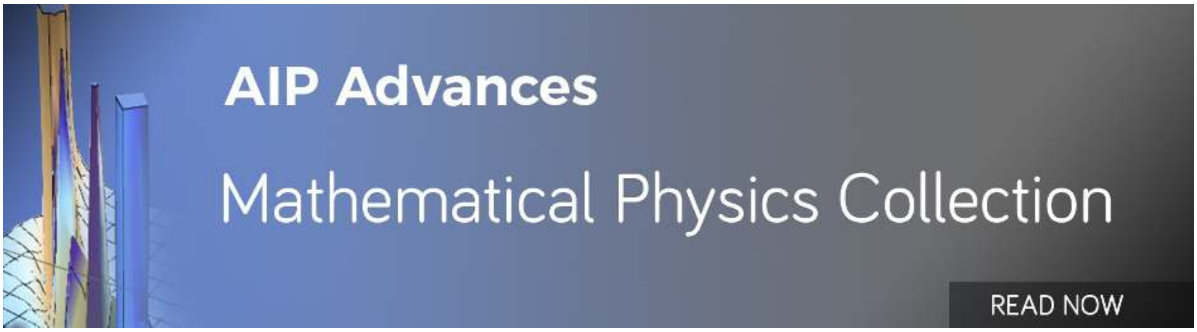
AIP Advances

A metamaterial electromagnetic energy rectifying surface with high harvesting efficiency

Cite as: AIP Advances **6**, 125020 (2016); https://doi.org/10.1063/1.4972121
Submitted: 25 August 2016 • Accepted: 29 November 2016 • Published Online: 15 December 2016

Xin Duan, Xing Chen and Lin Zhou



AIP ADVANCES **6**, 125020 (2016)

A metamaterial electromagnetic energy rectifying surface with high harvesting efficiency

Xin Duan, Xing Chen,[a] and Lin Zhou
College of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China

(Received 25 August 2016; accepted 29 November 2016; published online 15 December 2016)

A novel metamaterial rectifying surface (MRS) for electromagnetic energy capture and rectification with high harvesting efficiency is presented. It is fabricated on a three-layer printed circuit board, which comprises an array of periodic metamaterial particles in the shape of mirrored split rings, a metal ground, and integrated rectifiers employing Schottky diodes. Perfect impedance matching is engineered at two interfaces, i.e. one between free space and the surface, and the other between the metamaterial particles and the rectifiers, which are connected through optimally positioned vias. Therefore, the incident electromagnetic power is captured with almost no reflection by the metamaterial particles, then channeled maximally to the rectifiers, and finally converted to direct current efficiently. Moreover, the rectifiers are behind the metal ground, avoiding the disturbance of high power incident electromagnetic waves. Such a MRS working at 2.45 GHz is designed, manufactured and measured, achieving a harvesting efficiency up to 66.9% under an incident power density of 5 mW/cm^2, compared with a simulated efficiency of 72.9%. This high harvesting efficiency makes the proposed MRS an effective receiving device in practical microwave power transmission applications. [http://dx.doi.org/10.1063/1.4972121]

In 1968, Dr. Peter E. Glaser proposed the Solar Power Satellite (SPS), which generates electrical power from sunlight in geosynchronous orbit and wirelessly transmits it to the earth by microwaves.[1] Driven by this concept, as well as other potential applications such as remotely powered unmanned aerial vehicles (UAVs), the microwave power transmission (MPT) has been theoretically and experimentally researched by many countries including the United States, Japan and China.[2–5] In such a system, the receiving device is a key element that collects incident electromagnetic (EM) waves and then converts the EM power into direct current (DC).[5,6] So far the rectenna has mainly been utilized, which is typically composed of two components - a receiving antenna and a rectifying circuit, for energy capture and rectification, respectively.[7]

The rapid research progress of functional metamaterials has provided a new approach for EM energy reception. Metamaterials, consisting of sub-wavelength periodic particles, are manmade materials that possess desired bulk effective permittivity (ε_r) and permeability (μ_r) enabling a variety of functional applications.[8–16] Among many applications, the metamaterial rectifying surface (MRS) has been proposed in recent years as a novel EM energy harvester.[17–19] Quite different from the rectenna, the MRS collects the EM power by an array of periodic metamaterial particles instead of a receiving antenna, and the metamaterial particles in the MRS normally have much smaller electrical dimensions (usually 1/14–1/4 wavelength[17–19]) than the radiation elements (usually 1/2 wavelength[5–7]) in the antenna.

