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Electrically small particles combining even- and odd-mode currents for microwave energy harvesting

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We present a structure composed of an ensemble of electrically small resonators for harvesting microwave energy. A flower-like structure composed of four electrically small split-ring resonators (SRRs) arranged in a cruciate pattern, each with a maximum dimension of less than \( \lambda /10 \), is shown to achieve more than 43% microwave-to-alternating current conversion efficiency at 5.67 GHz. Even- and odd-mode currents are realized in the proposed harvester to improve the efficiency and concurrently reduce the dielectric loss in the substrate. An experimental validation is conducted to prove the harvesting capability. © 2014 AIP Publishing LLC.

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Different designs and configurations of rectennas have been suggested for energy harvesting to improve, in general, the radio frequency-to-direct current (RF-to-DC) conversion efficiency.1–5 Conventional antennas which act as a collecting source in a rectenna system generally have dimensions comparable to a half free-space wavelength. Moreover, the interaction behavior of antennas in arrays and restriction on the total antenna array footprint require certain antenna separation to be maintained to avoid destructive coupling between the array elements.6–9 An empirical study showed that approximately 33% harvesting efficiency from the source to the load was reported utilizing an array of 400 microstrip patch antennas.8

Artificially engineered structures (metamaterials) have received much attention in recent years owing to their unique electromagnetic properties.10 Various applications utilizing metamaterials had been reported, such as cloaking,11 electromagnetic field absorption,12 and sensing.13 Recently, metamaterial elements were used to harvest electromagnetic energy in the microwaves regime14 by converting incident microwave energy into an AC signal. These metamaterial elements showed ability to collect microwave energy when a resistive load is inserted within the elements gap. Metamaterial element integrated with a rectification circuit was also used for converting incident electromagnetic energy to DC.15 The concept of using metamaterial for electromagnetic energy harvesting was also used to harvest infrared energy where an ensemble of six square split-ring resonators (SRRs) and a microstrip transmission line were shown, using numerical simulation, to convert electromagnetic waves to AC with efficiency of more than 80%.16 In this Letter, we propose electrically small particles whose largest dimension is less than \( \lambda /10 \). In comparison to previous work,14 the proposed configuration allows higher suppression of dielectric loss, which in turn improves the harvesting efficiency. In addition, a microstrip line that serves as a power channeling mechanism is proposed and placed in the middle of the particles arrangement, whose gap opening is sharp allowing to coupling enhancement.17

Two configurations proposed here, one with two and the other with four circular SRRs, consist of SRRs positioned symmetrically as shown in Figs. 1(a) and 1(b). The SRRs used here have much wider splits unlike the most common SRRs discussed in the literature. The proposed structures are intended not only to harvest the impinging electromagnetic waves but also to channel the collected energy. A second proposed configuration (Fig. 1(b)) is designed such that even- and odd-mode currents can be induced within the SRRs at the resonance frequency of the SRRs, leading to an improvement of harvesting efficiency as will be discussed below.

The flower-like array is etched on one side of a Rogers substrate with a dielectric constant \( (\varepsilon_r) \) of 2.94, tangent loss \( (\delta) \) of 0.0012, and thickness \( (h) \) of 1.524 mm, while the other side is left metalized. The array structure is simulated using ANSYS® HFSS™. The geometric dimensions of the whole element, including the microstrip line, are optimized such that its resonance frequency, at which maximum energy harvesting can occur, occurs at approximately 5.8 GHz. Optimization yields an outer radius \( (r_o) \) of 2.5 mm, inner radius \( r_i = 1.875 \text{ mm} \), the two openings of the gap \( g_1 = 1.562 \text{ mm} \), and \( g_2 = 2.4 \text{ mm} \), the microstrip length \( l = 7 \text{ mm} \) and the microstrip width \( w = 1.2 \text{ mm} \), as illustrated in Fig. 1(c).

Depending on the mechanism of harnessing, the ambient energy either in the microwave or optical spectra, the proposed structure should generally enhance the interaction between the incident wave and the harvester. The configuration proposed here collects the incident microwave energy and channels it to the metallic traces (here, made of copper) rather than absorbing the energy in the dielectric substrate. The two configurations shown in Fig. 1 were first examined numerically inside a radiation box filled with air while the array was positioned at the center of the box. A plane wave with different incidence angles is shown at the two arrays. Since this structure aims to collect the incident power and channel it through the transmission line, a resistive load is needed to measure the received power. This structure resembles the case of a full system incorporating a...
harvester and a rectification circuit. At one terminal of the microstrip line, a resistive sheet is connected to the ground plane, while the other terminal is shorted to the ground, as shown in Fig. 2. The resistive sheet value was varied until the highest power efficiency was achieved (while keeping the frequency fixed at resonance). The optimal resistance was found to be 12 kΩ. Two ports are realized by defining two sheets on the left and right of the examined structure. Then, the scattering parameters were extracted from the calculated electric field intensities (\(E_y\)) at the two ports, where the extraction implemented here is based on the method described in Ref. 18.

Fig. 3 shows the volume current distributions in the dielectric substrate for the two harvesters shown in Figs. 1(a) and 1(b). As shown in the left side of Fig. 3, the array with only two resonators results in higher dielectric losses. The interpretation of this increment in dielectric loss between the two structures can be explained by Fig. 4, where at resonance the two resonators on the left and right sides of the microstrip line create currents at the edges of their gaps that oppose the out-of-phase currents induced by the other two resonators. Eliminating the out-of-phase currents by adding the two lateral resonators improves current flow on the microstrip line (the channeling route) and yields more power efficiency and less dielectric loss.

