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Microwave energy harvesting based on metamaterial absorbers with multi-layered square split rings for wireless communications

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ABSTRACT

We propose the design of a multiband absorber based on multi-layered square split ring (MSSR) structure. The multi-layered metamaterial structure is designed to be used in the frequency bands such as WIMAX, WLAN and satellite communication region. The absorption levels of the proposed structure are higher than 90% for all resonance frequencies. In addition, the incident angle and polarization dependence of the multi-layered metamaterial absorber and harvester is also investigated and it is observed that the structure has polarization angle independent frequency response with good absorption characteristics in the entire working frequency band. The energy harvesting ratios of the structure is investigated especially for the resonance frequencies at which the maximum absorption occurs. The energy harvesting potential of the proposed MSSRs is as good as those of the structures given in the literature. Therefore, the suggested design having good absorption, polarization and angle independent characteristics with a wide bandwidth is a potential candidate for future energy harvesting applications in commonly used wireless communication bands, namely WIMAX, WLAN and satellite communication bands.

1. Introduction

Metamaterials (MTMs) are artificial materials fabricated -to produce properties that do not occur naturally. It is composed of a set of small resonators in a periodical array so as to provide the desired electromagnetic properties, such as negative refraction index, backward Cerenkov radiation and subwavelength diffraction [1]. MTMs have great potential and wide application prospects in invisible cloaks [2–4], antennas [5–7], optic lenses [8], filters [9], perfect metamaterial absorbers [10–13], and so on. Geometric parameters of a metamaterial unit are important for perfect absorption because the frequency response and the absorption characteristics of a structure are determined by those parameters. Therefore, by changing the geometrical dimensions of the conductive pattern and the dielectric constant of the substrate, a metamaterial absorber with an adjustable frequency band ranging from RF to optical frequencies can be designed [14–17]. There are lots of studies given in the literature working at the microwave region because of its easy fabrication. Thanks to the features mentioned above, the MTMs can be widely used in many applications such as energy harvesting [18], thermal detection sensors [19], solar cells and stealth technology. Besides, adapter based on MTM absorber system is also studied to convert electromagnetic energy into electrical energy [20].

Most of the metamaterial absorbers (MAs) proposed in literature have dual or triple band frequency responses. Although these absorbers have a perfect absorption at the resonance frequency; they only have a few resonant frequencies and a narrow bandwidth which are deficit for total efficiency. Vertically assembled multiple layer metamaterials can extend the absorption bandwidth of metamaterials without decreasing absorption strength [21–24]. However, the increment of the layer number results in a larger thickness. Hence, the reduction of the thickness is realized by the multi-unit pattern method which provides half of thickness with same absorption bandwidth [25]. Each layer in these types of multiple layer MTMs contributes one narrow resonance band with a good absorption [25,26].

In this paper, we investigated a multiband and wideband MA consisting of multi-layered resonators. The numeric simulations and experimental results show that as the number of layers increases, the

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bandwidth and the number of resonances also increase. The proposed structure also provides a very wide bandwidth which is the widest one reported in the literature. This characteristic of the proposed structure distinguishes this structure from other dual and triple band structures in the literature with its polarization and incident angle independent features.

2. Design and numerical setup of the proposed structure

In this study, we designed a multi-layered MA structure with multiband frequency response and investigated its harvesting capability. The unit cell of the proposed structure has three resonator layers; each layer forming the unit cell is composed of a metal resonator placed on a dielectric substrate. The backward of the third layer, namely the layer containing the largest resonator is covered by a metal to block transmission. Since the dimensions of the resonators in each layer are different in size, they resonate at different frequencies close to each other. The overall response of the structure can then be obtained by summing all the overlapping frequency responses corresponding to each layer [15]. The frequency response and absorption characteristics of the structure depend on both the number of resonators determining the number of resonances and the geometric dimensions of resonators on each layer, as well as the widths and the orientation of the gaps in resonators [16]. The schematic and unit cell of the proposed MSSR structure are shown in Fig. 1(a) and (b), respectively. The dielectric substrate of each layer is FR4 with relative permittivity of ϵ_r=4.3 and loss tangent of tan δ=0.025. Copper is used as a resonator on the dielectric substrate with an electrical conductivity of σ=5×8 s/m. The optimized dimensions of the structure determined by parametric study and genetic algorithm are given in Table 1.