In the MRS, the metamaterial particles are designed to have identical ε_r and μ_r to yield the same impedance as free space, expecting to completely capture incident EM waves with no reflection.[20,21] By properly integrating rectifiers, the MRS is able to further convert the captured EM power to

---

[a] Author to whom correspondence should be addressed. Electronic mail: xingc@live.cn.

DC.[18,19] Just as with the rectenna, the overall efficiency (here called harvesting efficiency) of the MRS is defined as the product of two efficiencies: the capture efficiency and the conversion efficiency.[7] The former is the ratio of captured EM power to spatial EM power incident on the surface, and the latter is the ratio of DC output power to captured EM power.

For maximum harvesting efficiency, the MRS needs precise design to realize perfect impedance matching (between free space and the surface, as well as between the metamaterial particles and the rectifiers), which is difficult due to the use of nonlinear components like diodes. Additionally, existing MRSs usually expose the diodes in high power EM incidence, so the diodes' performance may be hindered. Hence, the design of the MRS is still a major challenge.

As a novel device, the MRS has only been reported in a few articles before now. However, the harvesting efficiencies reported in those articles are very low. For example, in Ref. 18, 5 split-ring resonators with embedded diodes are positioned in parallel to harvest incident EM waves, and the harvesting efficiency is 36.8% at most under power densities ranging from 0.1 to 1.6 mW/cm^2. Ref. 19 proposes a metamaterial artificial perfectly matched layer for SPS applications, but only gives a low-power harvesting efficiency of 27.7% under 0.1 mW/cm^2. Obviously, those aforementioned efficiencies are inadequate for realistic utilization in MPT.

Aiming at practical MPT applications, a novel MRS with high harvesting efficiency is presented in this work. It is fabricated on a three-layer printed circuit board (PCB), consisting of metamaterial particles on the front layer, a metal ground in the middle, and integrated rectifiers on the back layer. By optimizing the dimensions of the metamaterial particles, the MRS obtains impedance equal to that of free space, leading to nearly full capture of the incident EM wave with minimum reflection. Through optimally positioned vias, the EM energy captured by the metamaterial particles is mostly delivered to the rectifiers with matched impedance. Efficient rectification is then carried out by the diodes deployed behind the metal ground, avoiding the high power EM interference.

Fig. 1 illustrates the exploded view of a unit cell of the proposed MRS. The metallic metamaterial particle is patterned on the 3-mm thick top substrate, while the rectifier traces are etched on the 1-mm thick bottom substrate. Both dielectric substrates are polytetrafluoroethylene (PTFE) composites, and have a relative permittivity of 2.65 and a loss tangent of 0.0007. A via with a diameter of 0.5 mm goes through the metal ground sandwiched between the substrates, and connects the metamaterial particle and the rectifier. Two Rogers RO4450F bondplys, each 0.1 mm thick, are employed to combine the substrates into a three-layer PCB.

As shown in the block diagram of Fig. 1, there are two interfaces where impedance matching should be carefully designed. One is interface 'A' between free space and the MRS, whose input

