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A 3-Dimensional Stacked Metamaterial Arrays for Electromagnetic Energy Harvesting

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Abstract—We present the design of 3-D metamaterial stacked arrays for efficient conversion of electromagnetic waves energy into AC. The design consists of several vertically stacked arrays where each array is comprised of multiple Split-Ring Resonators. The achieved conversion efficiency is validated by calculating the power dissipated in a resistive load connected across the gap of each resonator. Numerical simulations show that using stacked arrays can significantly improve the efficiency of the harvesting system in comparison to a flat 2-D array. In fact, the per-unit-area efficiency of the 3-D design can reach up to 4.8 times the case of the 2-D array. Without loss of generalization, the designs presented in this work considered an operating frequency of 5.8 GHz.

1. INTRODUCTION

The emergence of metamaterials has greatly expanded the boundary of electromagnetic research. Metamaterials can be realized by having a periodic or aperiodic arrangement of electrically-small resonators which produces material properties not available in nature such as negative permeability and/or permittivity. The possibility of unconventional permeability or permittivity values has enabled numerous and exciting applications such as flat lenses [1], directive emission [2], electromagnetic cloaking [3] and perfect absorbtion [4, 5]. In a recent article [6], a new application of metamaterials was introduced where electrically-small Split Ring Resonators (SRRs) were used for the first time for electromagnetic energy harvesting. When an SRR is excited by an impinging electromagnetic, electromagnetic energy is absorbed by the resonator and concentrates mostly within its gap. This mechanism is indicative of the ability of such resonators to absorb the electromagnetic energy from an incoming wave, which makes these resonators strong candidate as electromagnetic energy collectors in comparison to conventional antennas conceived originally for communication systems [6].

In difference to metamaterial absorbers where the energy is absorbed by structures tuned to have an impedance matched to the wave impedance in free space, our proposed mechanism is to harvest the energy stored within the gap of the resonator at the resonance frequency by inserting a resistive load across the gap of the resonator. The resistor represents a load that is the end recipient of the harvested energy. Here, we show that when an array of SRRs is used, a higher collection efficiency and a wider bandwidth can be achieved when compared to a single unit cell. This is because when placed in close proximity to each other, electrically small resonators interact (couple) in a manner different from coupling between conventional antennas [7].

In this work we present the design of vertically stacked SRR arrays [8]. We show through numerical simulations that when metamaterial arrays are stacked they significantly improve the total efficiency of the harvesting system. Here, we focus on the electromagnetic wave to AC conversion efficiency; however, one can extend the design to DC conversion by connecting a rectification circuitry at the feed of the resonator without changing the conclusion achieved in this work [9–11]. The structure designed here is demonstrated for conversion of microwave energy to AC. Extension to the infrared and visible

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spectra regimes is possible since SRR cells were shown to be scalable vis-a-vis their energy harvesting potential [12].

2. RESULTS AND DISCUSSION

Practical electromagnetic energy harvesting systems (i.e., solar cells) are primarily constrained by available area in m^2 such as the rooftop of a building or a piece of land. This fundamental constraint represents a *footprint* over which any system of energy collection has to be fitted. In a recent paper [13], a concept for solar energy harvesting in three dimensions using solar panels was presented. This work has similar theme in that a three-dimensional electromagnetic energy harvesting structure is presented. The mechanism in photovoltaic-based solar panels, however, is fundamentally different from the physics of energy collection in electrically-small resonators. Solar panels absorb energy and are opaque to incident solar rays in the sense that a panel covered by a panel placed above it will not absorb solar energy. Electrically-small resonators, on the other hand, are part of array-panels that are semi-opaque to incident electromagnetic waves. This fundamental difference allows for higher flexibility in three-dimensional stacking of SRR arrays as we show below.

