Design of a perfect and multi-resonant metamaterial absorber for electromagnetic energy harvesting applications

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Abstract. In this work, a perfect absorber based on a split ring resonator structure is proposed and numerically analyzed. The software CST STUDIO was employed to carry out the numerical analysis and the optimization of the proposed structure. The electromagnetic properties of the proposed metamaterial cell were analyzed in the first phase of this study demonstrating that such structure resonates at 2.4 GHz and 4.2 GHz simultaneously. In fact, this structure has negative permittivity and permeability in these two bands. The optimization process has led us to obtain a compact resonator, which has a total size of 15 mm × 15 mm. Subsequently, the capacity of this structure as an absorber of electromagnetic energy is analyzed. The obtained results reveal that this structure has absorption efficiencies of 98.2% and 99.7% for the first and second bands respectively. Also, other characteristic parameters were evaluated. This shows that the proposed structure has a high electrical performance and can be used for the collection of electromagnetic energy, which can be used to power wireless sensor networks.

1. Introduction

Recently there has been an increase in the number of wireless sensing networks (WSN), which has been mainly due to the emergence of new technologies such as the internet of things (IoT), 5G networks, and the interest in automating different industrial processes [1–3]. Due to the wireless and electronic sensors must be installed in the outdoors in most cases, it has become necessary to implement energy harvesting systems to obtain energy from the environment and supply power to low-energy electronic devices or recharge their batteries. Different energy harvesting mechanisms such as thermal energy, wind energy, solar energy, and electromagnetic energy (EM) have been explored [4]. This last alternative has attracted a lot of attention in recent years because EM energy is omnipresent today in our environment due to the abundance of EM signals available from different sources such as mobile stations, Wi-Fi signals, or television antennas [4].

In addition, they open the possibility of supplying power wirelessly, i.e., build wiring-free power distribution systems. For this reason, the design of electromagnetic energy collectors plays a fundamental role in the capture and conversion of this energy to be used in sensing nodes [5,6]. To solve this problem, several alternatives have been explored. The most used mechanism are antenna arrays [7], rectennas [8], and metamaterial absorbers [6,9]. The metamaterial absorbers are composed of unit cells arranged periodically in a 2-D plane. These unit cells have unique characteristics such as negative permittivity and negative permeability [10–12]. In fact, the unique characteristics of these metamaterial
cells have aroused strong interest in other applications such as antenna miniaturization [13,14] sensing devices [15–17], and among others [12,18].

The main advantage of a metamaterial absorber energy harvesting system is that this kind of structure is smaller in comparison with conventional systems based on antennas. Likewise, these structures exhibit a strong resonance and a purely effective surface resistance, which facilitates electromagnetic wave absorption [4]. On the other hand, the metamaterial absorber receives the EM wave from the environment at the resonant frequencies and stored the energy (electric and magnetic) due that these structures have capacitance and inductance associated [4,19]. Thus, the maximal absorption is achieved when the structure impedance matches that of free space. After that, the stored energy is dissipated through the dielectric substrate or a load. Then, the performance of the absorber can be evaluated based on the absorption efficiency, the harvesting efficiency, and its conversion efficiency.

Therefore, we propose to design a double split-ring resonator with a compact size to operate at 2.4 GHz and 4.2 GHz simultaneously in this work. In comparison with other previous studies, the proposed structure has some important advantages. Firstly, the unit cell resonates at two different frequencies. Secondly, the proposed structure has the capability to absorb the EM radiation with higher efficiency, this has an efficiency of more than 98% in both bands.

2. Methodology

Figure 1 shows the proposed metamaterial unit cell; this metamaterial cell consists of three concentric rings. The bigger resonator has a square shape with one gap in the middle of each side of two adjacent lines, while the other ones correspond to conventional split ring resonators (SRRs) with a circular shape, which are rotated -45 degrees to induce a high asymmetry in the structure. The ring resonators are made of copper lines with a metal thickness of 35 µm, and the bottom layer is a continuous layer of copper. On the other hand, the three-ring SRR structure was designed and simulated on a RO4003C substrate (Rogers Corp.), which has a relative permittivity of 3.55, a thickness of 1.524 mm, and a loss tangent of 0.0021. The total size of this unit cell is 15 mm × 15 mm and operates at 2.4 GHz and 4.2 GHz simultaneously; Table 1 summarized the most important geometrical parameters of the unit cell.

| Parameter | Value (mm) |
|-----------|------------|
| L         | 14.00      |
| Wc        | 1.00       |
| Wr        | 1.00       |
| W         | 1.00       |
| g         | 0.70       |
| g1        | 0.65       |
| K         | 15.0       |
| \(\alpha\) | -45°       |

Table 1. Metamaterial unit cell design parameters.

The performance of the proposed unit cell was numerically evaluated using CST Microwave Studio, which is a software based on the standard finite-difference time-domain (FDTD) method. To carry out the simulation was important to choose the correct boundary conditions. Then, the unit cell was placed between two floquet ports to study its electromagnetic response, while perfect electric and perfect magnetic boundary conditions were imposed on the metamaterial unit cell (see Figure 1(b)); from Figure 1(b), the structure was excited using a uniform plane wave, which is propagated on the z-axis with open end boundary condition. Likewise, a perfect electrically conducting (PEC) was used in z-direction, while the unit cell condition was applied in x-direction and y-direction. Therefore, the electric field (E-field) of the incident wave is polarized along x-axis, while the magnetic field (H-field) is polarized along y-axis.
Figure 1. (a) Schematic of the proposed metamaterial unit cell, (b) boundary condition defined in CST Microwave STUDIO for the studied metamaterial unit cell.