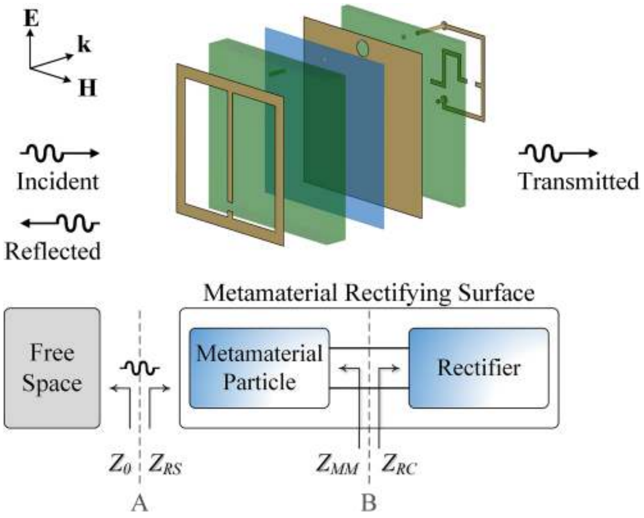


FIG. 1. The schematic of a unit cell of the proposed MRS. Lumped elements including the diode, the capacitor and the resistor are not shown in the illustration. The layers from left to right are the metamaterial particle, the top dielectric substrate, two Rogers RO4450F bondplys, the metal ground, the bottom dielectric substrate, and the rectifier, which is connected between a via to the metamaterial particle and a blind via to the metal ground.

impedance is denoted as Z_0 and Z_{RS}, respectively. The other is interface 'B' between the metamaterial particle and the rectifier, whose input impedance is denoted as Z_{MM} and Z_{RC}, respectively. In order to achieve full capture of the incident EM wave, as well as the largest EM power delivery to the rectifier, Z_{RS} should be designed to have the same value of Z_0 (376.73 Ω), and Z_{MM} is equal to the complex conjugate of Z_{RC}.[19]

First, we design the metamaterial particle of the MRS with the same impedance as that of free space, to yield maximum capture efficiency at the working frequency of 2.45 GHz. The simulation is carried out in Computer Simulation Technology (CST) Microwave Studio. As shown in Fig. 2(a), the metamaterial particle used in this work is an EM resonator which comprises two mirrored inductive loops sharing a capacitive gap, and a supporting substrate backed by a metal ground. The shared arm of the split rings is aligned parallel to the electric field component of the normal incident plane wave, and 'Unit Cell' boundary conditions are used to virtually repeat the model up to an infinite periodicity. From Ref. 17 we know that the anti-circulating currents will merge at the top of the particle, and thus a via is placed at the very location to create an optimal energy delivery path. In the simulation, a lumped port is defined with source impedance equal to the rectifier's input impedance Z_{RC}, and placed on the bottom substrate between the via and the blind via to represent the rectifier.[18] The dimensions of the EM resonator and the periodicity of the unit cell can be modified to control the metamaterial particle's operating frequency. And the position of the capacitive gap can be adjusted to further tune the input impedance of the MRS. The parameters are listed in Fig. 2(a) as labeled.

Fig. 2(b) illustrates the simulated input impedance of the MRS (Z_{RS}) retrieved from scattering parameters.[22] At 2.45 GHz, Z_{RS} is engineered to be 370.60+j0.64 Ω, sufficiently close to the free space impedance Z_0 (376.73 Ω). Owing to this nearly perfect impedance matching, the incident EM power is captured by the MRS with almost no reflection. Moreover, the metal ground in the middle of