A critical figure of merit that measures the effectiveness of the energy harvester in utilizing an available footprint is the efficiency of the system. The efficiency definitions commonly used in electromagnetic systems such as the absorption efficiency can provide information on the ability of collectors in general to scavenge energy but it does not give information relevant to the footprint constraint that is paramount here. The absorption efficiency, for instance, is indicative of the ability of the resonator to capture or block energy from passing through the absorber but it does not convey any information regarding energy delivery to the load. For example, In metamaterial absorbers where the absorption can reach close to 100%, some of the absorbed power is lost in the substrate holding the resonators' array. In fact, the main contributor for the absorbance in some structures is the dielectric loss [4]. Therefore, high energy absorption does not necessarily equate to high energy delivery to the load. A more meaningful definition had to be introduced in [6] that describes the ability of collectors to utilize the available electromagnetic energy on a given area and the ability of the collectors to deliver the absorbed energy to the load. The electromagnetic to AC conversion efficiency of an energy harvester occupying a specific footprint can be described by

$$\eta = \frac{P_{av}}{P_{area}} \tag{1}$$

where P_{area} is the total time-average power incident on the footprint, and P_{av} is the the maximum available time-average AC power received by the collector or by all collectors (i.e., SRRs) occupying the specific footprint under consideration and which is available at the feed terminal of the receiving collectors. Therefore, P_{av} is given by

$$P_{av} = \sum_{i=1}^{n} \frac{{V_i}^2}{R_i} \tag{2}$$

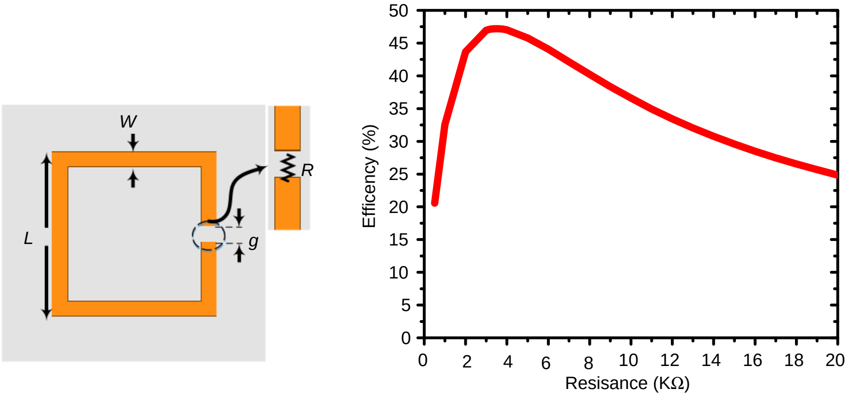
where V_i and R_i are the voltage across and the resistance of collector i. The total number of collectors on a specific footprint is denoted by n [6].

The efficiency of a 3-D electromagnetic harvesting structure is studied based on the efficiency definition presented above. A single unit cell of the proposed 3-D metamaterial collector consists of a metallic loop with a gap as shown in Figure 1(a). The metallic ring is placed on top of an RO4003 substrate having a thickness of $t = 0.813\,\mathrm{mm}$ and a dielectric constant of $\epsilon_r = 3.55$. The SRR was designed to resonate at around 5.8 GHz with dimensions of $L = 5.3\,\mathrm{mm}$, $g = 0.5\,\mathrm{mm}$, and $W = 0.5\,\mathrm{mm}$ (see Figure 1(a)). Using commercial electromagnetic full-wave simulator ANSYS-HFSS [14], the SRR was excited by a plane wave having different polarizations to test the ability of the resonator to capture the electromagnetic energy from various angles.

A resistive sheet is placed across the gap of the resonator which represents a load as shown in Figure 1(a). The resistance value is critical and has a great effect on the total efficiency of the resonator. According to the maximum power transfer theorem, maximum power is delivered to the load if the resistance of the load equals the Thevenin resistance seen at the gap of the resonator. To find such resistance value, a plot was generated using HFSS where the efficiency of a single resonator is calculated for a range of resistance values. Figure 1(b) shows that maximum power transfer to the load occurs when a resistor of $R = 3.5\,\mathrm{k}\Omega$ is placed across the gap of the SRR.

