Efficient Metasurface Rectenna for Electromagnetic Wireless Power Transfer and Energy Harvesting

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Abstract—This work presents a design for a metasurface that provides near-unity electromagnetic energy harvesting and RF channeling to a single load. A metasurface and a feeding network were designed to operate at 2.72 GHz to deliver the maximum power to a single load. Numerical simulations show that the metasurface can be highly efficient delivering the maximum captured power to one load using a corporate feed network reaching Radiation-to-RF conversion efficiency as high as 99%. A prototype was fabricated incorporating a rectification circuit. Measurements demonstrated that the proposed metasurface harvester provides Radiation-to-DC conversion efficiency of more than 55%, which is significantly higher than earlier designs reported in the literature.

1. INTRODUCTION

Wireless power transfer is the process of transferring power between remote devices and converting it to usable electrical energy. The most important aspect of the energy transfer link is the Radiation-to-RF conversion and RF-to-DC conversion. The primary objective of this work is to provide a design that maximizes the conversion efficiency between the incident electromagnetic radiation and the DC power at the receiving load. In energy harvesters, the main energy collectors are conventional antennas and rectifiers (rectennas). Previous works utilizing rectennas to harness the energy from space and the surrounding environment have focused primarily on the AC to DC conversion efficiency [1, 2]. Generally, any enhancements in recetnna systems are focused on the rectifier circuit and the matching circuit, rather than the antennas.

Recently, interest has been growing in using metamaterial cells as electromagnetic collectors. Metamaterials are artificial electromagnetic materials engineered to allow manipulation of the electromagnetic field through control of the permittivity and permeability of the material [3]. The property of tuning the permittivity and permeability of the metamaterials have led to full absorption by matching the material surface impedance to the free-space impedance. Various metamaterial absorber designs have been proposed to operate in both the microwave and infrared regimes [4]. Metamaterial designs for energy harvesting and absorption have been evolving rapidly to address different aspects such as polarization of the incident field, dual and multi bands harvesters, and multiple incident angles [5, 6]. The primary and most-important goal in all these designs is maximizing the energy harvesting per footprint. Energy collectors for either energy harvesting or wireless power transfer, however, require not only this important feature but also the ability to efficiency convert the RF energy collected by the antenna to DC power.

First, we propose a design for a unit cell that achieves near-unity Radiation-to-RF conversion efficiency operating in the microwave regime. Full absorption of the incident field occurs when the surface impedance of the cell is matched to the free-space wave impedance. The unit cell employed in

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this work is the Electric Inductive Capacitive (ELC) resonators [7]. After achieving full absorption, the same unit cell design was used to channel the received RF power to a load through a via. Then, an array of the ELC resonators, operating in the microwave regime, is proposed to maximize energy collection per footprint. A mechanism is then proposed that channels the energy received from all individual cells into one shared load rather than each cell channeling the energy to its own individual load. Finally, a prototype of the metasurface is fabricated along with a rectifier circuit. Validation is carried out through measuring the collected DC power in an anechoic chamber setting. We emphasize that the energy harvesting system presented in this work is composed of sub-blocks proposed in earlier works for energy absorption and metasurface antennas [7, 8].

2. DESIGN METHODOLOGY

Figure 1 shows the ELC resonator element (unit cell) used in this work to collect the EM energy. The cell consists of two split-ring resonators joined and placed opposite to each other. The host material is a Rogers RT6006 substrate with a thickness of $t = 2.5$ mm and a dielectric constant of $\epsilon_r = 6.15$ and a loss tangent of $\tan \delta = 0.0027$. The cell is backed by a highly conducting plane as shown in Fig. 1. The geometric dimensions of the cell were optimized to achieve full absorption at 2.72 GHz. There was no particular reason for choosing this frequency except as a demonstrative example. The optimization resulted in the following design parameters: strip length: $L = 7$ mm, strip width: $W1 = 1.2$ mm, width of the parallel wire: $W2 = 0.5$ mm, split gap: $g = 0.5$ mm, separation distance: $S = 0.25$ mm, and copper thickness of $t = 35$ μm (see Fig. 1).