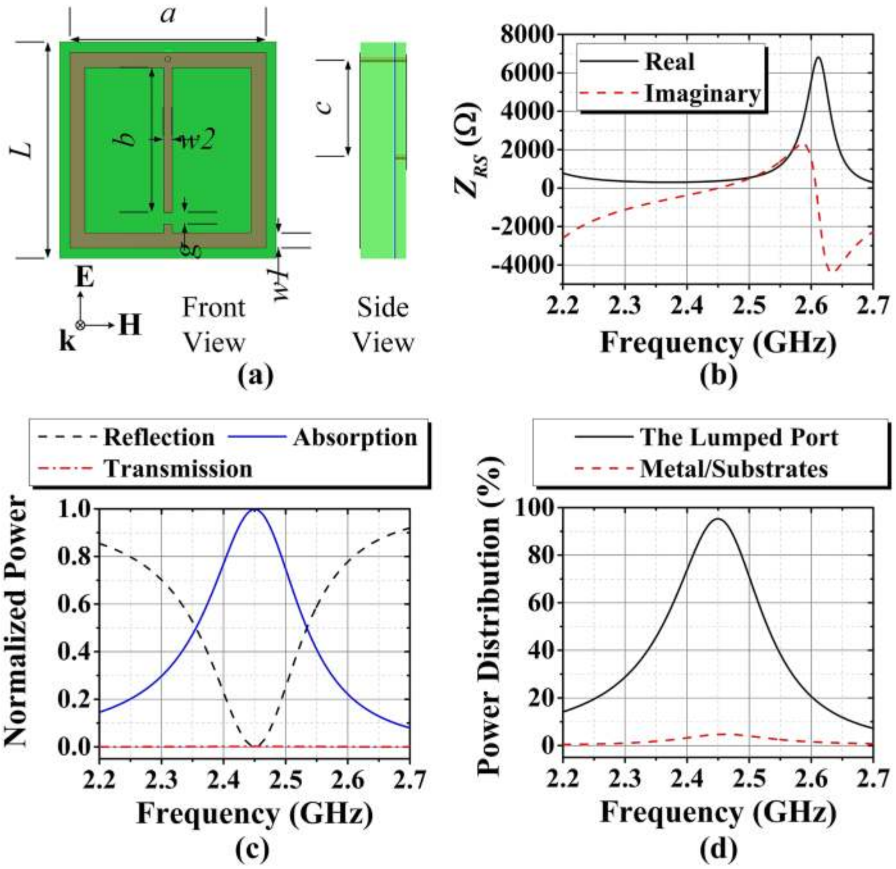


FIG. 2. (a) The design of a metamaterial particle: L=20 mm, a=18.1 mm, b=13.4 mm, c=9 mm, g=1.1 mm, $w1$=1.4 mm, $w2$=1.1 mm, and Z_{RC}=100 Ω. Simulated (b) input impedance of the MRS (Z_{RS}), and (c) power reflection, transmission and absorption under normal incidence. (d) The distribution of the captured energy within a unit cell.

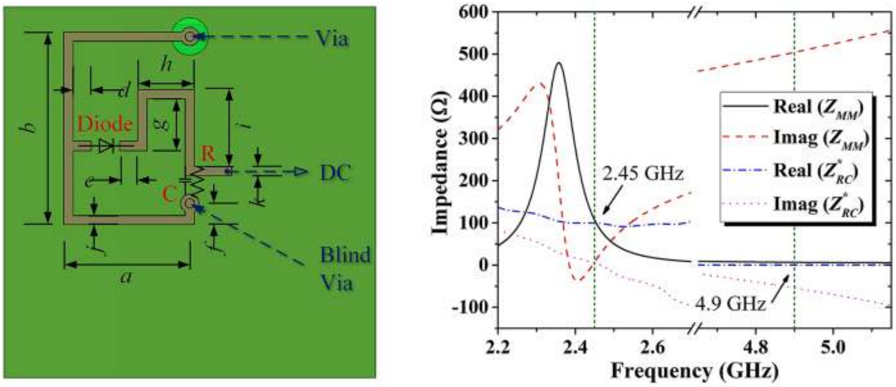
the three-layer PCB blocks the incidence and prevents it from being transmitted to the space behind the MRS. Hence, the simulation results (see Fig. 2(c)) estimate that the MRS achieves a very high capture efficiency of up to 99.8%.

The distribution of the captured EM power within a unit cell is also simulated over a range of frequencies, as depicted in Fig. 2(d). According to the simulation, at the working frequency of 2.45 GHz, the majority of the captured EM power (95.3%) enters the lumped port, while only a very small amount (4.7%) is dissipated in the metal and substrates collectively. This means most EM power is channeled to the rectifiers through vias.

The next step is to design the rectifier with high conversion efficiency, and meanwhile realize impedance matching between the metamaterial particle and the rectifier. Fig. 3(a) illustrates the rectifier's layout. A Schottky diode HSMS-282B with low open junction capacitance and fast switching capabilities is used as the rectifying component. An inductive microstrip line connects the via, the diode and the blind via, suppressing the imaginary part of the diode's impedance and matching its real part to that of the metamaterial particle. At the back end of the diode, another microstrip line with a capacitor C works as a DC pass filter, reflecting microwave energy back and outputting DC voltage across a resistor R.

