A Broadband CPW Fractal Antenna for RF Energy Harvesting

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***Abstract* —** A novel broadband CPW-fed 2-iteration fractal antenna based on the circular patch and the equilateral triangle slot is designed for RF energy harvesting. The simulated and measured results show that the proposed antenna offers an impedance bandwidth of 162% from 0.88 to 8.45 GHz and a peak gain of 8.7 dBi. Afterwards, the single-stage voltage multiplier rectifier with a T shape LC matching network to reduce the reflection losses is used to realize RF-to-DC conversion in energy harvesting; here, it is also integrated with the fractal antenna to form the rectenna. Accumulating RF power from 2G (GSM), 3G (the third generation), 4G-LTE and WLAN frequency-bands, the measured results across an optimized load resistor of 4.7-kΩ show that the maximum rectenna efficiency is 51.8%, 46.1% and 45.08% at the center frequency of 2.4 GHz, 2.1 GHz and 1.9 GHz, respectively. Additionally, the measured peak conversion efficiency of the system is 24.03% at 2.4 GHz.

***Index Terms* —** Broadband, energy harvesting, fractal antenna, rectenna.

I. INTRODUCTION

Recently, the ambient RF power density is growing since there is an increasingly frequency bands are being occupied such as WLAN, GSM, DCS, 3G and 4G LTE. The idea of using RF energy harvesting technique to convert these ambient RF energy into usable electrical energy to power low-power electronic devices has become an upsurge of research [1-3]. In general, the system of this technique is mainly composed of the rectifying antenna (rectenna). For weak ambient RF power density, the designed rectenna requires high gain to improve the input power and also need wide impedance bandwidth to accumulate more RF power from different frequency bands, such as Yagi antenna array [4] and six-band dual circular polarization (CP) log-periodic rectenna [5], respectively. However, the mentioned antennas cannot be satisfied because of their large dimension and complex structure. On the other hand, other various designs have been investigated, such as the anti-spiral slot resonator [6], differential structure [7], circularly polarized [8, 9] and so on. Analogously, most of these proposed antennas only accumulate RF power within narrow frequency-bands, which greatly restricts the efficiency of energy harvesting. For this, antennas with multiband, high gain and compact structure are greatly preferred.

Since the self-similarity and spatial filling can be converted into multi-frequency characteristics and dimension reduction in antenna design, the fractal technique can be proposed to be one of the potential candidate for increasing antenna bandwidth. Numerous fractal techniques have been investigated, for instance, elliptical fractal shapes [10] and Sierpinski [11] have been discussed for bandwidth enhancement. In [10], a novel printed elliptical nested fractal antenna operates at 910 MHz, 2.4 GHz, 3.2 GHz, 3.8 GHz and additional 5 GHz band, the ground plane located on both sides of the antenna feeding line adopts Hilbert fractal structure, which greatly increases the impedance bandwidth. In [12], a broadband bent triangular omnidirectional antenna with a bandwidth from 850 MHz to 1.94 GHz is presented. Due to the advantage of receiving both horizontal and vertical polarized waves, a peak rectenna efficiency of 60% and 17% is obtained over a resistor of 500 Ω at 980 MHz and 1800 MHz, respectively. Whereas, the input power is higher than the low-power density ambient too much during its measurement process.

In this paper, a novel CPW-fed broadband fractal antenna is presented for RF energy harvesting. By using the novel fractal technique with a 2-iteration circular-based triangle slot, the antenna designed for receiving 2G (GSM), 3G (the third generation), 4G-LTE and WLAN RF signals can offer a relative bandwidth of 162% (0.88-8.45 GHz). Afterwards, the rectifier with a T shape LC matching network is proposed for making up a rectenna. By actual manufacturing and debugging, the measurement for rectenna efficiency and system efficiency are performed. The results have verified that our proposed rectenna not only has advantages over the bandwidth and dimension, but also the RF-to-DC conversion efficiency, which make it suitable for multiband RF energy harvesting application.

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II. FRACTAL ANTENNA DESIGN

The structure of the proposed fractal antenna with a 2-iteration circular-based triangle slot is depicted in Fig. 1 (a). It can be seen that top of the antenna substrate covers radiation metal patch, while the bottom does not. The ground plane located on both sides of the feeder forms the structure of coplanar waveguide (CPW) feed, which decreases the losses of signal transmission. According to [13], antennas with CPW-fed are easy to be fabricated and integrated with circuits, especially the impendence bandwidth can be extended.

