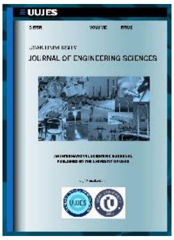

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Research article

DESIGN AND SIMULATION ANALYSIS OF A TEXTILE BASED METAMATERIAL PERFECT ABSORBER FOR ENERGY HARVESTING APPLICATIONS AT WIFI BAND

Murat Ercan[1], *Gamze D. Tetik*[2]*, *Muharrem Karaaslan*[3]

[1]*Department of Materials Science and Nanotechnology Engineering, Graduate Education Institute, Usak University, Turkey*
[2]*Department of Materials Science and Nanotechnology Engineering Faculty of Engineering, Usak University, Turkey*
[3]*Department of Electrical and Electronics Engineering, Faculty of Engineering and Natural Sciences, Iskenderun Technical University, Turkey*

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Abstract

Metamaterials, which are called as left-handed materials, exhibit electromagnetic properties that do not exist in nature, such as negative refractive index and reverse Doppler effect, at the frequency range for which they are designed. These unique properties of metamaterials have made them indispensable in a wide variety of applications such as sensor applications, signal absorption, antenna, and energy harvesting. In this study, the design and analysis of a metamaterial (MTM) perfect absorber at 5 GHz frequency band were performed to investigate the usability of the proposed structure in energy harvesting applications. A negative refractive index of -0.15 was obtained at 5GHz. The variation of absorption, transmission, and reflection of the proposed MTM structure exhibited that a maximum absorbance was monitored at 5 GHz as 0.9949. According to the harvesting application study, the proposed structure has a maximum absorption of 88.3% at 4.98 GHz which is close to resonant frequency in 8000 Ω resistor value. The results of the study revealed that the proposed MTM structure has potentials to be used in energy harvesting applications.

Keywords: *Metamaterials, energy harvesting, perfect absorber, wifi band, electronic textiles*

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*Corresponding author: Gamze D. Tetik
E-mail: gamze.tetik@usak.edu.tr (ORCID: 0000-0002-5968-7244)
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1. Introduction

The rapid increase in the world population and the decrease in the energy resources direct researchers to work on energy. Recycling, renewable energy sources, advanced materials for energy applications, and energy harvesting are some hot topics of this area. Energy harvesting is known as the process of converting kinetic energies such as distortion energy, vibration, etc. into electrical energy [1]. The most used energy sources of the portable devices are batteries or battery-like devices. However, some disadvantages of these devices can be regarded as heaviness, big size, and rapid discharge. These disadvantages also prompted researchers to study on energy harvesting methods. Electromagnetic energy harvesting concerns with electromagnetic induction which is the electric potential generated in the conductor by the change of the magnetic field around it. Metamaterials (MTMs) are unique materials that can be utilized in electromagnetic energy harvesting applications. Their interesting features such as negative refractive index, negative dielectric constant, and negative magnetic permeability make them advantageous in various areas [2]. They are called as left-handed materials and they are not found in nature per se.

The metamaterial foundations that were laid by Veselago about fifty years ago continued with experimental studies in the 2000s, and since then these unique materials have attracted academic interest [3, 4]. The efficient preparation of these MTMs, in other words artificial electromagnetic structures, determines the EM (electromagnetic) properties [5] which are basically permittivity ε (ω) and permeability μ (ω). These properties were determined by the structural design of the MTMs according to the applications. Till date plus [6], rectenna [7], C shaped rectangular [8], Hilbert [9], U and L [10], ring circle [11], serpentine [12], hegzagonal [13], octagonal [14] shaped MTM designs have been proposed for energy harvesting applications. Besides, conductive textile materials such as felt, zelt, and pure copper polyester taffeta fabrics (PCPTF) have been used as components of MTMs in various researches [15-17].