The $S_{11}$ and $S_{21}$ parameters of the proposed unit cell were analyzed, and these results were used to determine the electromagnetic behavior between 2 GHz and 5 GHz; then, the Nicolson Rose Weir (NRW) method was employed to extract and get the permeability and permittivity of the proposed structure from the S-parameters [11,20]. These parameters can be obtained easily from the following Equation (1), and Equation (2) [20].

$$
\mu_r = \frac{2\varepsilon(1-S_{21}+S_{11})}{j\omega d(1+S_{21}-S_{11})^2},
$$

$$
\varepsilon_r = \mu_r + \frac{2\varepsilon S_{11}}{\omega d}.
$$

where c is the speed of light, $\mu_r$ is the relative magnetic permeability, $\varepsilon_r$ is the relative dielectric permittivity, $\omega$ is the angular frequency, $S_{11}$ represents the reflected power, $S_{21}$ represents the transmitted power, and d is the slab thickness. A similar procedure was performed to analyze a 3×3 array configuration. The structure of the proposed array is illustrated in Figure 2; here, the unit cells are separated from each other by a distance $\Lambda = 15$ mm.

Figure 2. Schematic of the proposed 3×3 array configuration of unit cells.

3. Results and discussion

The metamaterial unit cell was studied using the methodology described in the above section. Figure 3 shows the obtained S-parameters (the reflection coefficient, $S_{11}$, and the transmission coefficient, $S_{21}$) from 2 GHz to 5 GHz. The results reveal that the proposed structure has a strong resonance at two different bands. The first one is 2.4 GHz, where the $S_{11}$ parameter reaches a magnitude of -17.6 dB, while the magnitude of the $S_{21}$ parameter is -1.07 dB. Similarly, this unit cell resonates at 4.2 GHz.
In fact, the $S_{11}$ and $S_{21}$ parameters at this frequency present a magnitude equal to $-29.8$ dB and $-0.29$ dB respectively. Another important characteristic of this kind of electromagnetic absorber is the bandwidth because it determines the range of frequencies in which the proposed structure can work. Then, the bandwidth of the proposed absorber was calculated at both resonances. Thus, the bandwidth in the first band was 36 MHz, while the second band reported higher bandwidth. In fact, this band has a bandwidth equal to 125.65 MHz. Thus, the second band has at least three times more bandwidth than the first band.

![Figure 3. Magnitude of the $S_{11}$ and $S_{21}$ parameters of the proposed metamaterial unit cell. The continuous line indicates the magnitude of parameter $S_{11}$, and the dashes indicate the magnitude of parameter $S_{21}$.](image)

To confirm that the proposed unit cell has left-handed frequency bands, the effective material electromagnetic parameters were obtained using the Equation (1) and Equation (2). Figure 4(a) and Figure 4(b) shows the obtained retrieved effective real and imaginary part of the permittivity and permeability as a function of the operating frequency. The numerical results corroborate that the proposed metamaterial unit cell exhibit negative permeability and permittivity at 2.4 GHz and 4.2 GHz simultaneously. So, this structure shows double negative property and can be used as double negative (DNG) medium [21].

![Figure 4. Simulation results of the (a) permittivity (b) permeability. The obtained results were obtained using the NRW method. Solid curves represent the real part, while the dashed lines show the behavior of the imaginary part.](image)
Finally, the capability to absorb the electromagnetic energy of the proposed structure was evaluated. Figure 5 illustrates the numerical values of the absorbance $A(\omega)$, the transmittance $T(\omega)$, and the reflectance $R(\omega)$. Here, the absorbance can be calculated using the Equation (3) [6].

$$A(\omega) = 1 - R(\omega) - T(\omega),$$  \hspace{1cm} (3)

where the frequency-dependent reflectance and transmittance are defined as $R(\omega) = |S_{21}|^2$ and $T(\omega) = |S_{11}|^2$ respectively [6]. Figure 5 reveals that the absorbance of the proposed metamaterial absorber has an absorbance of 98.2% and 99.7% at 2.4 GHz and 4.2 GHz respectively. Likewise, the reflectance is 0.13% and 0.032% in the first and second operating bands of the proposed absorber. Finally, the transmittance is near zero across the analyzed frequency range. The proposed absorber can be employed to collect electromagnetic energy in one of the most used electromagnetic bands because most current wireless networks radiate close to 2.4 GHz. Therefore, this absorber can surely be used in the capture of high energy rates, which at the same time can be used to power wireless networks, batteries, or other electronic components [4-7].

![Figure 5](image.png)

**Figure 5.** Numerical results of the reflectance, transmittance, and absorbance for the proposed metamaterial absorber.

4. Conclusions
In summary, we proposed a novel metamaterial unit cell based on three concentric split-ring resonators, which can be used to collect electromagnetic energy. First, the capability of this structure to absorb the incident electromagnetic energy at 2.4 GHz and 4.2 GHz was numerically demonstrated. The numerical results demonstrate that the proposed metamaterial structure presents a high absorbance in both bands. Likewise, this metamaterial absorber offers several advantages over conventional electromagnetic energy collection systems because it is compact, thin, and offers a high absorption coefficient in multiple bands simultaneously. Thus, the proposed structure is an ideal candidate for energy harvesting applications due that it offers high performance to collect and store electromagnetic energy.

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