Rectifying Metasurface with High Efficiency at Low Power for 2

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October 30, 2023

Abstract

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is a two-sided structure consisting of modified electric inductive-capacitive unit cells on one side and a rectifying circuitry on the other, designed to resonate and rectify at 2.45 GHz. Each unit cell is directly connected to a voltage doubler rectifier, allowing the incident microwaves to be directly rectified upon reception. The impedance characteristics and rectification performance of the proposed rectifying metasurface are tested via numerical simulation

and measurement, respectively. The measured results demonstrate the overall conversion efficiency electromagnetic power absorption + rectification) of 75% at 0.4 dBm incident power.

Rectifying Metasurface with High Efficiency at Low Power for 2.45GHz Band

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***Abstract*— This letter presents a novel rectifying metasurface with high efficiency at low power applicable to wireless power transfer and energy harvesting. The proposed rectifying metasurface is a two-sided structure consisting of modified electric inductive-capacitive unit cells on one side and a rectifying circuitry on the other, designed to resonate and rectify at 2.45 GHz. Each unit cell is directly connected to a voltage doubler rectifier, allowing the incident microwaves to be directly rectified upon reception. The impedance characteristics and rectification performance of the proposed rectifying metasurface are tested via numerical simulation and measurement, respectively. The measured results demonstrate the overall conversion efficiency (electromagnetic power absorption + rectification) of 75% at 0.4 dBm incident power.**

***Index Terms*— Wireless Power Transfer, Energy Harvesting, Metamaterials, Metasurface, Rectifiers**

I. Introduction

With ever-increasing use of electronic devices, recent years have seen a surge in demand for wireless charging for a range of applications. Wireless power transfer (WPT) and energy harvesting (EH) play a key role in realizing wireless charging of various electronic devices and systems. In particular, the use of microwaves has been considered promising and practically realizable. That is, microwave transmitters for WPT can be designed and implemented with relative ease and lower cost compared to other higher frequency regimes, and for EH there are various ambient microwave signals that are readily available (i.e. GSM, LTE, Wi-Fi, etc.) for harvesting. While both microwave WPT and EH are based on far-field radiation that allows for longer distances between source and receiver compared to magnetic coupling, the spreading of radiated waves inherently limits the overall source-to-receiver efficiency. For WPT, measures such as beamforming can be applied on the transmit side to help make up some radiation loss, but the receiver must also be designed to maximize power reception and rectification. For EH, designing an efficient receiver is even more essential as one does not have any control over the design of the transmitter.

One way to increase the energy efficiency on the receive side is to use a metasurface. A metasurface is a subset of metamaterials that is configured in the form of a thin structure. The use of metamaterials allows one to control the effective permittivity and permeability to match the impedance for perfect wave absorption, which can provide higher power absorption (aperture) efficiency than using conventional antennas (or antenna arrays). To this end, various designs of metasurface structures loaded with resistors have been proposed with excellent power absorption efficiencies [1-9].

However, in the context of WPT and EH, the overall EM-to-DC efficiency of the receiver must include not only the absorption efficiency (the measure of the portion of the incident EM waves captured by the receiving structure), but also the rectification efficiency (the measure of RF-to-DC conversion of the captured waves). Hence, in order to fully account for the overall efficiency of a metasurface receiver, the whole system aspect (i.e. metasurface + rectifier) must be considered. In this regard, several studies have been presented in recent years that consider various designs of metasurfaces fully integrated with rectifiers (hereafter referred to as “rectifying metasurfaces”) [10-18].

In this letter, we propose a novel rectifying metasurface designed for 2.45 GHz band that offers high efficiency at relatively low power compared with the previously reported works. The proposed rectifying metasurface is a two-layer structure, one side comprising modified electric-inductive-capacitive (ELC) unit cells and the other side consisting of a rectifier for each unit cell. The efficiency and rectification performance of the proposed rectifying metasurface are validated via numerical simulation and measurement, and the results demonstrate an overall efficiency of 75 % at 0.4 dBm of incident power.

