Serpentine-Shaped Metamaterial Energy Harvester for Wearable and Implantable Medical Systems

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***Abstract*—Integration with the curvilinear, soft, and time-dynamic surfaces of the human body is critical for most implantable and wearable biomedical systems. Devices that can imitate the mechanics of the body provide opportunities to create human-machine interfaces. Additionally, wireless functionality is essential to monitor health/wellness, study disease conditions, and execute other functions. The use of metamaterials in wireless applications is becoming widespread due to its extraordinary properties such as evanescent wave amplification and negative refractive index. This paper studies a soft, flexible and stretchable Complementary Split Ring Resonator (CSRR) metamaterial energy harvester using a volume of $5.6 \times 5.6 \times 1$ mm^3 on a Polydimethylsiloxane (PDMS) substrate. The CSRR is backed by a ground plane to absorb the incident power, and a via (load) is used to maximize the power harvesting efficiency. For stretchability, a typically rigid patch of the CSRR is replaced by the serpentine mesh. From the ANSYS HFSS simulation, it is found that the serpentine structure helps to reduce the size of the CSRR due to an increase in electrical length. The structure can also achieve high-quality factor (Q-factor), thereby enabling almost unity efficiency. The CSRR metamaterials can be used in future for wireless applications to integrate with the skin, the heart, and the brain.**

Keywords—Energy harvesting, implantable devices, metamaterial, resonator, stretchable devices.

I. INTRODUCTION

A new wave of technologies based on the mechanically stretchable microwave systems is central to the Internet of Things (IoT) and can be applied in implantable, wearable, agricultural, and industrial environments [1-3]. Recently, breakthroughs in materials science have guided us to experience a wide array of stretchable microwave systems, including reconfigurable antennas [4], wearable radio-frequency identification (RFID) tags and sensors [5], wireless and self-powered devices [1, 6] and wireless epidermal electronics [7]. The mechanical flexibility and stretchability properties are crucial in particular for implantable and wearable medical purposes that can mimic the softness and conform to the curves of the human body (and organs like the brain), as illustrated in Fig. 1.

In general, two strategies exist to translate microwave components such as transmission lines, antennas, and impedance elements, from stiff to stretchable form:

(1) Develop stretchable devices by applying materials, such as liquid metals [8], silver/polymer inks [9], or conductive nanowire networks [10]. This strategy of using composite materials limits the microwave performance owing to the low conductivities of these materials, which are is in the range of 104 S/cm.

(2) Design a typical, lossless microwave material into serpentine-shape geometries [1-2] or lateral spring structures [11]. This design then can be transfer printed on an elastomeric substrate such as Polydimethylsiloxane (PDMS). In that regard, the use of an open-mesh, serpentine geometry is beneficial because of the maximum numbers of intersections and continuity, which results in enhanced electrical and mechanical properties of the conductive layer. However, there are few studies that explores the influence of serpentine networks on the electromagnetic (EM) properties of microwave structures [1-2].

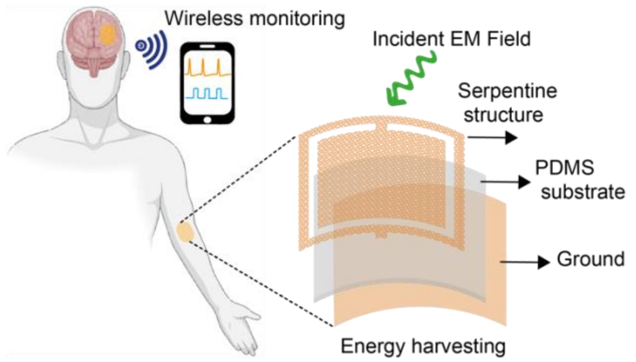

Fig. 1. Schematic illustration of the future applications of the soft and stretchable metamaterials.