3. Simulation results and discussion

In this study, numerical simulations are carried out by CST Microwave Studio which is based on Finite Integration Technique. It provides parametric and genetic algorithm investigations in the microwave frequency band. Boundary conditions are assigned as electric, magnetic and open (add space) along x, y and z directions, respectively. For numerical analysis, electric and magnetic field components are assumed to be polarized along x and y direction, respectively and the direction of propagation is along the z direction as demonstrated in Fig. 1(c). The frequency dependent absorption A(ω) can be calculated by the equation; A(ω)=1-R(ω)-T(ω), where R(ω) and T(ω) define the reflection and transmission coefficients of the overall structure, respectively. In order to maximize the absorption of structure, both reflection R(ω)=$|S_{11}{}^2|$and transmission T(ω)=$|S_{21}{}^2|$ should be minimized at the operating frequency. Since the transmission is blocked by the metallic plate located at the back surface of the structure as shown in Fig. 1(a), there will be no transmission. Therefore, the absorption value only depends on the reflection coefficient related with S_{11} parameter, hence the reflection characteristics of the resonator is carried out to examine the effectiveness of the resonator. Simulation results of the MSSRs structure have been analyzed by using the revised absorption equation A(ω)=1-R(ω), where $|S_{21}{}^2|$=0 since T(ω)→0. As can easily be seen from the equation, when the reflection coefficient is minimum, the absorption coefficient will be maximum. Hence, the perfect absorption can be satisfied by both perfect impedance matching between intrinsic impedance of the metamaterial absorber and free space to provide full penetration and blocking the transmission by backside metal to keep electromagnetic energy in the metamaterial absorber.

Table 1
The typical geometric dimensions of the structure.

Bottom SSR(mm)	a_1=33	w_1=1
Middle SSR(mm)	a_2 =29	w_2=2.5
Top SSR(mm)	a_3 =22	$w_{3=}$1
Others(mm)	b=37	d=1.6
	g=1	Copper layer Thickness=0.035

In order to understand the separate and combined effects of each layer on the absorption characteristics and band width better, each layer needs to be investigated separately. The separate and combined effects of each layer are investigated in the frequency range from 2 GHz to 13 GHz in the microwave region and the simulation results are plotted on the same graph as shown in Fig. 2.

The absorption values of the bottom layer having the largest resonator are 80%, 90%, and 85% at 2.8 GHz, 5.4 GHz and 10.5 GHz, respectively. These frequencies are within the frequency bands used in wireless communications, such as GSM, WIMAX and satellite communications. Hence, the absorber consisting of three layers has potential for microwave energy harvesting application in the environment that we live. As it can be seen in Fig. 2, the bottom layer having a resonator with the largest size is responsible for the lower resonance frequencies. Due to the effect of its size, the first resonance frequency of the resonator in the top layer having the

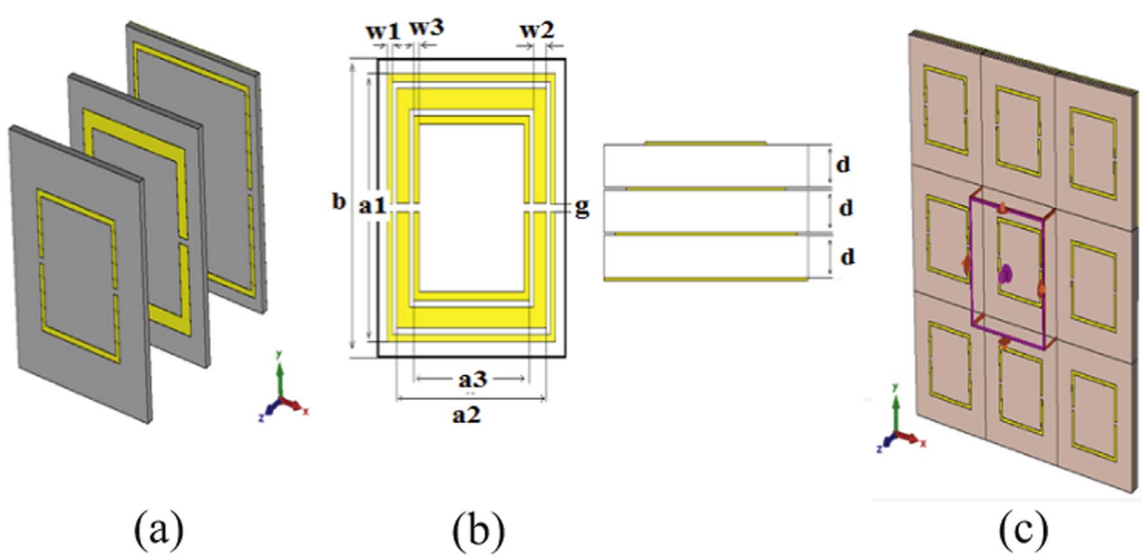

Fig. 1. (a) Proposed multi-layered structure for harvesting application in microwave range, (b) typical size of the SSRs and layers' thickness and (c) simulation setup of the unit-cell and the boundary conditions.