The 0-iteration fractal antenna based on the CPW-fed planar circular patch is depicted in Fig. 1 (b), which can motivate a variety of resonant modes. R_1 is the radius of circular patch and can be explained by the equation:

$$R_1 = \frac{1.841c}{2\pi f\sqrt{\varepsilon_r}}, \tag{1}$$

where ε_r is the relative permittivity of the substrate, f represents the center frequency of the designed antenna and c is the speed of light in vacuum. Meanwhile, Fig. 1 (c) shows the 1-iteration fractal antenna, it can be seen that an equilateral triangle is slotted on the circular patch. The 2-iteration fractal antenna is based on the 1-iteration structure, as described in Fig. 1 (a), an inner circle inserts the slotted equilateral triangle, simultaneously, a smaller equilateral triangle horizontally symmetrical to the previous is slotted on the inner circle. At last, it is worth noting that both of the triangles and the circles have the same center point.

Here, the scaling factor K (K>1) is introduced to describe the mathematical relationship of the proposed fractal structure. In general, the size of slotted equilateral triangles and inner circle are directly determined by the scaling factor K, the larger the value of K, the smaller the fractal slot is. Assuming the radius of the inner circle is R_i, the distance from the apex to the center of slotted triangle and the side length of slotted triangle is L_i and S_i, respectively. These mentioned parameters are summarized in the following equations: (i is the iteration of the fractal antenna):

$$R_i = \frac{R_1}{2^{i-1}\times K} + 2 \quad (i > 1), \tag{2}$$

$$L_i = \frac{R_1}{2^{i-1}\times K} \quad (i > 1), \tag{3}$$

$$S_i = \sqrt{3}\times L_i \quad (i > 1). \tag{4}$$

The designed 2-iteration fractal antenna is fabricated on a substrate with a relative permittivity of 4.4 and a thickness of 1.6 mm. The antenna has a total size of 100×100 mm^2. The width and length of the feeder is W_k and L_k, respectively. The length and width of the coplanar waveguide is M and B, respectively. Here, an optimized scaling factor K is 1.5 and the optimized antenna parameters are illustrated in Fig. 1 (a).

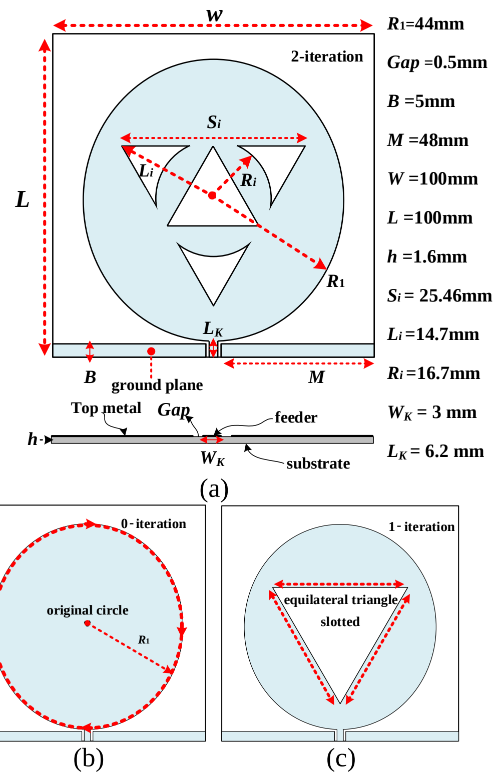

Fig. 1. Geometric structure and size of the antenna: (a) 2-iteration, (b) 0-iteration, and (c) 1-iteration.

III. PERFORMANCE ANALYSIS

For the designed antenna, the novel fractal technique is used to expand the impedance bandwidth. Then, the antenna is modeled and optimized by means of the HFSS software. To sufficiently investigate the impedance matching performance of the proposed fractal antenna with 2-iteration structure, here, the key parameters are selected and investigated as followings: the iteration of the fractal, the length of Gap, and the substrate thickness h. All these parameter simulations are based on the premise that the substrate thickness h is 0.6 mm and the value of scaling factor K is 1.5.