Artificial materials like metamaterials are comprised of engineered structures, exhibiting atypical EM properties which are not observed in natural materials, such as evanescent wave amplification and negative refractive index [12-13]. Among different applications of metamaterials, it can also be designed to construct a media where power neither transmit nor reflects, thereby absorbs most of the incident waves at a particular band of frequencies and polarization. However, a metamaterial absorber [14] is different from a metamaterial harvester [15] in a sense that apart from full absorption, metamaterial harvesters are also required to deliver maximum power to a load to make sure that the absorbed power is dissipated across the load. A few investigations reported the metamaterial energy harvester using Split Ring Resonator (SRR) and Complementary Split Ring Resonator (CSRR) structures [15-16]. However, all of these studies deployed traditional rigid patch geometries and rigid substrates.

For the first time, this paper studies a stretchable CSRR microwave metamaterial structure by using the serpentine-shaped patch geometry on a soft and flexible PDMS substrate. This kind of stretchable metamaterial can be

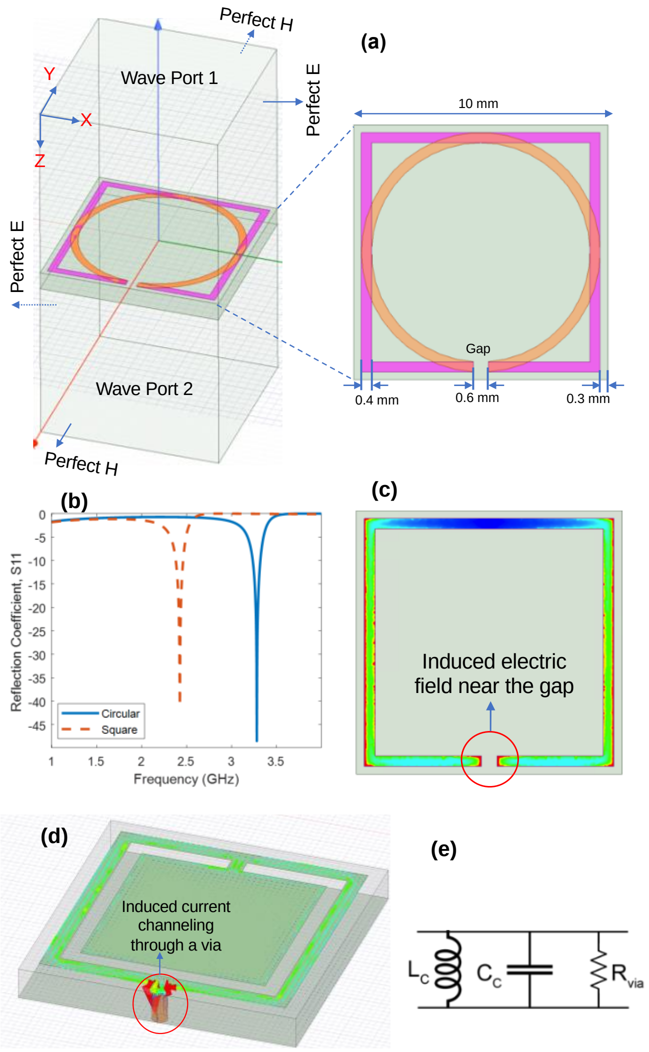

Fig. 2. (a) Ansys HFSS waveguide simulation setup indicating the Perfect E and Perfect H boundaries. The square and circular SRR dimensions are also indicated. (b) Variation in the reflection coefficient for circular and square shape resonator. (c) Induced and concentrated electric field near to the grounded SRR structure. (d) Induced current in case of grounded CSRR structure and channeling the current by introducing a ground plane and a via. (e) Equivalent circuit of the CSRR structure.

implemented in implantable and wearable applications in future to enable a fully wireless system [17-19]. This rest of the paper is arranged as follows: Initially, the optimum shape and geometry for the metamaterial structure are determined by simulations to implement the serpentine-shaped patch. Then the electromagnetic characteristics as well as metamaterial characteristics of the serpentine structure are discussed to achieve the maximum energy harvesting efficiency.