II. Unit Cell Design

Fig. 1 shows the proposed rectifying metasurface unit cell. The rectifying metasurface is a two-sided structure consisting of two dielectric laminates separated by a ground plane. The front side includes metasurface unit cells, while the backside contains a rectifying circuitry. Each metasurface unit cell is directly connected to a voltage-doubler rectifier through a via. This makes the number of rectifiers as many as the unit cells. For the front laminate on which the metasurface unit cells are

Manuscript received ---- ---, 2019. This work was supported by the National Research Foundation of Korea under grant NRF-2017R1C1B5018179 and Office of Naval Research Global under grant N62909-19-1-2049. (*Corresponding author: Sun K. Hong*)

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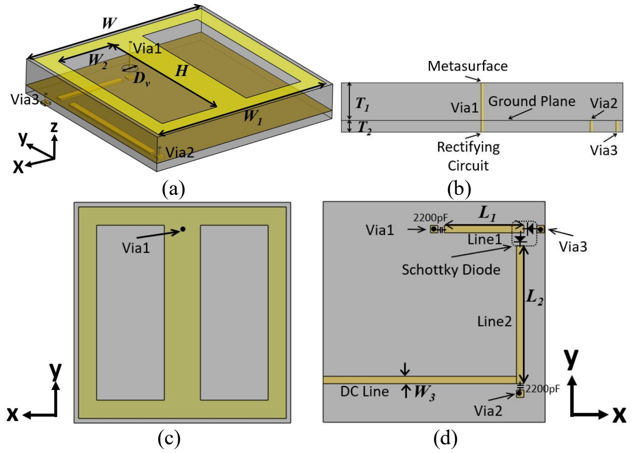


Fig. 1. Unit cell design of the proposed rectifying metasurface: (a) an overall view, (b) side view, (c) front view and (d) bottom view.

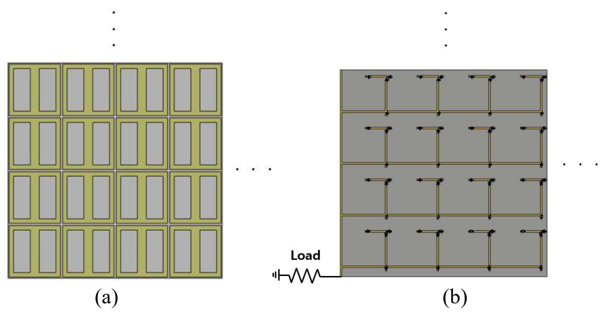


Fig. 2. Illustration of a multi-unit cell structure of the proposed rectifying metasurface: (a) front and (b) back. All DC lines from unit cell are combine in parallel and connected to a load.

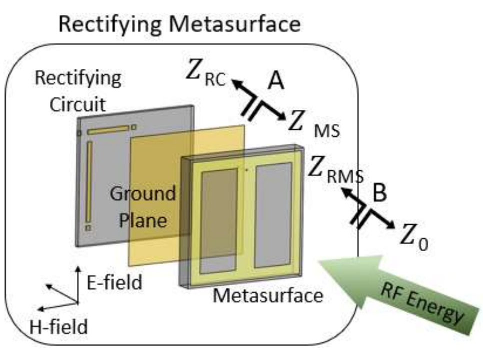


Fig. 3. Breakdown of each layer and impedance matching point in the proposed metasurface.

printed, a 3.175-mm-thick TACONIC TLX-8 (ε_r = 2.55) substrate is used. For the backside laminate where rectifier circuitry is printed, a 1.143-mm-thick TACONIC TLX-9 (ε_r = 2.5) substrate is used. All metal layers are made of copper.

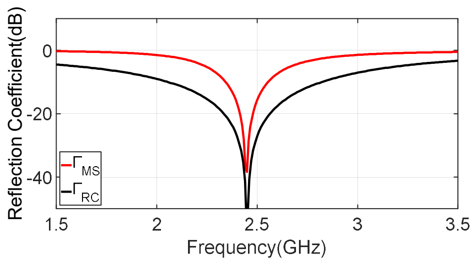
The proposed metasurface unit cell design is based on an ELC structure [7,13,19]. The ELC structures feature a relatively simple design and couple strongly to incident electric fields with the broadside parallel to the direction of the electric field. For this reason, this structure can be conveniently incorporated into a 2-D planar structure [19]. Here, we implement a modified ELC design by closing the gap in the middle column, as shown in Fig. 1a, to obtain optimal impedance. Since Via 1 (and via hole) generates an extra capacitance, closing the gap in the unit cell allows for this extra capacitance to be removed, thereby maintaining resonance at the intended frequency without much modification on the basic unit cell structure. Note that the basic shape of the unit cell is a square (i.e. $W\times W$ and $W_1\times W_1$).

For each unit cell, a voltage doubler rectifier is printed on the backside as shown in Fig. 1d. The rectifier starts with a series charging capacitor (2200 pF) connected to Via 1, followed by a section of microstrip line (Line 1) which leads to series and parallel Schottky diodes (SMS-7630). Another section of microstrip line (Line 2) connects the series diode with a parallel capacitor (2200 pF) and DC line. The same width is used for all three microstrip lines (i.e. Line1, Line2, and DC line). In a multi-unit cell structure, DC lines from the unit cells would be combined in parallel and eventually be connected to a load as illustrated in Fig. 2.