The return loss of the fractal antenna with variation of iterations is depicted in Fig. 2. It can be seen that the impedance matching performance of the 2-iteration fractal structure is better than the 1-iteration fractal structure with the frequency-bands roughly from 0.8 to 1.4 GHz and 1.85 to 6 GHz. Also, the same relationship that the 1-iteration fractal structure is better than the 0-iteration fractal structure. This is because employing the fractal technique, the current path on radiation metal patch is increased, which greatly expands the antenna impedance bandwidth. Thus, the 2-iteration fractal antenna is more suitable for RF energy harvesting.

Then, the length of Gap is varied and the effect on the impedance matching is investigated as depicted in Fig. 3. It is found that the 2-iteration fractal antenna with good impedance matching can be implemented when *Gap* is greater than 0.3 mm. When the frequency is below 3 GHz, the antenna impedance matching becomes better along with the increase of the length of *Gap*, which can be accounted for the reason that antenna input impedance is affected by the variation of waveguide parameters. On the other hand, to reduce the reflection losses and parasitic effects caused by electromagnetic waves when propagating in coplanar waveguide, the length of *Gap* should not be too large. Parasitic effects also arouse high order harmonics to interfere with the antenna radiation performance. Hence, the length of *Gap* is more suitable for 0.5 mm.

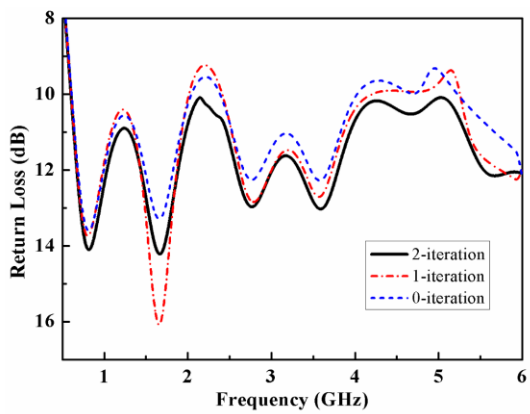

Fig. 2. Effects of fractal iterations on the return loss.

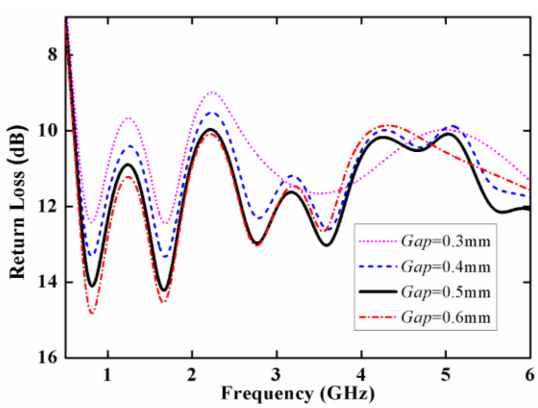

Fig. 3. Effects of the length of *Gap* on the return loss.

Figure 4 depicts the parameter effects on the impedance matching of the proposed fractal antenna with variation of the substrate thickness *h*. When *h* is selected 0.6 mm, the proposed fractal antenna has achieved a broad impedance bandwidth, while, keep on increasing the value of *h*, the impedance matching performance becomes better. This can be explained by some reasons, one is related to the empirical formula:

$$VSWR < 2: BW(MHz) = 5.04 f^2 (GHz) h(mm), \quad (5)$$

where it demonstrates the relationship between the thickness of substrate and the antenna bandwidth. In addition, the other reason can be explicated by the antenna cavity model calculation that antenna input impedance is determined by the thickness of substrate. Meanwhile, to restrain surface wave and improve the antenna radiation efficiency, the substrate thickness *h* should not too large. Thus, the parameter h = 1.6 mm is more suitable for antenna fabrication.

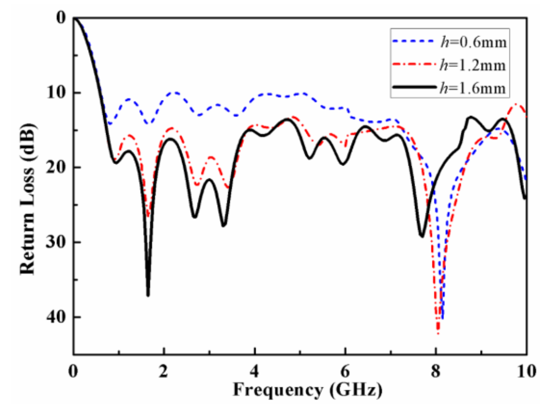

Fig. 4. Effects of substrate thickness *h* on the return loss.