II. Methodology and Results

A. *Shape and geometry*

Before designing the serpentine structure, it is important to determine the optimum shape (circular or square) and geometry (SRR or CSRR) to achieve the maximum harvested power. The electromagnetic simulation software ANSYS HFSS is used, where the unit cell of a simple SRR structure is excited by a waveguide. To introduce the TEM mode excitation within the waveguide, Perfect Electric (**E**) (YZ-plane) and Perfect Magnetic (**H**) (XZ-plane) boundary conditions are considered, as shown in Fig. 2a. The patch shape of the SRR can be either circular or square. The reflection coefficient (S_{11}) reveals that for the same patch size, square shape SRR resonates at a lower frequency (2.3 GHz) than a circular shape SRR (3.5 GHz), as plotted in Fig. 2b. It is because square shape SRR covers more area than the circular shape SRR and results in a lower frequency [20]. Due to this, rectangular patch shape is considered in this study for the serpentine mesh.

The field distribution for a similar SRR and CSRR structure is visualized in Fig. 2c. When a plane wave is incident normally on the SRR structure, a highly concentrated electric field is induced in the vicinity of the gap (Fig. 2c). By assigning a ground plane and an appropriate load (resistance) between the gap, a maximum efficiency ~50% can be achieved [16]. On the other hand, a strong current is induced at the identical location in case of the CSRR structure. As in Fig. 2d, by introducing a ground plane, this current can be channel through a via (i.e. load) and almost unity energy harvesting efficiency can be achieved [15]. Due to higher efficiency, a CSRR structure with square shape geometry is studied for the serpentine metamaterial. The equivalent circuit of the CSRR structure can be considered as a parallel LC tank circuit [21], where L_c, C_c and R_{via} are the equivalent inductance, capacitance and resistance of the load, respectively.

B. *Serpentine CSRR electromagnetic characteristics*

Fig. 3a shows a unit cell of the proposed CSRR structure with the serpentine geometry. The CSRR structure is backed by a ground plane so that it can be placed on any conducting

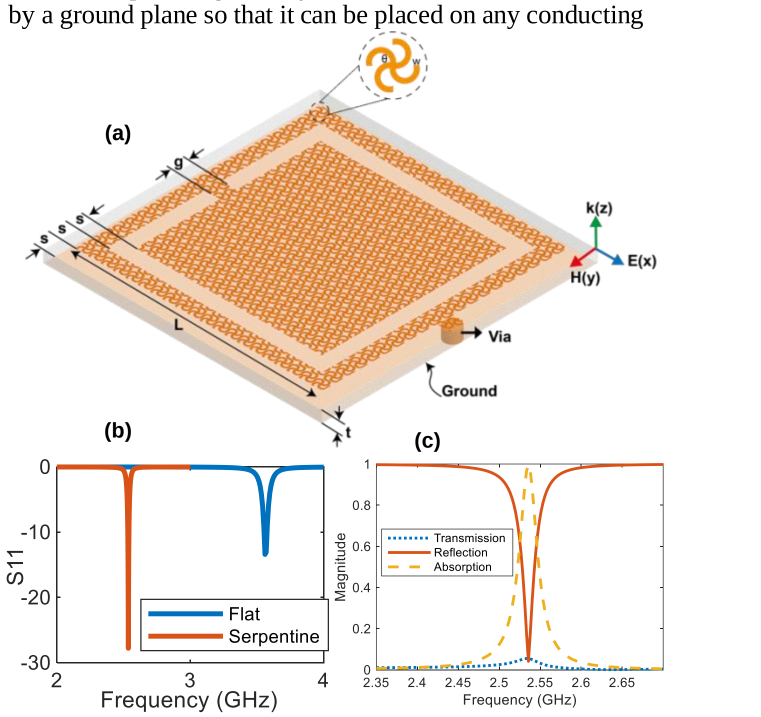

Fig. 3. (a) The proposed CSRR with the serpentine patch. (b) Comparison in the reflection coefficient between the rigid (flat) patch and serpentine patch. (c) Magnitude of the transmission, reflection and absorption coefficients for the proposed CSRR structure.