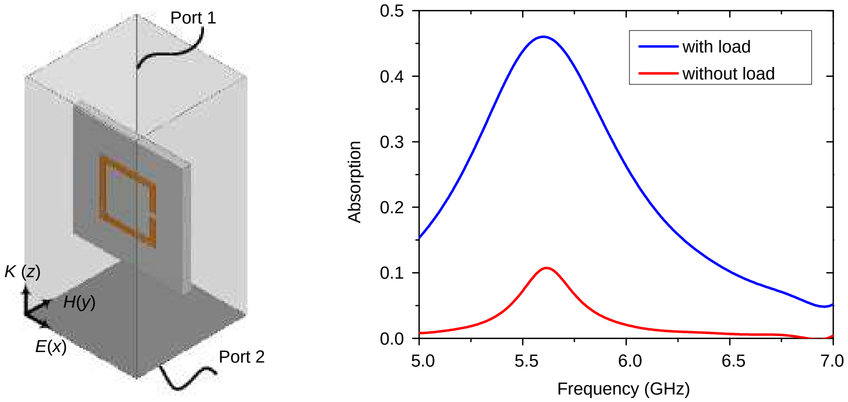
It is of interest to note that the role of the optimal resistor connected across the gap of the SRR is not only to harvest the energy stored within the gap but also to maximize the absorbed energy from the incoming wave. To this end we placed a single SRR in a waveguide with perfect electric boundaries at the y-z plane and perfect magnetic boundaries at the x-z plane as shown in Figure 2(a). The S-parameters were produced for two cases: an SRR cell with the same dimensions as above with and without a load. The absorption of the cell was calculated for the two cases by $A(\omega) = 1 - T(\omega) - R(\omega)$, where the reflection and transmission is obtained by $R(\omega) = |S(11)|^2$ and $T(\omega) = |S(21)|^2$ respectively [15] (the ports for the calculation of the S-parameters were indicated on Figure 2(a)). Figure 2(b) shows that the loaded SRR experienced an absorption improvement of 4.5 times the case without the loaded resistor. The dramatic improvement in the absorption and the bandwidth is attributed mainly to the presence of the optimal load connected across the gap. This is highly analogues to an RLC circuit where introducing loss in the circuit reduces the quality factor which in turn broaden the operating bandwidth of the circuit.

A single-array of the 3-D metamaterial harvester is designed using 5×5 SRR cells with separation distance between any two adjacent unit cells of $s = 3.5\,\mathrm{mm}$ as shown in Figure 3(a). The array occupies



(a) (b)

Figure 1. (a) Unit cell of the proposed 3-D metamaterial energy harvesting structure. (b) Efficiency as a function of the load resistance.



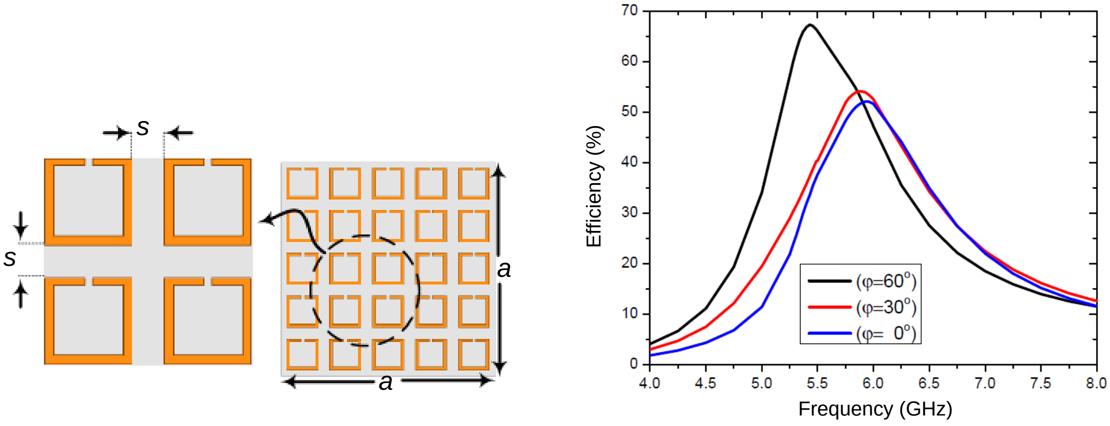
(a) (b)

Figure 2. (a) Simulation setup to study the absorption of a single SRR. (b) The absorption of a single SRR with (blue line) and without (red line) a load.

a footprint of $a \times a$ where $a = 44\,\text{mm}$. An advantage of metamaterial particles over other electromagnetic energy harvesters such as classical antennas is that the unit cell can be placed in close proximity to adjacent cells without degrading the total efficiency of the system. In fact, the coupling between SRR cells can indeed lead to improvement in both the efficiency and bandwidth. In the array, each SRR cell is loaded with a resistor of of $3.5\,\text{k}\Omega$. The array was illuminated by a plane wave and the efficiency of the array was numerically calculated for three angles $\theta = 0°$, $30°$, and $60°$ measured from a line parallel to the H-field vector as shown in the Figure 3(b). It is evident that the efficiency is higher for larger values of θ. This behaviour is expected as the H-field vector experienced by the resonators is higher for larger angles [16].