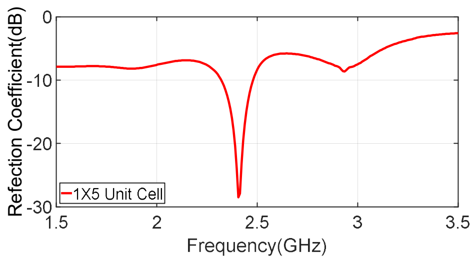
To maximize efficiency, impedance matching must take place at two points, namely A and B, as depicted in Fig. 3. At point A, which is the port created by Via 1, the impedance looking into the rectifier (Z_{RC}) needs to match the impedance looking into the metasurface (Z_{MS}). At point B, the impedance of the rectifying metasurface (Z_{RMS}) should match the impedance of air (Z_0). The parameters of the metasurface unit cell (i.e. L_1, L_2, L_3, and W_1) and rectifier circuit (i.e. L_4, L_5, and L_7) were adjusted to optimize impedance matching at points A and B. In the design and optimization process, SEMCAD X, a finite-difference time-domain full-wave solver [20], was used for modeling and simulation, where lumped element equivalent circuit models were used for Schottky diodes [21]. In addition, due to the nonlinear effects in the rectifier [22, 23], the design process must involve the dependence of the rectifier circuit on input power. To this end, we have performed impedance matching using an equivalent circuit model in ADS at the target input power and frequency of 0 dBm and 2.45GHz, respectively. Using the impedance of the rectifier obtained in the circuit simulation (at 0 dBm input power) as a load termination at the via hole, we then performed design optimization of the metasurface structure via full-wave EM simulation. The optimized parameters are listed in Table 1. In Fig. 4a the simulated reflection coefficients at point A looking into the rectifier and metasurface, Γ_{RC} and Γ_{MS}, respectively, are plotted. In Fig. 4b, the reflection coefficient of the rectifying metasurface at point B, Γ_{RMS}, is plotted. Here, the metasurface consists of 1x5 unit cells as used in measurement. In both plots, matched impedances (< -10 dB) are observed around the intended frequency of 2.45 GHz.

TABLE 1.
OPTIMIZED DESIGN PARAMETERS

Parameter	Value(mm)
W	24
W_1	23
W_2	7.5
W_3	0.8
H	19
L_1	8.6
L_2	15
T_1	3.175
T_2	1.143
D_v	1.8



(a)



(b)

Fig. 4. Simulated reflection coefficients vs. frequency at: (a) Point A and (b) Point B(single unit cell and 1x5 unit cell).

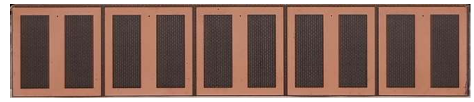
III. Measurement

To validate the performance of the proposed rectifying metasurface, a 1×5 structure was fabricated, as shown in Fig. 5. A 38-μm-thick TACONIC TacBond HT 1.5 (ε_r = 2.35) bondply was used to attach the two substrates. The fabricated rectifying metasurface was specifically configured to have a single row, so as to be measured in a quasi-2D setting using a parallel-plate apparatus. A parallel-plate waveguide environment allows waves to be contained within the plates while effectively maintaining the TEM wave characteristics. Therefore, measurements can be carried out using lower transmit power than that required for free-space measurements. Microwave absorbers were placed on all four sides to minimize the reflections from the edges of parallel plates, in order to better mimic the case of a plane wave incidence. The measurement setup is shown in Fig. 6, where Fig. 6a shows the actual photo of the metasurface placed in the parallel plates and Fig. 6b shows a diagram of the measurement setup. On the transmit side, a signal generator (Agilent E4436B) and power amplifier (MILMEGA AS0825) were used, whose output is directly connected to the feed probe of the parallel plate waveguide. The feed probe was placed 15 cm from the rectifying metasurface, which is sufficient for any non-propagating waves to be negligible [24]. The end of DC line and ground plane from the rectifying metasurface were connected to an electronic load (Prodigit 3312D) with wires to measure rectified DC voltage.