It should be noted that the performance of rectifiers has close relation to the input power level.[19] In this work, we choose an incident power density of 5 mW/cm^2, which is a common working specification in MPT applications. With the assistance of Advanced Design System (ADS), the rectifier's performance is simulated by adjusting C, R and the dimensions of the microstrip lines. As shown in Fig. 3(b), the complex conjugate of the rectifier's input impedance ($Z_{RC}{}^*$) and the metamaterial particle's input impedance (Z_{MM}) have approximately the same value around 100+j0 Ω at 2.45 GHz, thus allowing the incoming power at 2.45 GHz to maximally pass to the rectifier. Here, it is important to emphasize that Z_{MM} is the impedance seen from the rectifier, which is different from previously discussed Z_{RS} (impedance seen from free space) of the MRS loaded with the rectifier. Furthermore, for the harmonic power produced by the diode, there exists a severe impedance mismatch between the metamaterial particle and the rectifier. For example, $Z_{RC}{}^*$ at 4.9 GHz (the second-order harmonic of 2.45 GHz) is 0.28-j54.24 Ω, significantly deviating from Z_{MM} (6.62+j504.52 Ω). Such impedance mismatch blocks the harmonic energy, making it reflect back and forth between the metamaterial particle and the capacitor until it is completely rectified by the diode.[6] As a result, efficient DC conversion can be achieved, and the simulated harvesting efficiency η is maximized to 72.9% for an incident power density of 5 mW/cm^2.

Such a MRS with 6 × 6 unit cells is fabricated on a three-layer PCB as shown in Fig. 4(a) and (b). The rectifiers on the bottom layer are connected in parallel and output DC power to a resistive load,



(a) **(b)**

FIG. 3. (a) The layout of the designed rectifier. The parameters are as follows: a=6.8 mm, b=10.4 mm, d=1 mm, e=1 mm, f=1.15 mm, g=2.8 mm, h=3.05 mm, i=4.15 mm, j=0.5 mm, k=0.5 mm, C=10 pF and R=850 Ω. (b) The simulated complex conjugate of the rectifier's input impedance ($Z_{RC}{}^*$) compared with the metamaterial particle's input impedance (Z_{MM}) at the circuit interface.

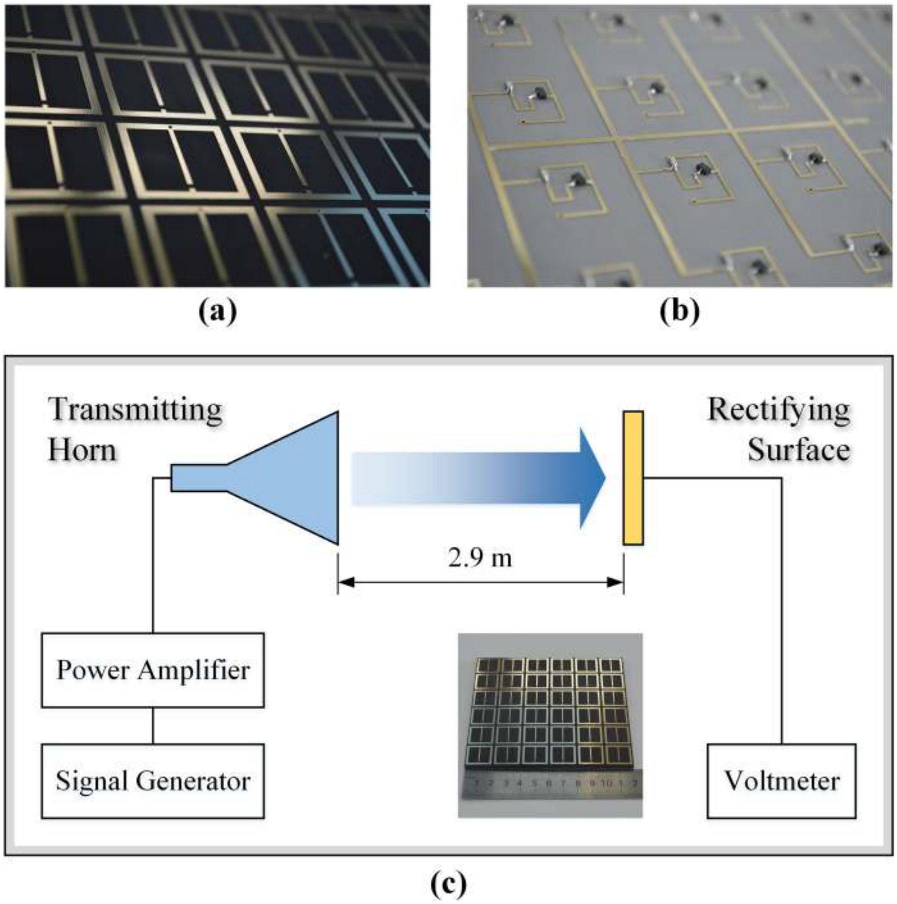


FIG. 4. A photograph of the fabricated MRS sample (a) top layer and (b) bottom layer showing the diodes and surface mount capacitors. (c) The measurement setup schematic.