Figs. 5 and 6 show the scattering parameters for the arrays with two and four circular resonators, respectively. By considering the cases without resistive loads and at normal incidence (Figs. 5(a) and 6(a)), a one dB difference in transmission and reflection coefficients between the two arrays can be observed. This implies that more than 11% of confinement occurs in the four-array structure compared with the two resonators case. After loading the two structures with a 12 kΩ resistive sheet at one port as discussed above, a slight shift in the resonance frequency appears; however, the array with four resonators achieves better power confinement than the array with two resonators, even with the resistive loading. Both \(S_{21}\) and \(S_{11}\) have dips at resonance frequency as presented in Figs. 5(a) and 6(a); this indicates that low reflection and low transmission occur at the same time, resulting in energy confinement in the harvester.

The fabricated flower-like array was etched on RT/duroid 6002 board material with a dielectric constant (\(\varepsilon_r\)) of 2.94 and thickness (\(h\)) of 1.524 mm. The fabricated structure is shown in Fig. 7. To measure the harvested power, a surface mount resistor with an optimal value of 12 kΩ is placed on the backside of the array where it connects one end of the microstrip line with the ground plane. The picture in Fig. 8.
shows the setup for measuring the voltage across the mounted resistor. An Agilent Infinium 13 GHz oscilloscope and Agilent PSG vector signal generator are used in this measurement. The signal generator is connected to a standard 18 dBi gain horn antenna at 5.8 GHz. The array was excited by the horn antenna with 19 dBm input power. The array was placed at a distance \( r \) of 30 cm from the horn antenna, such that the array was centered on a line perpendicular to the plane of the horn antenna. Then, the voltage across the surface mount resistor at 5.67 GHz was measured using a single-ended probe and was 121 mV, while the available voltage at the front of the harvester was 193 mV.

ANSYS® HFSS numerical full-wave simulation tool is used to compute the power harvesting efficiencies for both arrays presented in Figs. 1(a) and 1(b), by applying the following formula:

![Simulated current distributions of the flower-like energy harvester with four circular SRRs at resonance (left) and off resonance (right) with the electric field \( (E) \) polarized in y direction. The arrows indicate to the current direction.](image)

![Simulated scattering parameters for the flower-like energy harvester with four circular resonators. (a) at incidence angle \( \theta = 90^\circ \), (b) at incidence angle \( \theta = 60^\circ \).](image)

![Simulated scattering parameters for the flower-like energy harvester with two circular resonators. (a) at incidence angle \( \theta = 90^\circ \), (b) at incidence angle \( \theta = 60^\circ \).](image)

![Fabricated flower-like array on RT/duroid 6002 board material.](image)
where $P_{\text{incident}}$ is the total microwave power incident on the footprint of the array, and $P_{\text{received}}$ is the microwave power received by the array (dissipated by the resistive load at one end of the microstrip line). Fig. 9 depicts the harvesting power efficiencies of the two arrays at different incidence angles $\theta$. For the array with four circular SRRs, the highest efficiency, of approximately 44%, occurs at the resonance frequency with a perpendicular incidence angle $\theta = 90^\circ$ and a magnetic field horizontal to the inclusion’s surface. Such change in excitation condition (horizontal magnetic field) is attributed to presence of the transmission line since the current distribution over the transmission (microstrip) line, as presented earlier in Fig. 4, is dominant. Although the second plot (Fig. 9(b)) presents the same view as Fig. 9(a), except for a slight frequency shift, the power harvesting efficiency of the array with two SRRs is less than that of the array with four SRRs by approximately 6%. This degradation is related to the dielectric loss shown in Fig. 3. Moreover, a shift by 100 MHz in resonance frequency occurs when two of the SRRs are removed.

We have shown the ability of the flower-like energy harvester with four circular SRRs to harvest and channel the incident electromagnetic waves, numerically and experimentally. However, for practical scenario, multiple arrays are needed to provide adequate power for a potential system. Therefore, a set of $3 \times 3$ flower-like energy harvester array (see Fig. 10), each array is composed of four circular SRRs and a transmission line, has been simulated to calculate the overall harvesting efficiency. The horizontal and vertical spacing between any two adjacent arrays are $s = 0.8$ mm and $v = 0.6$ mm, respectively, where the two distances, $s$ and $v$, represent less than $\lambda_o/67$ and $\lambda_o/89$, respectively. More than 55% power harvesting efficiency at 5.56 GHz is achieved with the configuration of $3 \times 3$ array as depicted in Fig. 11. This finding indicates efficiency improvement is possible by increasing the footprint area and placing the elements in a close proximity. Taking advantage of the constructive coupling among the electrically small particles, an enhancement...
of 11% power harvesting efficiency is realized by utilizing closely-spaced multiple arrays compared with only one array consisting of four SRRs.

We designed and fabricated an array composed of electrically small resonators to harvest electromagnetic energy in the microwave regime. The proposed configuration creates in- and out-of-phase currents, which in turn increases the current flow on the microstrip line and concurrently limits the dielectric loss in the substrate. Approximately 44% at 5.67 GHz and 38% at 5.77 GHz power harvesting efficiencies were achieved with the four and two circular SRRs arrays, respectively, at normal incidence. We also validated the concept of power harvesting with the proposed configuration by measuring the voltage across the resistive load. Moreover, we showed that positioning any two elements of the proposed configuration in a closely-adjacent manner, contributes to improving the overall harvesting efficiency.

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