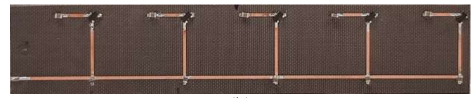
The overall EM-to-DC efficiency includes both the absorption efficiency of the metasurface and RF-to-DC conversion efficiency of the rectifying circuit. The EM-to-DC efficiency η can be calculated as follows:

$$\eta = P_{DC} / P_{inc} \tag{1}$$

where P_{DC} is the DC output power at the load and P_{inc} is the power incident over the cross-section of the metasurface. In our quasi-2D parallel-plate waveguide environment, waves spread radially and P_{inc} can be obtained as:

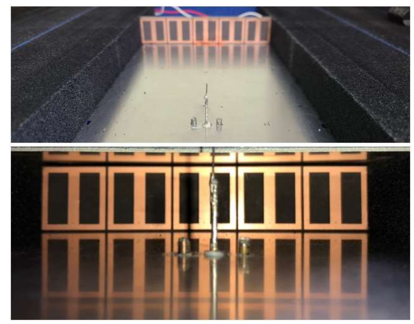


(a)

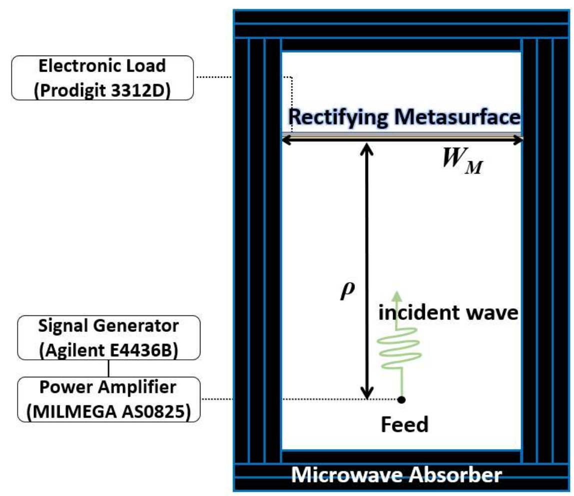


(b)

Fig.5 Fabricated 1 × 5 rectifying metasurface used in measurement: (a) front and (b) back.



(a)



(b)

Fig. 6. Measurement setup of the proposed rectifying metasurface: (a) photo of the metasurface placed inside the parallel plate waveguide, and (b) measurement setup diagram, where ρ =15cm and W_M=12mm.

$$P_{inc} = \frac{P_t}{2\pi} \int_{-W_M/2}^{W_M/2} \frac{1}{\sqrt{x^2+\rho^2}} dx \tag{2}$$

where P_t is the power transmitted from the feed probe, W_M is the width of the rectifying metasurface, and ρ is the radial distance between the feed probe and rectifying metasurface. To accurately obtain P_t, the cable loss and mismatch loss at the feed must be taken into account, i.e.

$$P_t = P_{amp} L_c^2 \left(1 - |S_{11}|^2\right), \tag{3}$$

where P_{amp} is the output power of the amplifier, L_c is the cable loss, S_{11} is the reflection coefficient at the feed. The DC output power is calculated from the DC voltage as

$$P_{DC} = V_{DC}^2 / R_L, \tag{4}$$

where R_L and V_{DC} are the load resistance and rectified DC voltage, respectively.