which is the equivalent of the parallel resistors. To observe power rectifying capabilities, the MRS is measured in a microwave anechoic chamber with the experimental setup depicted in Fig. 4(c). Connected to a signal generator and a power amplifier, a 15.9 dBi gain horn antenna transmits microwaves at 2.45 GHz. The MRS is placed 2.9 m away, in the far-field zone of the source antenna. The electric field component of the normal incident plane wave is aligned parallel to the shared arms of the metamaterial particles as shown in Fig. 2. An Agilent Data Acquisition/Data Logger as a voltmeter measures the DC output voltage V_{DC} across the resistive load.

The desired incident power density S_r can be obtained by adjusting the input power of the transmitting antenna P_t:

$$S_r = \frac{P_t G_t}{4\pi r^2}, \tag{1}$$

where G_t is the antenna gain, and r is the distance.

The harvesting efficiency η is then determined by

$$\eta = \frac{P_{DC}}{P_{EM}} = \frac{V_{DC}^2}{A_p S_r R}, \tag{2}$$

where P_{DC} is the DC power dissipated on the load, P_{EM} is the spatial power reaching the MRS, and A_p is its physical aperture area.

Fig. 5(a) illustrates the tested harvesting efficiency as the resistance increases under three incident power density values: 1 mW/cm^2, 3 mW/cm^2, and 5 mW/cm^2. It is found that the harvesting efficiencies reach peak values at the working efficiency 2.45 GHz when R=400 Ω. Fig. 5(b) shows

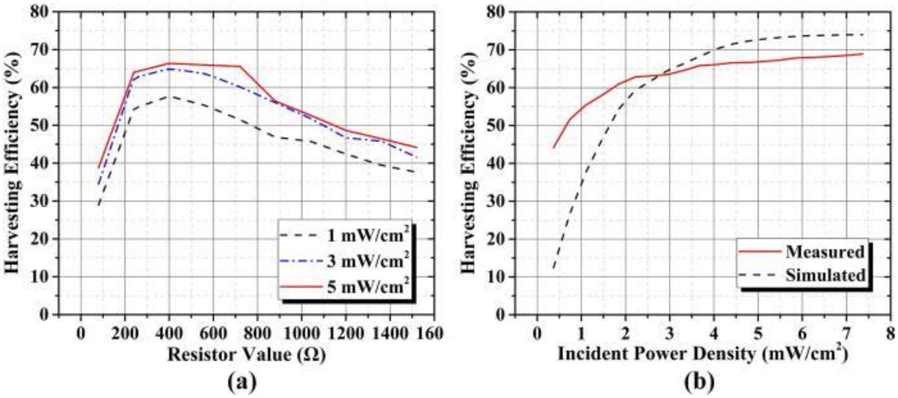


FIG. 5. The measured harvesting efficiency (a) as a function of the resistor *R*, and (b) as a function of the incident power density compared with the simulation.

the comparisons of the measured and simulated harvesting efficiency as a function of the incident power density. It indicates that the harvesting efficiency rapidly rises as the input power level grows. When S_r=5 mW/cm^2 (the target incident power density of our design), an efficiency of 66.9% is observed in the experiment, while the simulation yields 72.9%. Due to the nonlinear characteristic of the diode, the rectifier's input impedance varies with the input power. The more the incident power density deviates from 5 mW/cm^2, the more significant the impedance mismatch becomes between the metamaterial particle and the rectifier. Therefore, the harvesting efficiency tends to saturate for power densities above 5 mW/cm^2, and slowly increases to the highest value 68.9% when S_r=7.4 mW/cm^2, compared with a simulated efficiency of 74%. Overall, these measurement results demonstrated that the MRS achieves high harvesting efficiency which is desirable in practical MPT applications. The difference between the measurement and simulation may be caused by the inaccuracy of the diode's equivalent model in ADS under large signals. The fabrication flaws of the MRS may also affect the performance.