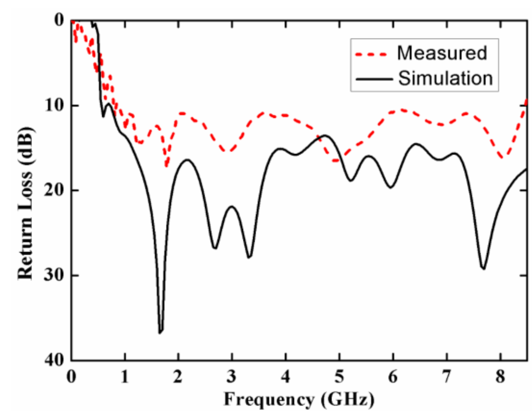

Fig. 5. The simulated and measured return loss.

Figure 5 depicts the simulated and measured impedance bandwidth of the designed fractal antenna. It can be seen that the measured return loss is more than 10 dB within the bandwidth from 0.88 to 8.45 GHz (the relative bandwidth is 162%), which shows a good impedance matching. Different from the ideal metal conductor in simulation, there may exist certain error partially due to the connector welding in actual fabrication, which directly degrades the performance of antenna impedance bandwidth. In general, the fabricated antenna meets the requirement for multiband RF energy harvesting. Figure 6 shows the gain of the proposed antenna varied with the frequency. We can find that the maximum gain of the antenna is 8.7 dBi.

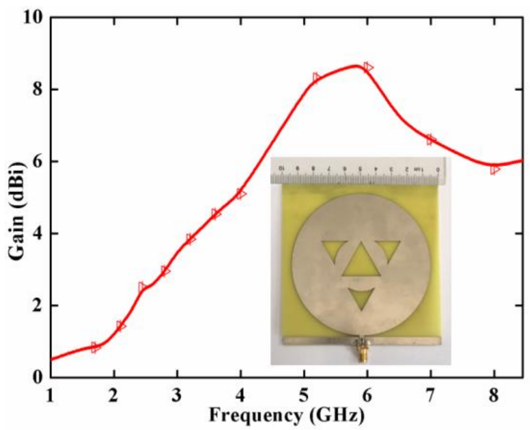

Fig. 6. The gain of the proposed fractal antenna.

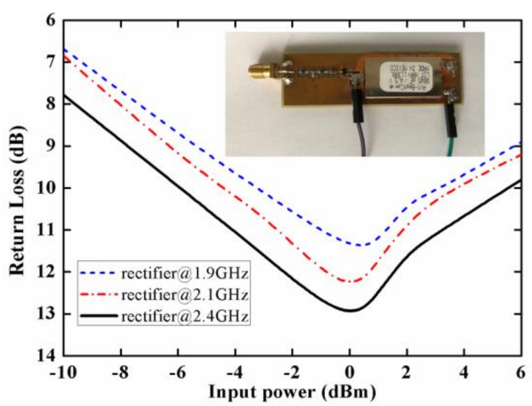

Fig. 7. Measured return loss versus input power of the rectifier at different frequency bands.