Several simulation and experimental studies have been conducted on MTMs for the EM harvesting in various operation frequency bands [18-21]. EM harvesting in radio frequency (RF) band was conducted by Kaur et al. with an ultrathin dual layer MTM design. They observed 76% and 94% absorption values for incidence angle up to 45° in transverse electric and 60 ° in transverse magnetic operation modes, respectively [22]. Coskuner and Garcia-Garcia proposed metamaterial-based transmission lines to improve the operation frequencies to 2.4- 5 GHz [23]. Another group conducted a simulation study about microwave energy harvesting and their results showed that the power absorption efficiency of the dual polarized single cell was 98% at 2 GHz [24]. Moreover, the harvesting efficiency of 96.5% at 2.45 GHz was calculated via the simulation results of a 9x9 fractal based MTM structure. The authors emphasized the potentials of the proposed harvesters for wireless sensor network applications [25]. Umaña-Idarraga et al. proposed a multi resonant MTM structure having absorption efficiencies of 98.2% and 99.7% at 2.4 and 4.2 GHz, respectively [26]. Another group working on the GSM and WIFI bands stated that the harvesting efficiency of their MTM structure was around 90% for the 2.60 and 5.80 GHz frequencies when the incidence angle was 30° [2].

The wireless local area network (WLAN) operations cover the industrial, scientific, and medical (ISM) frequency band (2.5 GHz) and the UN-II band (5 GHz) [27]. Nowadays, WLAN devices are deployed in a wide variety of environments. The importance of harvesting energy from such widely used devices is indisputable. The aim of this study is to design and analysis of the proposed metamaterial structure in order to reveal the potentials as an energy harvester. For this purpose, a textile based metamaterial perfect absorber is designed and simulated to calculate the absorption value at 5 GHz operating frequency.

2. Design and Simulation

The unit cell and the periodic array of the proposed MTM structure is given in Figure 1. The structure is composed of PCPTF substrate, felt dielectric layer, and PCPTF resonator. The thickness values of both the PCPTF substrate and resonator are 0.035 mm. The electrical conductivity, measured resistance, and surface resistance of PCPTF are 2.5 10^5 S/m, 0.031 Ω/sq, and 0.05 Ω/sq, respectively. On the other hand, the dielectric layer, felt has an ε value of 1.44, μ value of 1, and tangent delta of 0.044. The parameters of the structure are given in Table 1.

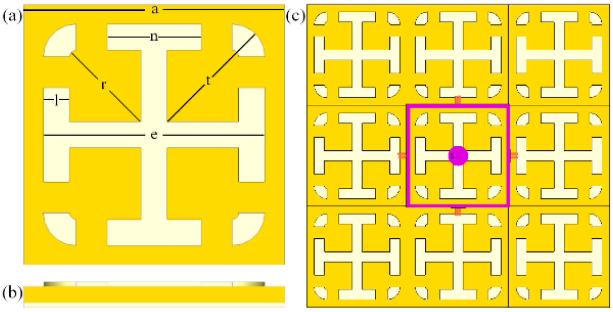

Fig. 1 (a) The front view, (b) the top view, and (c) the periodic array of the proposed structure

Table 1 The parameters of the structure

Parameter	Value (mm)
a	20.00
n	7.24
r	7.50
t	9.50
l	2.00
e	17.00

The simulation was conducted by a full-wave EM solver CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany) based on finite integration technique. 3.5-6.5 GHz frequency range were chosen for calculations. The unit cell was chosen as the boundary conditions for X_{min}, X_{max} and Y_{min}, Y_{max}. Besides, the Floquet boundaries were preferred by choosing Z_{min} and Z_{max} as open (add space) areas. The absorption equation used is

$$A(\omega) = 1 - R(\omega) - T(\omega) \tag{1}$$

Since $R(\omega) = |S_{11}|^2$and $\mathrm{T}(\omega) = |S_{21}|^2$,the $|S_{11}|$ and $|S_{21}|$ values should be minimized to raise the absorption value. Therefore, the substrate material was chosen as PCPTF and transmission value was minimized by this means. The reflection of the MTM structure is tried to be minimized by adjustment of S_{11} parameter. The absorption of the proposed MTM structure was calculated and presented as graph. In addition, the permittivity, the permeability, and the refractive index were given.