In conclusion, we present an EM energy MRS with high harvesting efficiency. Fabricated on a three-layer PCB, it comprises an array of periodic metamaterial particles, a metal ground, and integrated rectifiers. Perfect impedance matching is realized at the interface between free space and the surface, as well as the interface between the metamaterial particles and the rectifiers. Therefore, the MRS is able to almost fully capture the incident EM energy, and maximally convert it to DC power. To verify the design, such a MRS with 6×6 unit cells is manufactured and tested. The experimental results show that under a power density of 5 mW/cm^2, 66.9% of the incident 2.45 GHz microwave is rectified, compared with a simulated efficiency of 72.9%. The high harvesting efficiency enables the proposed MRS to serve in place of a commonly used rectenna for practical MPT applications.

[1] P. E. Glaser, Science **162**(3856), 857–886 (1968).
[2] W. C. Brown, IEEE Trans. Microwave Theory Tech. **32**(9), 1230–1242 (1984).
[3] J. C. Lin, IEEE Microwave Magazine **3**(1), 36–42 (2002).
[4] J. O. McSpadden and J. C. Mankins, IEEE Microwave Magazine **3**(4), 46–57 (2002).
[5] B. Strassner and K. Chang, Proceedings of the IEEE **101**(6), 1379–1396 (2013).
[6] B. Strassner and K. Chang, IEEE Trans. Antennas Propag. **51**(6), 1347–1356 (2003).
[7] J. O. McSpadden, L. Fan, and K. Chang, IEEE Trans. Microwave Theory Tech. **46**(12), 2053–2060 (1998).
[8] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184–4187 (2000).
[9] D. Schurig, J. Mock, B. Justic, S. Cummer, J. Pendry, A. Starr, and D. Smith, Science **314**, 977–980 (2006).
[10] J. Pendry, Phys. Rev. Lett. **85**, 3966–3969 (2000).
[11] I. V. Shadrivov, A. B. Kozyrev, D. W. van der Weide, and Y. S. Kivshar, Appl. Phys. Lett. **93**, 161903 (2008).
[12] H. Attia, L. Yousefi, M. M. Bait-Suwailam, M. S. Boybay, and O. M. Ramahi, IEEE Antennas Wirel. Propag. Lett. **8**, 1198–1201 (2009).
[13] Z. Duan, J. S. Hummelt, M. A. Shapiro, and R. J. Temkin, Phys. Plasmas **21**, 103301 (2014).
[14] D. Schurig, J. J. Mock, and D. R. Smith, Appl. Phys. Lett. **88**, 041109 (2006).
[15] G. Yang, X. Liu, Y. Lv, J. Fu, Q. Wu, and X. Gu, J. Appl. Phys. **115**, 17E523 (2014).
[16] Y. Cheng, Y. Wang, Y. Nie, R. Z. Gong, X. Xiong, and X. Wang, J. Appl. Phys. **111**, 044902 (2012).
[17] T. S. Almoneef and O. M. Ramahi, Appl. Phys. Lett. **106**, 153902 (2015).
[18] A. M. Hawkes, A. R. Katko, and S. A. Cummer, Appl. Phys. Lett. **103**, 163901 (2013).

[19] R. Wang, D. Ye, S. Dong, Z. Peng, Y. Salamin, F. Shen, J. Huangfu, C. Li, and L. Ran, IEEE Trans. Microwave Theory Tech. **62**(4), 1080–1089 (2014).
[20] O. M. Ramahi, T. S. Almoneef, M. AlShareef, and M. S. Boybay, Appl. Phys. Lett. **101**, 173903 (2012).
[21] S. Venkatesh, D. Shrekenhamer, W. Xu, S. Sonkusale, W. Padilla, and D. Schurig, Appl. Phys. Lett. **103**, 254103 (2013).
[22] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, Phys. Rev. E **71**, 036617 (2005).