The individual unit cells for the harvester were designed using the commercial 3D electromagnetic full-wave simulation software CST MICROWAVE STUDIO 2015 [9]. To examine the S-parameter properties of the cell, the unit cell was placed in the center of a waveguide with a perfect electric wall in the xz-plane, a perfect magnetic wall in the xy-plane, and two open ports in the z-directions (see Fig. 1 for the reference coordinates system). Such particular boundary conditions were chosen to ensure that the electric and magnetic fields were parallel to the metallic surface of the ELC resonator [10].

One can calculate the absorption of the unit cell using the S-parameters (S_{21} and S_{11} are the transmission and reflection coefficients, respectively) produced by the simulation. The absorption of the unit cell is obtained by the formula $A = 1 - S_{11}^2 - S_{21}^2$. Full absorption can be achieved by tuning ϵ and μ of the unit cell to match the metamaterial impedance to the free space impedance $377\,\Omega$ thus ensuring no reflectance occure. Full absorption also requires zero transmission, which can be done by using another layer serving as a ground plane. Fig. 2 shows the reflectance and absorbance of the proposed cell at 2.72 GHz, where the peak absorption was 99.9% and the bandwidth was. Both the
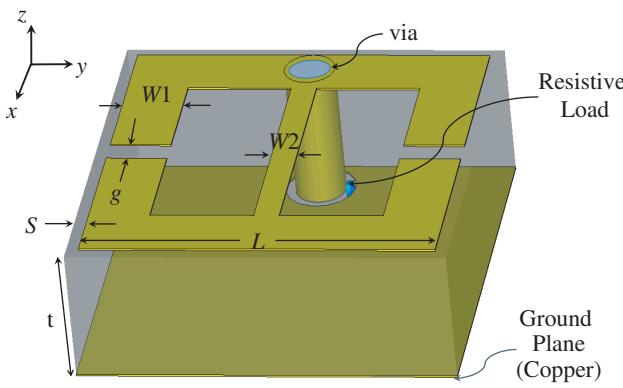
Figure 1. A schematic of the ELC unit cell. The incident field is a plane wave incident in the $-z$ direction and E-polarized in the x direction.
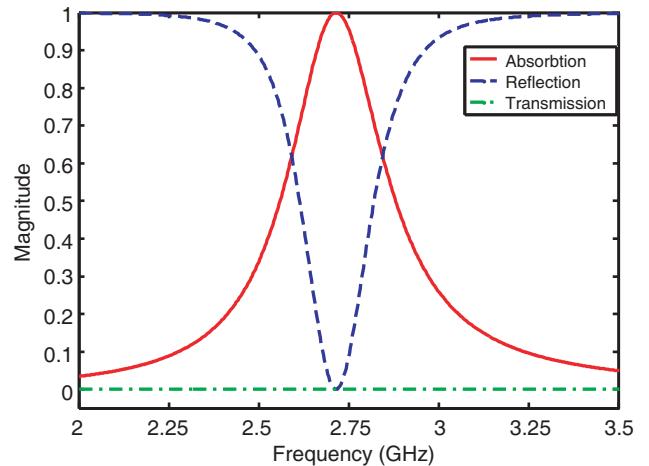
Figure 2. Simulation results of perfect metamaterial absorber: absorption, reflection and transmission.

absorber and harvester are tremendously affected by the small distance between the cells, because the coupling plays a key role of changing the metamaterial unit cell input impedance [11].

The critical design parameters for the energy harvesting unit cell are the optimal resistive load and the via position. The optimized resistance value was found to be $180\,\Omega$, which equal the impedance of the ELC resonator (as seen from the load). Having these matched impedance values ensured that maximum power was transferred from ELC to the load. The via was placed at the top of the ELC to create a path for the current to flow from the surface of the ELC to the resistive load (see Fig. 1).

3. METASURFACE ARRAY

For practical scenarios, an array is needed to supply a device or a system with sufficient power. Therefore, an array of 8×8 cells occupying a footprint of $60\,\text{mm} \times 60\,\text{mm}$ was designed as shown in Fig. 3. The entire array was numerically tested by placing it in the center of an open radiation box while excited by a plane wave polarized in the x direction and incident normally onto the surface. Both AC and DC energy conversion efficiencies were calculated as in [4]:

$$\eta = \frac{P_{\text{received}}}{P_{\text{incident}}},$$

where P_{received} is the total time-average power received by the metasurface array (dissipated in the resistive load), and P_{incident} is the total time average power incident on the array. When calculating the Radiation-to-RF conversion efficiency, P_{received} is measured across the optimal resistive load of $180\,\Omega$, whereas when calculating the Radiation-to-DC conversion efficiency, P_{received} is measured across a load placed at the output of a rectification circuitry.

