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A Planar, Layered Ultra-wideband Metamaterial Absorber for Microwave Frequencies

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ABSTRACT

In this paper, an ultra-wideband metamaterial absorber is designed and simulated. The proposed absorber is planar and low profile. It is made of a copper sheet coated with two dielectric layers. Each unit cell of the metamaterial structure is composed of multiple metallic split rings, which are patterned on the top and middle boundaries of the dielectrics. The designed absorber utilizes different resonances of the split rings with non-identical parameters. In order to achieve ultra-wideband absorption, dimensions of the rings are designed to represent dissimilar nearby resonant frequencies. An ultra-wide bandwidth of 67% for 85% absorption is achieved. The absorber's performance is investigated for TE and TM polarizations, and with varying incidence and polarization angles. Ultra-wide band performance of the structure for the case of normal incidence changes to multi-band absorption, with increasing the incidence angle. Electric field distribution of the rings for three low, middle and high frequencies in the absorption bandwidth is simulated and graphically demonstrated. The field distribution verifies that the rings with larger dimensions interact more effectively with low frequency electromagnetic waves, and the rings with smaller dimensions have stronger effects on high frequency waves.

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1. INTRODUCTION

Artificial metamaterials, since their first realization [1, 2], have been widely applied for microwave, terahertz and even enhancement of optical devices. Metamaterial applications in microwave frequency band include antennas, passive microwave circuits, absorbers etc. Using metamaterials, miniaturized wideband and high gain antennas can be designed [3, 4]. Furthermore, Metamaterials have been widely used in passive circuits like filters and power deviders [5, 6].

One of the major applications of metamaterials is in absorbers. Metamaterials have been extensively applied in design of microwave and terahertz absorbers. Using metamaterial structures, low cost, thin and planar absorbers, compared to conventional ones, can be designed.

Metamaterials are inherently resonant structures with relatively high quality factors. Therefore, design of a wideband MTM absorber is one of the main challenges in absorber design. A vast amount of researches has been reported in literature for metamaterial structures tailored for wideband absorbers. The structure of [7] utilizes four dielectric layers and ultra-wibe bandwidth in 5.65-21.16 GHz is achieved for 68.3% absorption. The designed MTM absorber of [8] is thin and has used one dielectric layer and provides a bandwidth of 43% (7.85-12.25GHz) for 90% absorption. An ultra-wideband absorption of 90% in X-band has also been reported [9]. However, in this design, lumped element capacitors and resistors are used in each unit cell and the structure consists of two dielectric layers with an air gap of 4mm between them, which cannot be considered as thin. In reference [10] a thin metamaterial absorber with 35% bandwidth for 90% absorption is designed. In literature [11] 63% bandwidth for 70% absorption is provided. Design of metamaterial absorbers providing multiband, polarization insensitive and perfect absorption

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properties (in some limited frequencies) are also of challenging topics [12-30].

In this paper, an ultra-wideband MTM absorber is designed and simulated. The absorber is made of a copper sheet coated with two dielectric layers. Periodic metallic split rings are patterned on the top and middle boundaries of dielectric layers. The whole absorber is a resonant MTM structure with multiple resonances which are designed to provide ultra-wide bandwidth performance. Compared to previous designs, the proposed structure is planar, thin and low profile and has improved absorption bandwidth. A bandwidth of 67% for 85% absorption is achieved.

The paper is organized as follows. The proposed MTM design is thoroughly explained in Section 2. Simulation results are provided in Section 3. Performance of the absorber for both TE and TM polarizations and with varying the incident and polarization angle, is investigated and discussed in this section. Electric field distribution on metallic rings are calculated and discussed in this section. Concluding remarks are provided in Section 4.

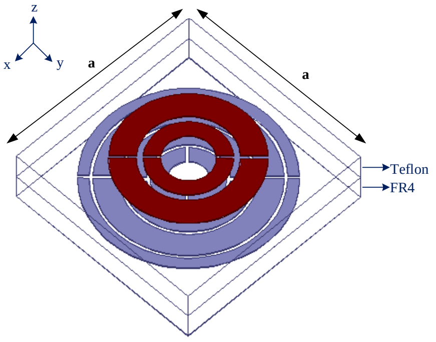
2. THE METAMATERIAL STRCUTURE

Metamaterials, with unit cells much smaller than the incident wavelength, can be treated as dispersive homogenous media with frequency dependent effective medium parameters. When subjected to electromagnetic waves, depending on the polarization and incident wave direction, metamaterials exhibit resonances in effective permittivity and permeability parameters. The structure can be tailored to represent equal effective permittivity and permeability parameters in certain frequencies, so that the effective impedance equals to that of the free space. In these conditions, nearly all of the incident power is absorbed by the structure and no reflection occurs. Due to resonant nature of metamaterial structures, the bandwidth of absorption is strictly limited. One of the main challenges in metamaterial absorbers is bandwidth improvement. In the present work, taking the advantage of nearby multiple resonances, absorption bandwidth is improved to 67% through a simple and low profile structure.