3. Results and discussion

3.1. Permittivity, permeability, and refractive index of the proposed structure

In an effective medium, MTMs are described by complex electric permittivity $(\tilde{\epsilon}(\omega)=\epsilon_1+i\epsilon_2)$ and magnetic permeability $(\tilde{\mu}(\omega)=\mu_1+i\mu_2)$. Since the EM properties of MTMs with a negative refractive index can be easily controlled by the components constituting the MTM structure and by the geometric parameters, these parameters can be adjusted according to the applications. The frequency dependent transmission, $T(\omega)$ and reflection, $R(\omega)$ of a MTM are the parameters affecting the absorption of the MTM. As stated in Eq. (1), maximizing the absorption, $A(\omega)$ is possible via minimizing $T(\omega)$ and $R(\omega)$, simultaneously at relevant frequency.

Fig. 2 shows the effective parameters and refractive index of proposed MTM structure at between 3.5 and 6.5 GHz. Figure 2 denotes that the values of the real ε, μ and n are 0.25, -0.28, and -0.15, respectively at the resonance frequency. The most important MTM property is a negative refractive index for real part, and this proves that the proposed structure provides this property at the 5 GHz frequency range.

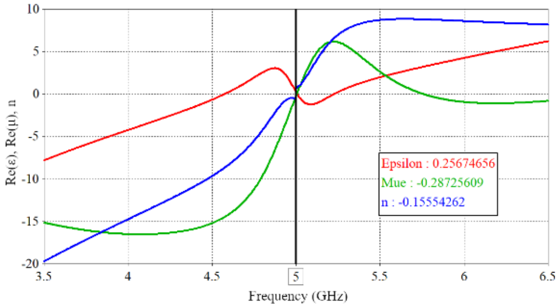

Fig. 2 Permittivity (ε), permeability (μ), and refractive index (n) of the proposed MTM structure

3.2. The absorption, reflection, and transmission of the proposed structure

The absorption, reflection, and transmission graph of the proposed MTM structure at 3.5-6.5 GHz is given in Figure 3. There was only one peak observed at the frequency range considered. The proposed MTM structure has an absorption value of 99.49 % as seen. This value indicates that the designed structure is a perfect absorber and has potentials to be used in energy harvesting applications.

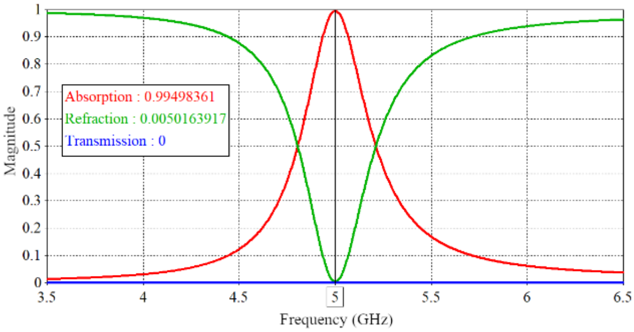

Fig. 3 Variation of absorption, transmission, reflection of the proposed MTM structure.

3.3. Harvesting application

The basis of energy harvesting studies is that the MTM provides excellent absorption of incoming waves in the desired frequency range. In addition, the MTM-based energy harvesting systems also require the highest power distribution to a load to ensure that the absorbed power is spread across the load. According to energy harvesting researches, energy harvesting devices can harvest several types of energy and convert EM energy into electrical energy.