In recent work, a metasurface array was designed using a corporate feed network, achieving a Radiation-to-RF conversion efficiency of 89% [8]. The design of the metasurface presented here achieved a Radiation-to-RF conversion efficiency of 99%, which is almost 10% increase in efficiency than in [8]. In energy harvesting and transfer consideration, 10% increase in efficiency is a significant improvement considering the impact on power consumption throughout the lifetime of the device.

The main idea behind the feed network is to channel the overall energy collected by the array to one resistive load by matching the unit cell impedance to the load impedance. A 0.5 mm Rogers
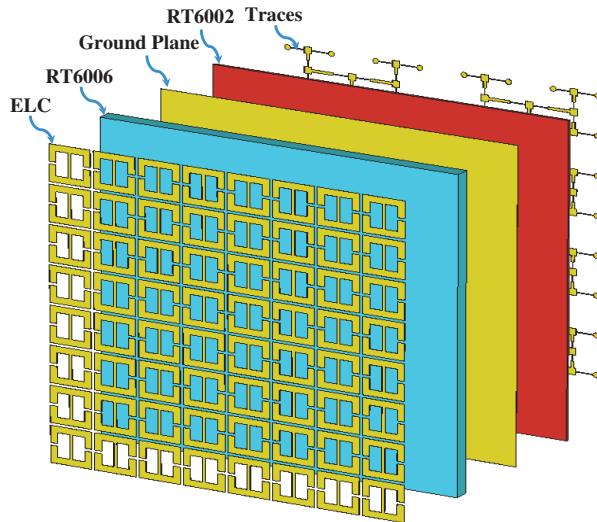
Figure 3. Schematic of the metasurface shown as an exploded view including the ELC resonators, Rogers RT6006 material as the first substrate, ground plane (copper), Rogers RT6002 as the second substrate, and the transmission line traces.
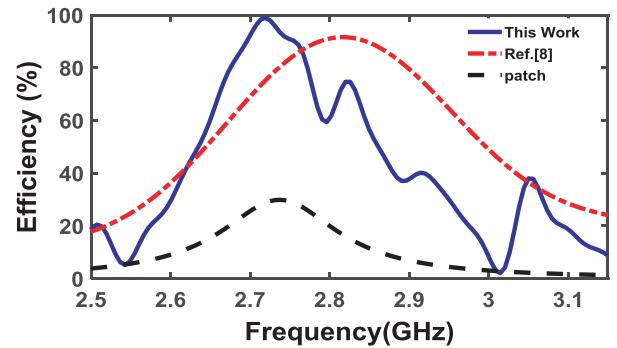
Figure 4. Comparison between the simulated Radiation-to-RF conversion efficiency of the metasurface design introduced here, the patch antenna and the metasurface design in [8].

RT6002 substrate having a dielectric constant of $\epsilon_r = 2.94$ and a loss tangent of $\tan \delta = 0.0012$ was attached underneath the ground plane to host the routing mechanism. As pointed above, each element has an optimal $180\,\Omega$ impedance value. The resistive load value was chosen as $50\,\Omega$ to match common measurement devices, which are mostly based on $50\,\Omega$ systems. This choice has significant advantages in the measurements stage, thus eliminating the need for a matching circuit. The routing mechanism employed a corporate feed network reported earlier in the design of metasurface antennas [8] (the details are not provided here for brevity).

4. SIMULATION RESULTS

Figure 4 shows the simulated Radiation-to-RF conversion efficiency of the proposed harvester. Comparison is made to [8]. High conversion efficiency of approximately 99.4% is observed at the resonance frequency. Additional comparison is made to a conventional microstrip patch antenna designed to operate at the same frequency. For fair comparison using the most critical criteria of energy harvesters, namely their physical footprint, we could only position one patch antenna on the area of the harvester (viz., 60 mm × 60 mm). As shown in Fig. 4, the metasurface harvester produced significantly more power than the patch antenna. We note that the placement of additional microstrip patches provided lower absorption than a single patch (the results are not shown here for brevity).