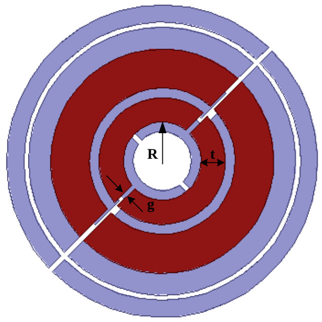
The MTM absorber is made of a copper sheet, regarded as ground plane, coated with two dielectric layers. Placing the ground plane ensures that no electromagnetic wave is transmitted through the structure. The incident power is absorbed and dissipated in the structure, or reflected back. Thickness of the copper sheet should be chosen greater that the skin depth of electromagnetic waves in the incident wave frequency range, to ensure no transmission by the structure. Presence of a thick copper sheet eliminates any transmission from the structure, and therefore absorption is defined as:

$$A = 1 - |S_{11}|^2 \tag{1}$$

The lower dielectric, directly on the ground plane, is FR4 with relative permittivity of 4.4, loss tangent of 0.022 and a thickness of 1mm. The upper dielectric is Teflon with relative permittivity of 2.1, loss tangent of 0.001 and a thickness of 1mm. The unit cell of the MTM structure is shown in Figure 1. Two circular split rings are patterned on the Teflon layer, and four rings are patterned on the middle boundary of the dielectric layers. Each ring contains two splits which are aligned oppositely and are rotated ±45 degrees relative to x and y axes. The rings are made of copper with thicknesses of 0.036mm.



(a) 3-D view

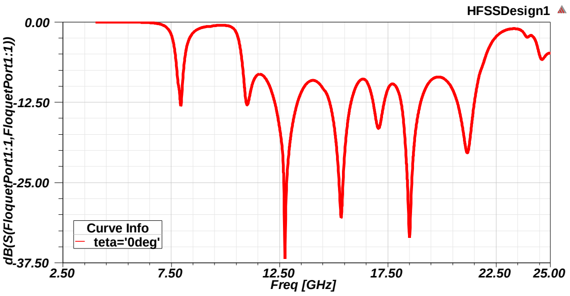


b) Parameters of the rings

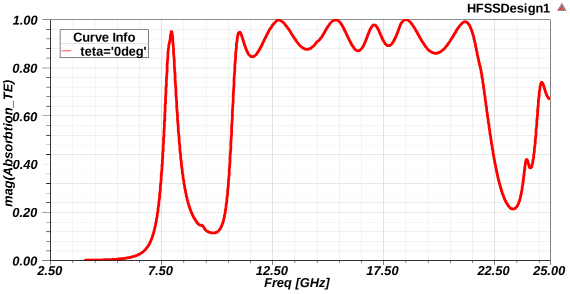
Figure 1. Unit cell of the MTM absorber, (a) 3-D view, (b) parameters of the rings

TABLE 1. Dimensions of the rings, in mm

Ring number	R	t	g
1	0.8	0.5	0.1
2	1.5	0.8	0.1
3	0.6	0.5	0.1
4	1.2	0.7	0.15
5	2	0.75	0.1
6	2.85	0.35	0.1



(a) Return loss



(b) Absorption

Figure 2. (a) Return loss, and (b) Absorption of the MTM structure for normal TE incidence

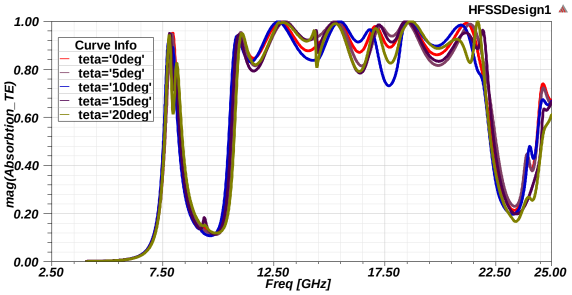
Unit cell of the structure is a square with dimensions 7mm×7mm. The gap width of the splits as well as inner and outer radii of the rings determine absorption bandwidth of the structure. Inner radius of each ring is denoted by "R", thickness by "t", and gap width by "g". The rings are numbered from top layer and from the inner to outer ones. Using this nomenclature parameters of the structure, all in mm, are represented in Table 1.