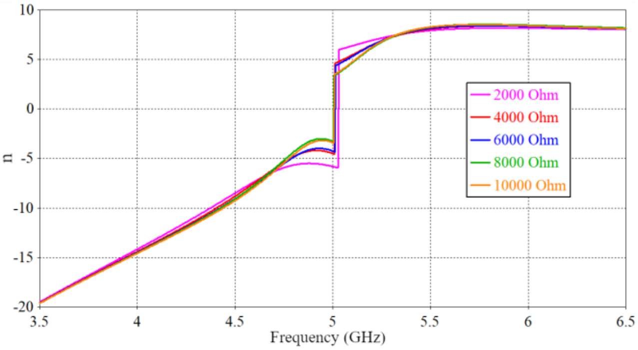

Fig. 4 Refractive index (n) of the proposed MTM structure in the 2000-10000 Ω range (in 2000 Ω increments)

The refractive index characteristics of the proposed MTM structure have been examined considering the resistor values in 2000-10000 Ω range in 2000 Ω increments. The proposed structure has refractive index values of - 5.50, -4.22, -4.03, -3.08, and -3.24 at 2000, 4000, 6000, 8000, and 10000 Ω for each resistor value, respectively (Fig. 4). The negative refractive index values obtained denote that the structure with added resistance also exhibits MTM characteristics. Moreover, the frequency values for these resistor values were obtained as 4.88, 4.94, 4.96, 4.98, and 4.97 GHz, which were very close to the resonant frequency. This discloses that the proposed MTM has a good yield in harvesting applications.

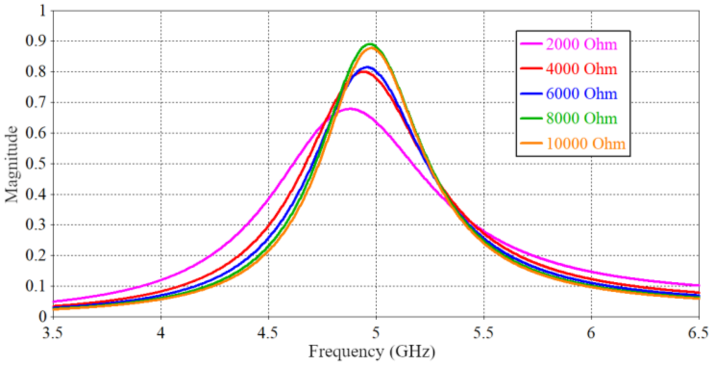

Fig. 5 The absorption of the proposed MTM structure in 2000 and 10000 Ω range (in 2000 Ω increments)

In Fig. 5, the absorption characteristics of the MTM structure have been investigated according to the abovementioned resistor values. The structure has absorption percentages of 67.8, 80.3, 81.1, 88.3, and 87.6 % at the frequencies 4.81, 4.92, 4.96, 4.98, and 4.97 GHz for each resistor value, respectively. Fig. 5 shows that the absorption is maximum in 8000 Ω resistor value. The overall results show that this structure exhibits perfect absorption properties and have potentials to be used in the perfect absorption based harvesting applications.

5. Conclusion

It was aimed to perform a design and simulation study of a MTM perfect absorber and to present the harvesting efficiency of this structure by simulation analysis. For this purpose, a textile based MTM unit cell was designed with three layers as PCPTF substrate, felt dielectric layer, and the PCPTF resonator. The substrate layer was chosen as PCPTF to minimize the transmission value. The reflection value was minimized by accurate selection of material type and the geometrical design. According to the simulation analysis results, the refractive index was negative, and the absorption value was 99.49 % at 5 GHz frequency band. The refractive index of the proposed MTM structure was investigated according to the resistor values in 2000-10000 Ω, in 2000 Ω increments. And the frequency values obtained in this range were very close to 5 GHz showing a good yield. When the absorption characteristics were taken into consideration, it was seen that the maximum absorption was obtained as 88.3% in 8000 Ω resistor value. The overall results of this study reveal that the proposed MTM structure is a good candidate for energy harvesting applications.

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