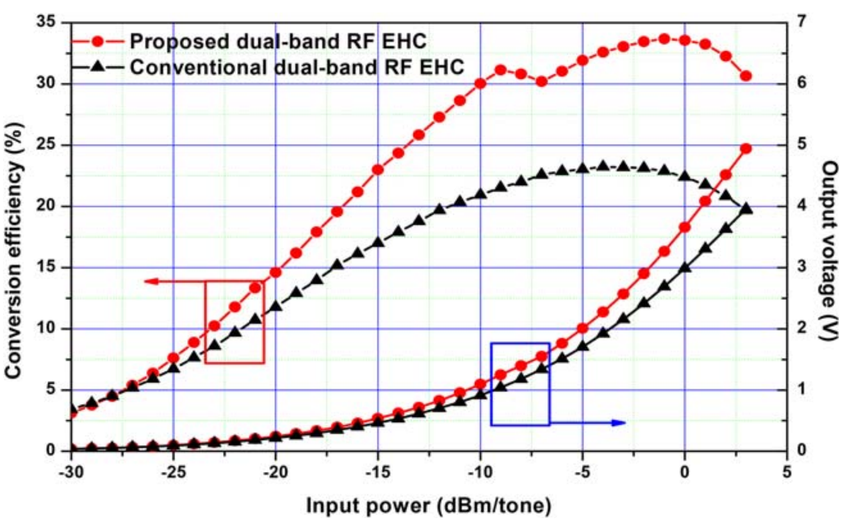

FIGURE 4 Comparison of measurement results of the proposed dual-band/dual-antenna RF EHC and the conventional dual-band RF EHC. [Color figure can be viewed at wileyonlinelibrary.com]

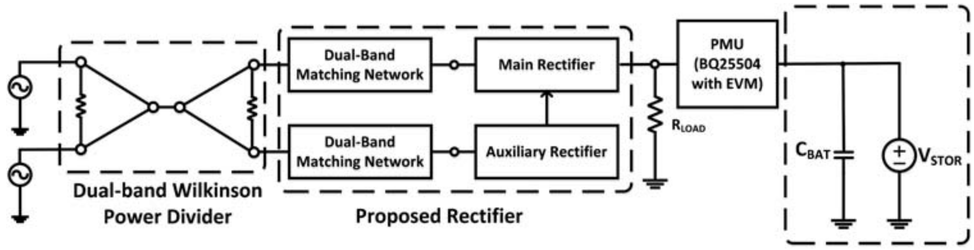

FIGURE 5 Measurement setup of dual-band/dual-antenna RF EHC with power management unit

mV. The load resistance was selected 20 kΩ and the values of capacitor and inductor on the LPF were 10 pF and 15 nH, respectively.

Figure 3 shows Matlab simulation results of the VVM output voltage according to the number of stages using Equation 3. V_{loss} was assumed as 0.2 V, and the input power was calculated from V_{peak_in} of the sinusoidal signal with a 50 Ω termination source. The output voltage is directly proportional to the input voltage. However, the minimum operating input power is inversely proportional to the number of stages. Therefore, the single stage RF EHC with the VVM was used for low input power operation.