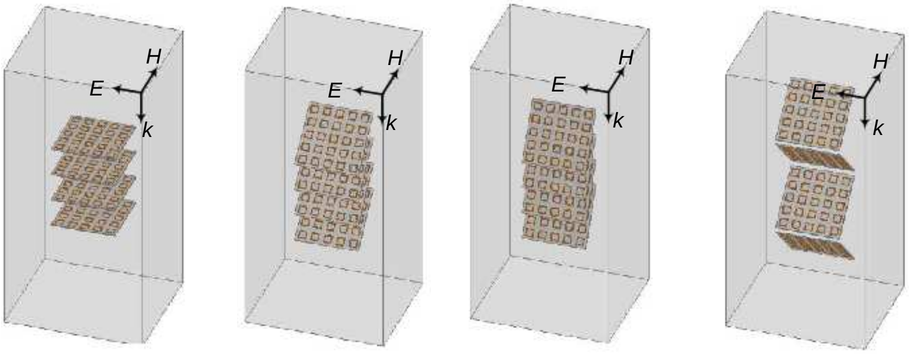
The 3-D structure is designed by stacking several 2-D arrays similar to the one discussed above. The key to this design is maintaining a fixed footprint while going vertical. The number of stacked arrays used here is not optimal as the main goal of this work is to present the concept of 3-D electromagnetic energy harvesting using metamaterials. However one can extend the study to optimize the number of stacked arrays with the goal of maximizing the harvested power while minimizing the cost of the structure. We numerically studied four different cases as shown in Figure 4. Cases a, b, and c consist of 4 stacked arrays each array is tilted with an angle $\theta = 0°$, $45°$ and $60°$ respectively as shown in Figure 3(b). In case d, the arrays are oriented in a zigzag fashion where two consecutive arrays are tilted with an angle $\theta = 45°$ and $\theta = -45°$ (see Figure 4). In all cases the cells where loaded with a resistor of $3.5\,\text{k}\Omega$ and illuminated by a plane wave with a polarization as shown in Figure 4.

In Figure 5, a plot of the per-unit-area efficiency of the system for the four cases shows a dramatic



(a) (b)

Figure 3. (a) A single array of the proposed 3-D metamaterial harvesting system. (b) The efficiency of a single array with angles $\theta = 0°$, $30°$ and $60°$.



Case a Case b Case c Case d

Figure 4. Schematic showing the four cases for the 3-D stacked metamaterial arrays.

enhancement in both the efficiency and the bandwidth. When compared to a single array with 60° illumination, the four cases experience power efficiency of 2.5, 3.47, 4.84, and 2.74 times the single case respectively. In all cases the frequency where the power is maximum has shifted from the operating frequency of 5.8 GHz for an isolated single cell due to the strong coupling among the cells, however one can always scale the size of the cells to operate at the desired bandwidth. We note that the higher than 100% efficiency (see Figure 5) is perfectly physical as per the definition given above. The efficiency here describes the ability of the proposed 3-D metamaterial structure to capture the electromagnetic energy *available* on a 2-D plane. An efficiency of 100% implies the capture of all the power incident on the specified footprint. Therefore, efficiencies higher than 100% indicate that the 3-D structure is capturing more power than the maximum available on a 2-D plane occupying the specified footprint.

The electric and magnetic field distributions (projection on the array plane) for case c are shown in Figure 6 and Figure 7, respectively. It is evident from the field plot that each array has contributed to the total efficiency of the system. In fact, all the cells received certain amount of power even for the cells that are covered by the layers above. This is different from the case when solar cells are used for

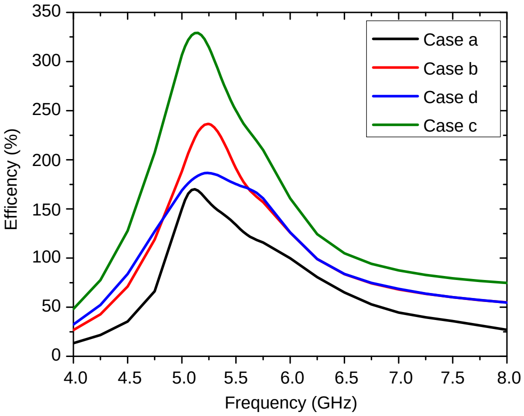


Figure 5. The efficiency as a function of frequency for the four cases described in Figure 4.