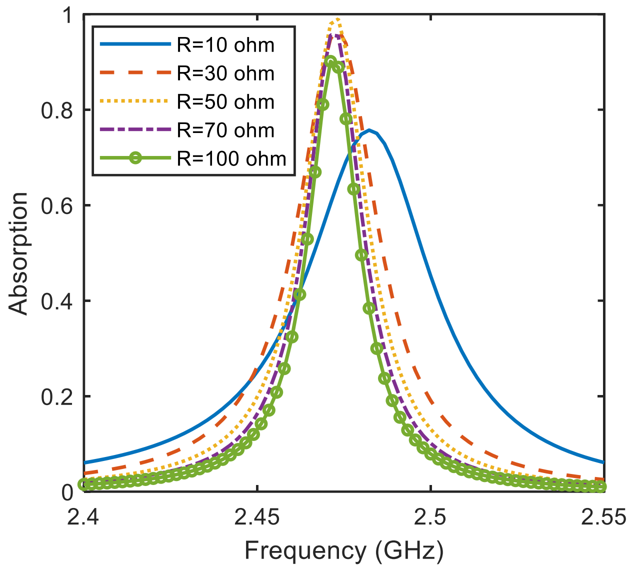

Fig. 4. Variations in absorption with respect to different load resistance, R.

surface, which enables complete shielding from other wireless devices nearby. A via, connecting the serpentine patch and ground plane is placed to channel the surface current generated on the patch. This via is used to mimic a load (resistance) and can be replaced with a rectification circuit. The CSRR is capable of absorbing most of the incident wave and can channel almost all the absorbed power through the via. The unit cell is optimized to work at 2.53 GHz having dimensions of t = 1 mm, s = g = 0.3 mm, L = 5 mm, w = 0.024 mm, and θ = 45°. Flexible and stretchable PDMS is applied as a substrate having a loss tangent, tanδ = 0.001 and relative permittivity, ε_r = 2.5 [19]. Fig. 3b compares the changes in resonant frequency between the same-size flat (rigid) and serpentine patch CSRR structure. A significant reduction in resonant frequency (from 3.6 GHz to 2.53 GHz) is observed. It is because, as the patch structure is converted from the rigid traces to the serpentine traces, the overall electrical length of the CSRR increases [1]. This ensures that serpentine geometry helps to reduce the size of electromagnetic structure for a desired frequency.

The quality factor (Q-factor) is another important parameter that need to be considered to obtain the maximum harvested energy. Q-factor is inversely related to the bandwidth (BW) and high Q-factor is desirable to achieve high power efficiency. In general, higher bandwidth reflects higher losses in the structure and results in a lower Q-factor. The quality factor at the desired frequency can be retrieved by using the eigenmode solution in the HFSS. From simulation Fig. 3b, it is observed that rigid-patch CSRR structure achieves higher bandwidth than the serpentine-patch CSRR structure, which confirms the increase in quality factor (Q-factor) due to the serpentine mesh.

To maintain the full absorption while maximizing the power in the load, both via position and load resistance (R) are varied. The absorption of the unit cell can be calculated based on the following equations:

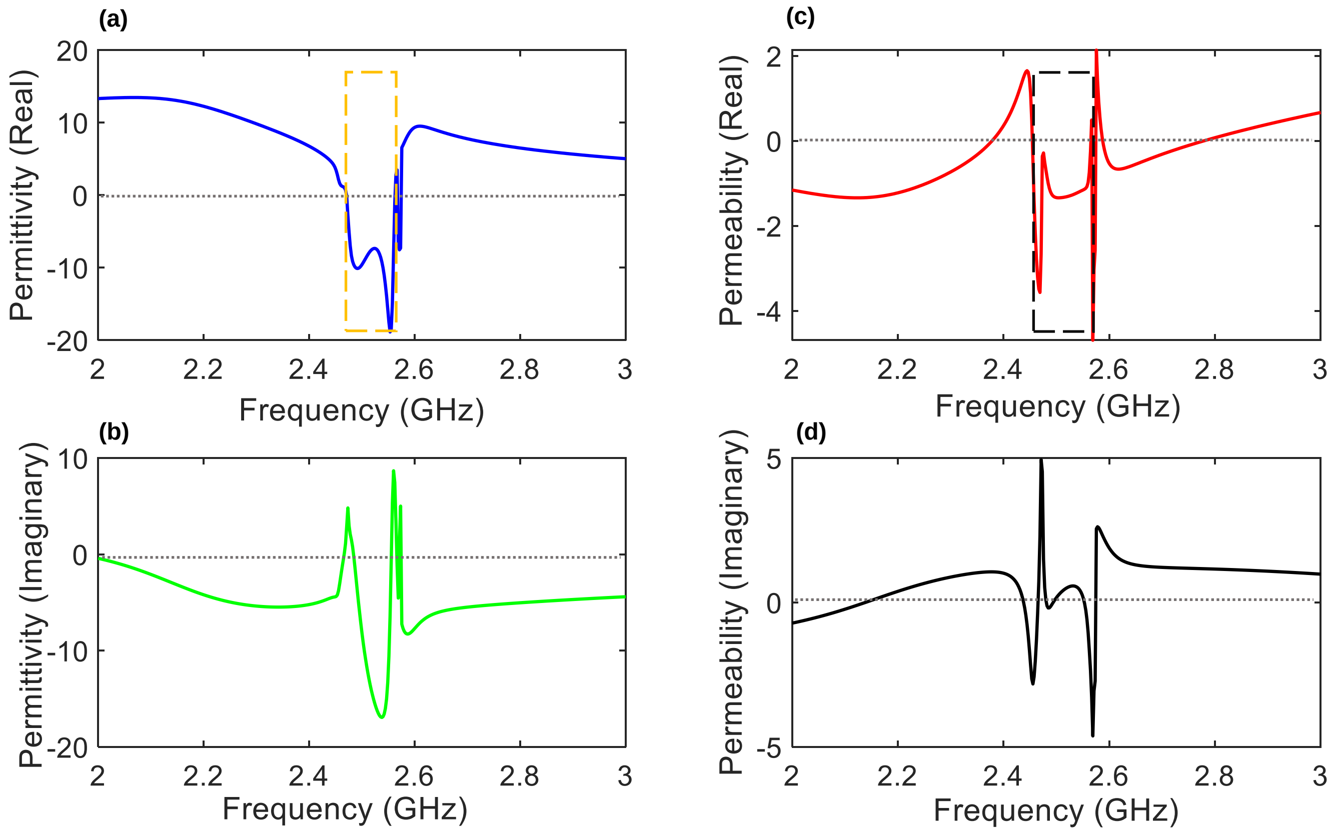

Fig. 5. Extracted parameters by using the scattering parameters. Effective permittivity, ε_{eff} (a) real part, (b) imaginary part. Effective permeability, μ_{eff} (c) real part, (d) imaginary part. The rectangular box indicates the bandwidth in which both permittivity and permeability are negative and CSRR act as a metamaterial.

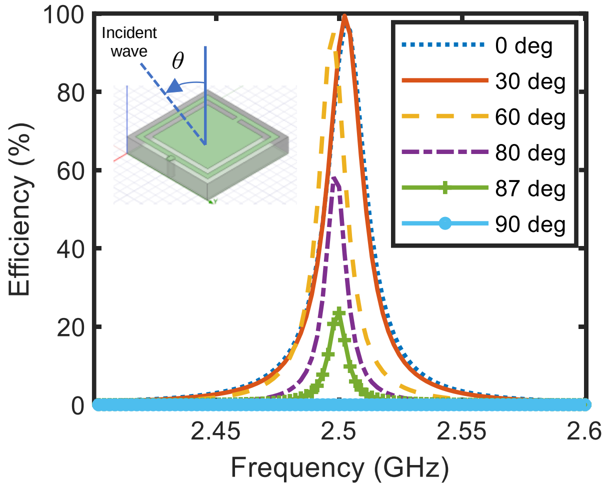

Fig. 6. Variation in energy harvesting efficiency at various incident angle, θ. More than 50% efficiency can be obtained at θ = 80º due to the high Q-factor of the CSRR structure.