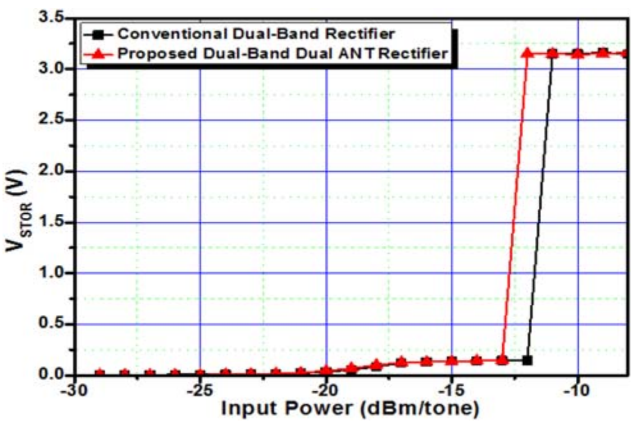

FIGURE 6 Measured store voltages of the dual-band/dual-antenna RF EHC and conventional RF EHC with power management unit. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Measured conversion efficiencies of the dual-band/dual-antenna RF EHC and conventional RF EHC with power management unit. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 4 shows the output voltages and conversion efficiencies of the conventional and proposed dual-band RF EHCs. Conventional RF EHC is consisted of dual-band single antenna, dual-band VVM. In the case of input power of −30 to −28 dBm/tone, the conversion efficiency of the conventional dual-band RF EHC is slightly higher than that of the proposed circuit. However, over −28 dBm/tone power, the proposed dual-band RF EHC can generate higher output voltage and conversion efficiency than the conventional RF EHC in the overall input power range.

Figure 5 shows the measurement setup of the dual-band/dual-antenna RF EHC with the BQ25504. The source meter unit used for the measurement of V_{STOR} in Figure 5 is the Keysight Technologies B2902A. Figures 6 and 7 show the measured store voltage V_{STOR} and overall conversion efficiency results of BQ25504, respectively, with the conventional and proposed RF EHCs. Figure 6 shows that the stored battery voltages of both RF EHCs with PMU. The minimum operating input powers of the proposed and conventional RF EHCs are −13 dBm and −12 dBm, respectively. This means that the proposed dual-band RF EHC can operate BQ25504 unit with 20% lower input power of the conventional RF EHC. The overall conversion efficiencies in Figure 7 are calculated as fixed 3.2 V store voltage and measured current by the B2902A. Generally, the overall conversion efficiency of both RF EHCs is directly proportional to the input power level. The proposed dual-band EHC has higher conversion efficiency than the conventional RF EHC over the −20 dBm input power range.

4 | CONCLUSION

In this letter, a novel dual-band RF EHC with PMU for low power applications is presented. To obtain improved electrical performances at the low RF power range, a novel dual-band/dual-antenna RF EHC is realized well along with a PMU. Compared with the conventional dual-band RF EHC, the proposed dual-band/dual-antenna RF EHC has good RF to DC conversion efficiency and output voltage performances. The proposed dual-band/dual-antenna RF EHC is applicable to low input power applications, such as wearable devices and sensor networks in IoT applications.

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A novel UHF Minkowski fractal antenna for partial discharge detection

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Abstract

A compact and wideband ultra-high-frequency antenna is developed in this work. Based on the Minkowski fractal geometry of the lateral boundaries of monopole and the upper boundary of ground plane, miniaturization is realized. Meanwhile, by optimizing the dimension of the semi-elliptical part of monopole and the triangular notch of ground plane, the impedance bandwidth is enhanced. To confirm the performance of antenna, a series of experiments are conducted. The size and ratio bandwidth of antenna are compared with existing broadband ones. The proposed antenna with size of $0.3\ \lambda_L \times 0.25\ \lambda_L$ covers the frequency ranging from 700 MHz to more than 3 GHz and possesses an average gain of 4.08 dBi.

KEYWORDS

compact antenna, Minkowski fractal, partial discharge, ultra-high-frequency detection, wideband antenna

1 | INTRODUCTION

Partial discharge (PD) is a localized dielectric breakdown of an electrical insulation system. It can cause progressive deterioration of dielectric materials.[1,2] Ultra-high-frequency (UHF) approach for PD detection has attracted much attention over past decades due to its prevailing advantages, such as, strong anti-interference capability and high sensitivity.[3,4]

As an essential component, UHF antenna plays a crucial role on the accuracy and sensitivity of measurement. Various multiband UHF antennas have been investigated so far, for examplem Hilbert fractal antenna[1] and modified loop antenna.[2] In spite of a compact profile, these antennas only cover part of frequency band of PD signal, which ranges from 300 MHz to 3 GHz. Planar equiangular spiral antenna,[3] horn antenna,[4] and biconical log-periodic antenna[4] are sometimes used as UHF antenna. However, they suffer from the inconvenience for installation due to their large size. Obtaining compact and wideband UHF antenna is a challenge.