5. EXPERIMENTAL VERIFICATION AND DISCUSSION

An 8×8 elements metasurface antenna was fabricated based on the simulated design. In the simulation, the minimum width of the transmission lines was $0.0224\,\text{mm}$ for $180\,\Omega$ transmission line. Due to lab fabrication limitations that require a minimum transmission line width of $0.1\,\text{mm}$, a $0.1\,\text{mm}$ for $180\,\Omega$ transmission line has been used instead of a $0.0224\,\text{mm}$ one. Fig. 5 shows the fabricated metasurface harvester. A rectifier was then designed using Agilent Advance Design Systems (ADS) having an input impedance of $50\,\Omega$ at the resonance frequency. The diode was connected to the feed of the antenna through a matching network containing a short circuited stub, open circuited stub and a series transmission line. Then a DC filter containing two series transmission lines and two open circuited stubs connected to the HSMS 2860 Schottky diode along with a $150\,\text{pF}$ capacitance and a resistive load. Fig. 6(a) shows the design schematic with parameters' values of the rectification circuit. The fabricated rectifier is shown in Fig. 6(b).

(a)   (b)
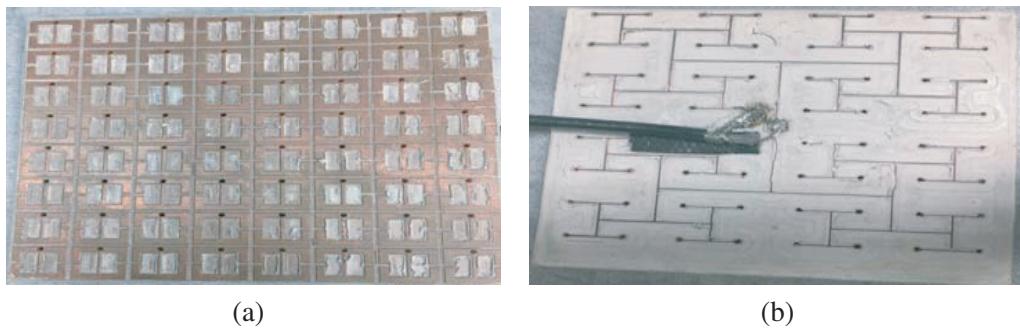
Figure 5. The fabricated metasurface, (a) top view, (b) bottom view.

The received power was measured in an anechoic chamber. The metasurface antenna was placed at a distance of 1 m away from the transmitting antenna such that the electric field is parallel to the arm of the ELC cell containing the via (see Fig. 1) and also to ensure far-field behavior. For a frequency of 2.85 GHz, the diode operates most efficiently when the power of the source is $-2\,\text{dBm}$ and a load resistance of $200\,\Omega$. (Note the slight shift in the frequency of maximum efficiency is due to change in feed lines width and fabrication imperfections.) The peak Radiation-to-DC power conversion efficiency of the array including the rectifier was 55% at 2.85 GHz and 51% at 2.72 (see Fig. 7). The proposed

(a)   (b)
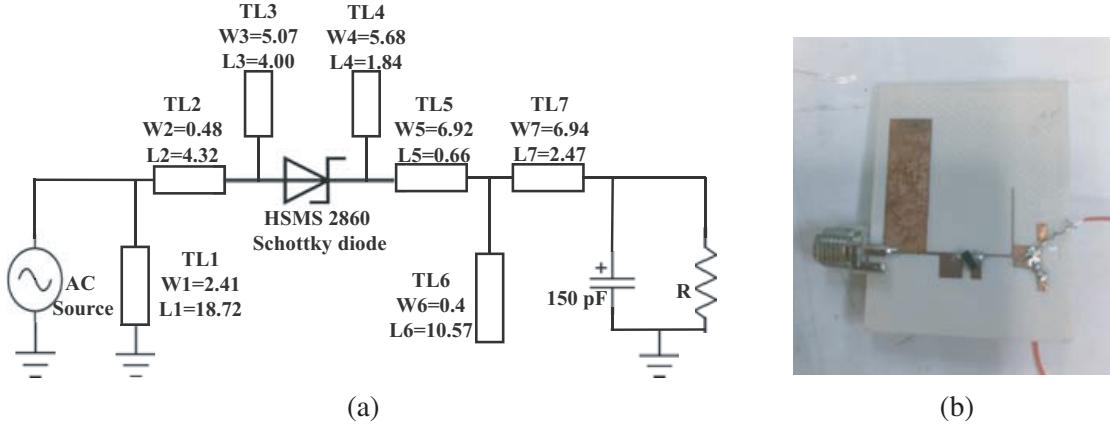
Figure 6. Rectifier circuit, (a) schematic design showing the transmission lines' widths and lengths, (b) photograph of the fabricated rectifier.
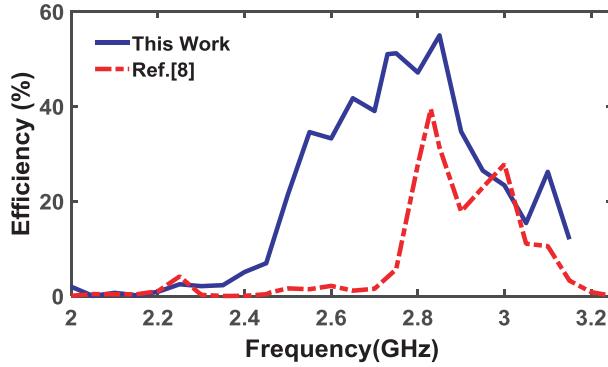
Figure 7. The measured Radiation-to-DC efficiency of the metasurface harvesters and the metasurface in [8].