3. SIMULATION RESULTS

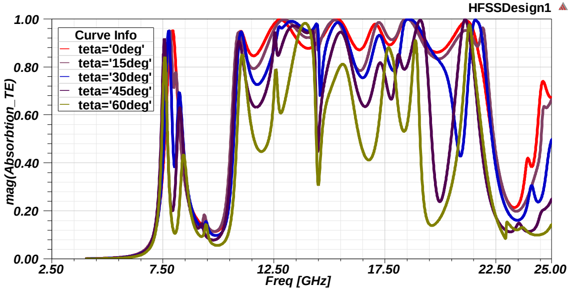
The proposed absorber is simulated with finite element method using High Frequency Structure Simulation, HFSS software. One unit cell is simulated. Periodic boundary conditions are applied in lateral directions, i.e. x and y directions, and Floquet ports in z directions. A plane wave impinges upon the MTM structure. Electromagnetic manipulation of the structure for both TE and TM waves and for different incident and polarization angles are simulated and discussed thoroughly.

Firstly, for normal TE incidence, with electric field parallel to y axis, the metamaterial absorber is simulated. Return loss and absorption of the structure are simulated and depicted in Figures 2(a) and 2(b), respectively. In the ultra-wide bandwidth of 10.8GHz to 21.7GHz absorption is at least 85%, as shown in the figures. This ultra-wide bandwidth performance is due to different resonant frequencies of the split rings. Multiple nearby resonances are clearly visible in the absorption plot. Dimensions of the rings are designed so that their resonant frequencies be properly separated to provide a wide absorption bandwidth.

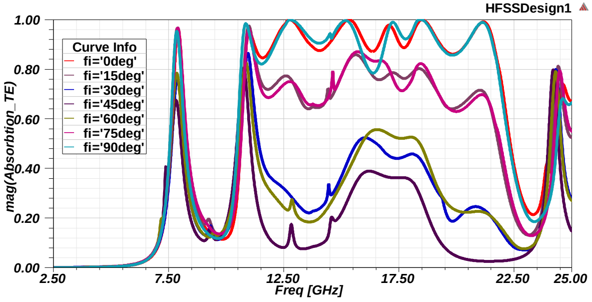
In order to investigate the effect of incidence angle and polarization on absorption performance, the structure is simulated with varying θ and φ. Incident angle is denoted by θ, and the polarization angle, is denoted by φ. Simulation results are demonstrated in Figure 3. For θ angles less than 20 degrees there is a slight degradation in absorption performance, as shown in Figure 3a. For a broader range of variations of θ in 0-60 degrees, absorption is simulated and shown in Figure 3b. With increasing θ, absorption of the structure reduces and results in multiband operation. Variations of the polarization angle, φ, for 0-90 degrees is investigated and is plotted in Figure 3c. With increasing φ absorption reduces, so that minimum absorption occurs at φ=45 degrees. Further increase of polarization angle results to an increase of absorption, and at φ=90 maximum absorption is again achieved. This effect is due to the symmetrical shape of circular split rings.



(a) incident angle of 0-20 degrees



(b) incident angle of 0-60 degrees



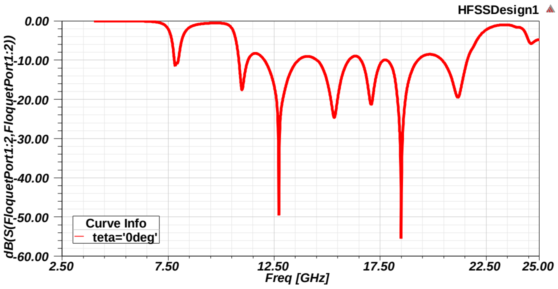
(c) polarization angle of 0-90 degrees

Figure 3. Absorption of the MTM structure for TE incidence and (a) incident angle of 0-20 degrees, (b) incident angle of 0-60 degrees, and (c) polarization angle of 0-90 degrees

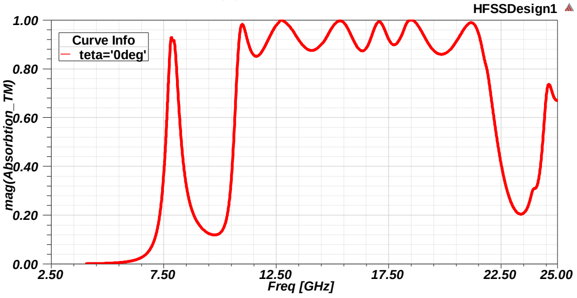
Performance of the structure for TM incidence and for various polarizations and incident angles is investigated and is demonstrated in Figures 4 and 5. In this case, magnetic field of the incident wave is parallel to the y axis. Return loss and absorption, for normal incidence is simulated and depicted in Figures 4(a) and 4(b), respectively. As shown in the figures, return loss and absorption are similar to the TE case for normal incidence. That is again due to symmetry of split rings.