IV. ANTENNA APPLICATION IN RF ENERGY HARVESTING

The rectifying circuit performs the function of RF-to-DC power conversion, to reduce the power loss, the designed rectifying circuit should only consist of few components, as proposed in [14] the rectifier is directly integrated with the antenna. In this paper, a single-stage voltage multiplier rectifier is proposed and the Schottky HSMS-2852 diode is adopted as the core rectifying component due to its low threshold voltage, high switching frequency and low power consumption. It has been demonstrated in [15] that the number of rectifying diodes is sensitive to the RF-to-DC efficiency. For the low input power, the more voltage multiplier stages, the lower RF-to-DC efficiency can be gained. Whereas, it is the opposite for the high input power. Hence, in case of weak ambient sources, the designed single-stage voltage multiplier rectifier is more suitable for RF energy harvesting. Since the nonlinearity of rectifying diodes, the input impedance of the rectifier varies as a function of frequency and input power level, thus, the broadband matching between the rectifier and the fractal antenna is a huge challenge. By using harmonic-balance and large signal analysis of ADS software, here, an optimized T shape LC matching network is employed to decrease the power reflection. Final topology of the rectifier is shown in Fig. 7 with a fabricated example. The substrate is FR4, with a relative permittivity of 4.4 and a thickness of 1.6 mm. To convert the accumulated RF power from 2G (GSM), 3G (the third generation), 4G-LTE and WLAN bands, the main center frequency for measurement is selected as 1.9 GHz, 2.1 GHz and 2.4 GHz, respectively. Figure 7 depicts the return loss of the proposed rectifier versus input power levels at three main frequency bands. It is found that the rectifier is well matched for input power levels between -6 dBm and 5 dBm at 2.4 GHz.

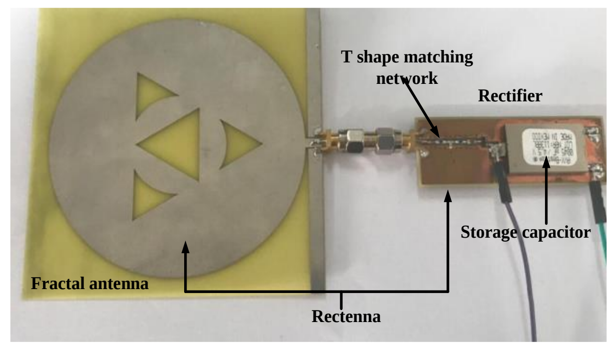

Fig. 8. The structure of the fabricated rectenna.

The rectenna combined by the fabricated rectifier and the fractal antenna is shown in Fig. 8, which is used as the receiver for energy harvesting. Meanwhile, the another identical fractal antenna is connected with the AV1442 signal generator to form the transmitting antenna. In actual measurement, the distance between transceiver antennas is 15 cm. The received RF power P_{RF} is measured by connecting the fractal antenna with the spectrum analyzer. Subsequently, the spectrum analyzer will be removed and rectenna is placed at the same position, then the DC voltage V_{out} is measured across an optimized load resistor R_{load} of 4.7-kΩ. The output DC power P_{out} of the rectenna and the rectenna efficiency η_1 can be calculated according to the following equations:

$$P_{out} = \frac{V_{out}^2}{R_{load}}, \tag{6}$$

$$\eta_1 = \frac{P_{out}}{P_{RF}}. \tag{7}$$

The measured rectenna efficiency η_1 is depicted in Fig. 9. It can be seen that the maximum efficiency is 51.8%, 46.1% and 45.08% at 2.4 GHz, 2.1 GHz and 1.9 GHz, respectively, in case of the input power is 0 dBm.

The measured efficiency η_2 of the whole system is also depicted in Fig. 9. The system efficiency η_2 including air loss can be calculated by the equation:

$$\eta_2 = \frac{P_{out}}{P_{in}}, \tag{8}$$

where the input power P_{in} is generated by the AV1442 signal generator. It can be seen that the maximum system efficiency η_2 is 24.03% at 2.4 GHz with the input power of 0 dBm. Table 1 shows the comparison between our designed rectenna and other designs reported previously. It can be seen that our design not only has advantages over the antenna impedance bandwidth and dimension, but also the satisfied conversion efficiency in low input power level.

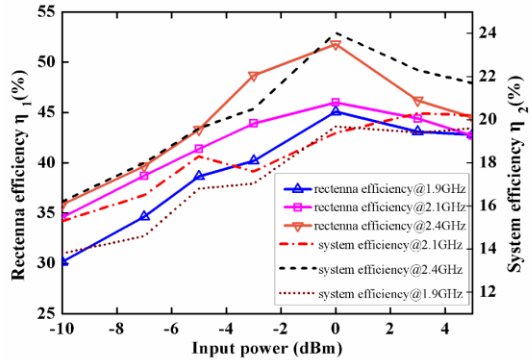

Fig. 9. The measured rectenna efficiency η_1 and system conversion efficiency η_2.