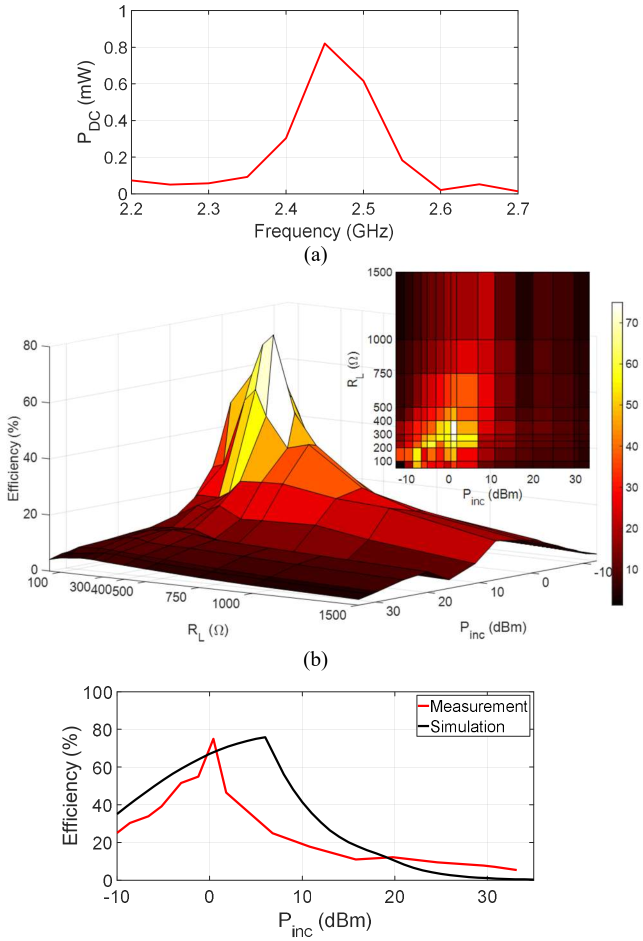


Fig. 7. Plots of measured results: (a) Measured DC power vs. frequency at 300 Ω load for P_{inc} = 0.4 dBm, (b) Measured efficiency as a function of R_L and P_{inc} 2.45 GHz, and (c) Measured efficiency vs. input power at 2.45GHz with 300Ω load in comparison to the simulation.

The first set of measurement was to validate the operating frequency of the proposed rectifying metasurface. To this end, a frequency sweep was performed from 2.2 to 2.7 GHz at an increment of 0.5 GHz. Here, R_L was set at 300 Ω, which is found to be an optimal value from simulation. Fig. 7a shows the resulting P_{DC} vs. frequency when P_{inc} is 0.4 dBm. A maximum value of P_{DC} is observed at 2.45 GHz, validating the design frequency of the rectifying metasurface.

The next set of measurement was to validate optimal load resistance and incident power. Using the electronic load, a load sweep was performed at various discrete R_L between 50 and 1500 Ω. An incident power sweep was also performed at various discrete values of P_{inc} between -10 to 36 dBm. Fig. 7b shows efficiency vs. R_L and P_{inc} at 2.45 GHz, which shows that a maximum efficiency occurs for R_L = 300 Ω at P_{inc}= 0.4dBm.

Fig. 7c shows the measured and simulated η vs. P_{inc} 2.45 GHz for R_L=300 Ω. The simulation was performed using ADS by importing the impedance characteristics of Ports A and B from full-wave simulation into the rectifier model, which allowed for the rectification simulation of the whole structure using an equivalent circuit model. As shown in the figure, the simulated and measured efficiencies show good agreement in general with a slight difference in the incident power level at which the maximum efficiency occurs. From the measured data, a maximum efficiency of 75% is observed at an incident power level of 0.4 dBm. Furthermore, at least 40% efficiency is maintained for incident power levels of -5 to 4 dBm. The efficiency seems to rapidly drop after 0.4 dBm possibly due to the impedance mismatch and diode breakdown at higher power levels. Table 2 compares the performance of the proposed rectifying metasurface with that of the ones from other recent works. In the table, only the references that feature fully rectifying metasurfaces (or metamaterials) are included for comparison of EM-to-DC efficiency. It can be seen that the proposed rectifying metasurface exhibits higher maximum efficiency at low power, indicating that it is well suited for WPT and EH at relatively low power (i.e. below 5 dBm).

IV. Conclusion

In this paper, a novel rectifying metasurface with high efficiency at low power designed for 2.45 GHz band was proposed and tested. The proposed rectifying metasurface utilizes a modified ELC structure with a voltage-doubler rectifier for each unit cell. The performance of the proposed structure was validated via simulation and measurement, where a maximum EM-to-DC efficiency of 75% is observed at an incident power level of 0.4 dBm, while at least 40% efficiency is maintained from -5 to 4 dBm. The design of the proposed structure can also be adopted for operation at other microwave frequencies. With high efficiency at relatively low power, the proposed rectifying metasurface can be utilized in various WPT and EH scenarios.

Table 2.
Performance Comparison with Other Reported Rectifying Metasurfaces.

Reference	Freq. (GHz)	Max. Efficiency (%)	Power Level (dBm)	Unit Cell Size(λ)	Resonator Structure	Rectifier
[10] (2013)	0.9	36.8	24	0.12	SRR	Voltage Doubler
[11] (2014)	1	25	-6	0.12	Gridded Square Loop FSS	Voltage Multiplier
[12] (2014)	2.18	28	0	0.21	I-shaped Resonator	Bridge Rectifier
[13] (2016)	2.45	66.9	10**	0.16	ELC Resonator	Half-wave Rectifier
[14] (2016)	2.45	67	10	0.12	SRR	Half-wave Rectifier
[15] (2017)	2.82	40	12	0.15	Electric Ring Resonator	Half-wave Rectifier
[16] (2017)	2.1	70	9	0.14	ELC Resonator	Half-wave Rectifier
[27] (2017)	6.75	50	0	0.67	Cut-Wire Resonator	Half-wave Rectifier
This work	2.45	75	0.4	0.19	Modified ELC Resonator	Voltage Doubler

**converted from 5mW/m^2 provided in [13]

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