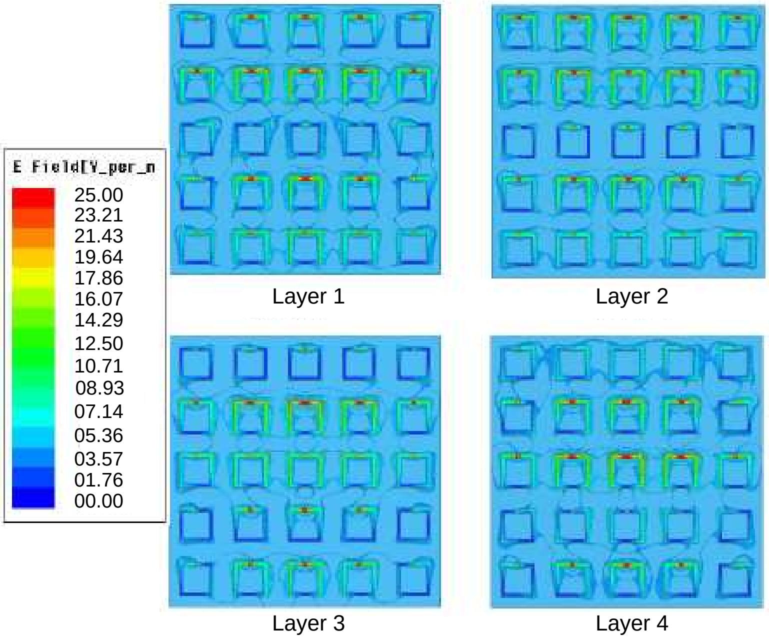


Figure 6. Electric field distribution in the plane of the 4 layers of case c.

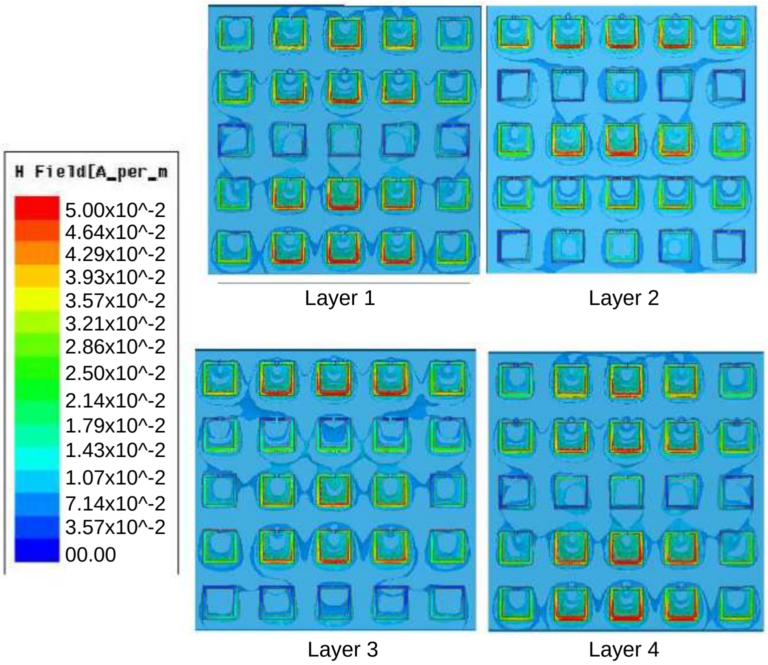


Figure 7. Magnetic field distribution in the plane of the 4 layers of case c.

the 3-D electromagnetic energy harvesting, as the arrays must all be exposed to sun light as in [13]. We note that the SRR cells on each array were placed periodically and uniformly. It is possible that higher efficiency can be realized if the orientation of the SRR cells is optimized [12].

3. CONCLUSION

In summary, we presented the concept of electromagnetic energy harvesting in 3-D using metamaterial arrays. The model demonstrated here consisted of 4 stacked arrays, each with 5×5 SRR cells. The energy was collected by means of a resistor placed across the gap of the resonator. It was found that using a 3-D stacked array results in per-unit-area efficiency reaching up to 4.8 times than that of a 2-D structure. We expect the 3-D array concept to have strong impact not only on energy harvesting systems but also on energy transfer systems such as Wireless Power Transfer (WPT) [9] and Space Solar Power (SSP) systems [17, 18].

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