Table 1: Comparison of the proposed rectenna and the related designs reported previously

Ref.	Frequency (GHz)	Antenna Dimension (mm^3)	Maximum Gain (dBi)	Input Power Level for Peak Efficiency (dBm)	Conversion Efficiency (%)
[4]	Dual-band 1.8, 2.2	300×380×1.6	10.9, 13.3	3 to 5	50
[12]	0.85-1.94	94×82×1.6	2	>0	60
[16]	0.9-1.1, 1.8-2.5	NS	3.3	0-23	75
[17]	Dual-band 0.915, 2.45	60×60×60	1.87, 4.18	-10 to 0	50
This work	0.88-8.45	100×100×1.6	8.7	-5 to 0	51.8

V. CONCLUSION

In this paper, a novel broadband CPW-fed fractal antenna is proposed. The simulation and measurement have demonstrated that the designed antenna offers a bandwidth of 162% (0.88–8.45 GHz) and a peak gain of 8.7 dBi. Then, the rectifier with a T shape LC matching network is fabricated and integrated with the fractal antenna to form a rectenna. The measured results show that the maximum rectenna efficiency is 51.8%, 46.1% and 45.08% at 2.4 GHz, 2.1 GHz and 1.9 GHz, respectively. The peak energy conversion efficiency of the whole system is 24.03% at 2.4 GHz. At last, the designed rectenna is suitable for RF energy harvesting.

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REFERENCES

[1] A. Collado and A. Georgiadis, "Conformal hybrid solar and electromagnetic (EM) energy harvesting rectenna," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 8, pp. 2225-2234, Aug. 2013.

[2] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," in *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 757-789, May 2015.

[3] H. J. Visser and R. J. M. Vullers, "RF energy harvesting and transport for wireless sensor network applications: Principles and requirements," in *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1410-1423, June 2013.

[4] H. Sun, Y. X. Guo, M. He, and Z. Zhong, "A dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting," in *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 918-921, July 2013.

[5] C. Song, *et al.*, "A novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3160-3171, July 2016.

[6] M. Palandöken, "Microstrip antenna with compact anti-spiral slot resonator for 2.4 GHz energy harvesting applications," in *Microwave & Optical Technology Letters*, vol. 58, no. 6, pp. 1404-1408, June 2016.

[7] M. Arrawatia, M. S. Baghini, and G. Kumar, "Differential microstrip antenna for RF energy harvesting," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1581-1588, Apr. 2015.

[8] C. C. Kang, *et al.*, "Corporate feed with dual segment circular polarized array rectenna for low power RF energy harvesting," in *Journal of Engineering Science & Technology*, vol. 11, no. 6, pp. 796-805, June 2016.

[9] S. B. Vignesh, Nasimuddin, and A. Alphones, "Circularly polarized strips integrated microstrip antenna for energy harvesting applications," in *Microwave & Optical Technology Letters*, vol. 58, no. 5, pp. 1044-1049, Mar. 2016.

[10] M. Taghadosi, L. Albasha, N. Qaddoumi, and M. Ali, "Miniaturised printed elliptical nested fractal multiband antenna for energy harvesting applications," in *IET Microwaves, Antennas & Propagation*, vol. 9, no. 10, pp. 1045-1053, July 2015.

[11] C. A. Figueroa-Torre, J. L. Medina-Monroy, and H. Lobato-Morales, "A novel fractal antenna based on the Sierpinski structure for super wide-band applications," in *Microwave & Optical Technology Letters*, vol. 59, no. 5, pp. 1148-1153, Mar. 2017.

[12] M. Arrawatia, M. S. Baghini, and G. Kumar, "Broadband bent triangular omnidirectional antenna for RF energy harvesting," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 36-39, Apr. 2016.

[13] H.-D. Chen and H.-T. Chen, "A CPW-fed dual-frequency monopole antenna," in *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 4, pp. 978-982, Apr. 2004.

[14] Y.-J. Ren and K. Chang, "5.8-GHz circularly polarized dual-diode rectenna and rectenna array for microwave power transmission," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 4, pp. 1495-1502, June 2006.

[15] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," in *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, no. 1, pp. 24-33, Mar. 2012.

[16] C. Song, *et al*., "Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3950-3961, May 2017.

[17] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis, and M. M. Tentzeris, "A compact dual-band rectenna using slot-loaded dual band folded dipole antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1634-1637, Dec. 2013.

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