$$A(w) = 1 - |S_{11}|^2 - |S_{21}|^2, \qquad (1)$$

where, $A(w)$ is the absorption, S_{11} and S_{21} are the transmission and reflection coefficients, respectively. Fig. 3c shows the magnitude of the reflection, transmission and absorption coefficients. This plot indicates almost all of the incident wave is absorbed by the CSRR structure, and negligible amount (< 0.1%) is transmitted. The via is placed at a concentrated surface current location to channel most of the current to maximum power dissipation (Fig. 3a). According to Fig. 4, by increasing R, the CSRR absorption increases up until R = 50 Ω. However, by increasing CSRR beyond R = 50 Ω reduces the CSRR absorption. As a result, optimum value of the resistance corresponds to the maximum absorption is found to be 50 Ω.

Scattering parameters such as reflection coefficient, S_{11} and transmission coefficient, S_{21} are related to the impedance (z) as well as the refractive index (n). Therefore, to extract the metamaterial characteristics of effective permittivity (ε_{eff}) and effective permeability (μ_{eff}) of the CSRR unit cell following equations are applied:

$$z = \pm\sqrt{\frac{(1+S_{11})^2 - {S_{21}}^2}{(1-S_{11})^2 - {S_{21}}^2}}, \qquad (2)$$

$$e^{ink_0 d} = \frac{S_{21}}{1 - S_{11}[(z-1)/(z+1)]}, \qquad (3)$$

$$\varepsilon_{eff} = n/z \text{ and } \mu_{eff} = n.z\,, \qquad (4)$$

where, k_0 and d represent the wave number and thickness of the structure, respectively. The real and imaginary parts of the retrieved ε_{eff} and μ_{eff} are plotted in Fig. 5. A negative real part of the effective permittivity or (and) effective permeability reveals the metamaterial properties of the structure, whereas the imaginary part is responsible for the losses within the structure. The rectangular box within the plot highlights the negative refractive index region. It is evident that highlighted part falls within the selected 2.53 GHz frequency and confirms the metamaterial characteristics of the structure. On the other hand, both of the imaginary parts are close to zero at the desired frequency indicating negligible loss in the structure.

Fig. 6 illustrates the variation in harvesting energy efficiency in terms of different angle of incidences (θ). The efficiency, η can be calculated based on the following equation:

$$\eta = \frac{P_{out}}{P_{in}}, \qquad (5)$$

where, P_{out} is the developed time-average power across the load resistance and P_{in} is the total incident power on the CSRR unit cell. The serpentine CSRR maintains almost unity efficiency even with θ = 30º and more than 50% efficiency at θ = 80º. This is owed to the high Q-factor of the serpentine CSRR. A highly resonant CSRR structure can catch a sufficient amount of the incident power as long as the plane of incidence is less than θ = 90º (Fig. 6).

III. Conclusion

This paper studies the energy harvesting capability of a soft and stretchable CSRR metamaterial structure. A ground plane is designed to absorb most of the incident power, and a load of 50 Ω is found to be optimum to channel the absorbed power through a via. To achieve the lower size and stretchability of the CSRR, traditional rigid patch element is replaced by the serpentine mesh. The metamaterial structure achieved almost unity efficiency at 2.53 GHz due to high Q-factor. As future work, more analysis regarding the variations in metamaterial characteristics, harvesting efficiency, mechanical characteristics due to changes in the serpentine geometry will be carried out. Finally, the optimum CSRR structure considering both electromagnetic and mechanical properties will be fabricated and experimentally validated.

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