harvester has higher RF Radiation-to-DC efficiency than the previous work [8] as shown in Fig. 7 by more than 10%.

6. CONCLUSION

This work presented an efficient metasurface rectenna for wireless power transfer based on the full absorption technique. A unit cell was designed showing a high capability to absorb and channel practically all the power of the incident wave into AC power (99%). An ensemble of 8×8 ELC cells was designed using a corporate feed network to channel the power to one load. For validation, the metasurface array was fabricated and tested showing a maximum Radiation-to-DC conversion efficiency of 55%, which is 15% higher than what was achieved in previous works.

In our future work, our main goal for energy harvesters will be suppling low-power for small electronic systems. By converting surrounded electromagnetic energy to electric power, these energy harvesters will be optimal candidates to replace batteries [12].

ACKNOWLEDGMENT

REFERENCES

1. Brown, W. C., "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," *NASA STI/Recon Technical Report N*, Vol. 77, 31613, 1977.

2. Suh, Y.-H. and K. Chang, "A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 7, 1784–1789, 2002.

3. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, Vol. 292, No. 5514, 77–79, 2001.

4. Ramahi, O. M., T. S. Almoneef, M. Al Shareef, and M. S. Boybay, "Metamaterial particles for electromagnetic energy harvesting," *Applied Physics Letters*, Vol. 101, No. 17, 173903, 2012.

5. El Badawe, M. and O. Ramahi, "Polarization independent metasurface energy harvester," *Wireless and Microwave Technology Conference (WAMICON), 2016 IEEE 17th Annual*, 1–3, IEEE, 2016.

6. Gunduz, O. and C. Sabah, "Polarization angle independent perfect multiband metamaterial absorber and energy harvesting application," *Journal of Computational Electronics*, Vol. 15, No. 1, 228–238, 2016.

7. Padilla, W., M. Aronsson, C. Highstrete, M. Lee, A. Taylor, and R. Averitt, "Electrically resonant terahertz metamaterials: Theoretical and experimental investigations," *Physical Review B*, Vol. 75, No. 4, 041102, 2007.

8. El Badawe, M., T. S. Almoneef, and O. M. Ramahi, "A metasurface for conversion of electromagnetic radiation to dc," *AIP Advances*, Vol. 7, No. 3, 035112, 2017.

9. Suite, C. S., "Computer simulation technology," CST Computer Simulation Technology AG, www.cst.com, 2017.

10. Schurig, D., J. Mock, and D. Smith, "Electric-field-coupled resonators for negative permittivity metamaterials," *Applied Physics Letters*, Vol. 88, No. 4, 041109, 2006.

11. Landy, N., S. Sajuyigbe, J. Mock, D. Smith, and W. Padilla, "Perfect metamaterial absorber," *Physical Review Letters*, Vol. 100, No. 20, 207402, 2008.

12. Kawahara, Y., K. Tsukada, and T. Asami, "Feasibility and potential application of power scavenging from environmental RF signals," *IEEE Antennas and Propagation Society International Symposium, 2009, APSURSI'09*, 1–4, IEEE, 2009.