Absorption for various incidence angles is illustrated in Figure 5(a). As is clear in the figure, with increasing incidence angle, absorption reduces. Effect of polarization angle, φ, is also simulated and shown in Figure 5(b). The figure indicates that, with increasing φ, absorption reduces, and for φ=45° reaches to its minimum value. Due to symmetry of the unit cell configuration, further increase of φ results in increase of absorption, as the same phenomenon is observed in TE case.

To better understand the manipulation of electromagnetic waves by the proposed structure, the electric field distributions for three frequencies of 10.5GHz, 17.5GHz and 21.5GHz is investigated and depicted in Figure 6. The figure illustrates that for the lower frequency of 10.5 GHz electric field is mainly distributed on the outer rings.

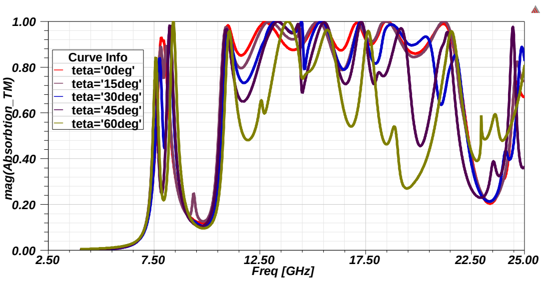


(a) Return loss

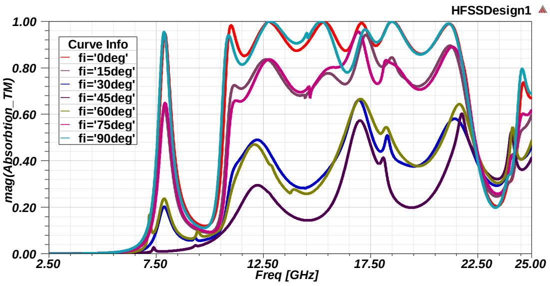


(b) Absorption

Figure 4. (a) Return loss, and (b) Absorption of the MTM structure for normal TM incidence

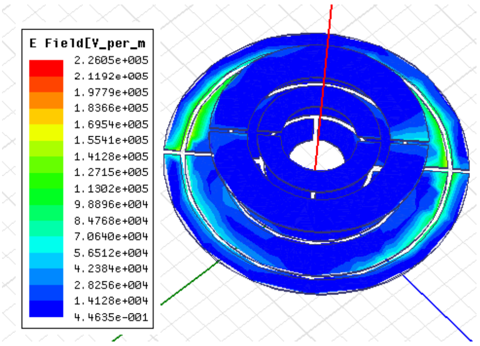


(a) Incident angle of 0-60 degrees

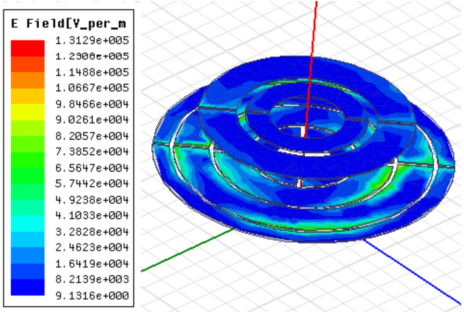


(b) Polarization angle of 0-90 degrees

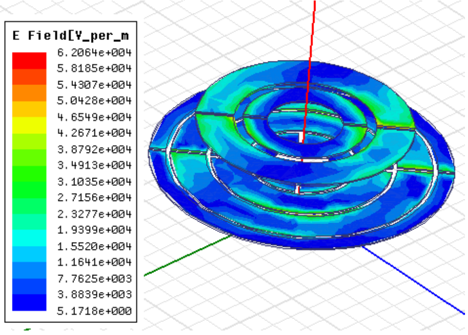
Figure 5. Absorption of the MTM structure for TM incidence and (a) incident angle of 0-60degrees, and (b) polarization angle of 0-90 degrees



(a) 10.5GHz



(b) 17.5GHz



(c) 21.5GHz

Figure 6. Electric field distribution for three frequencies of (a) 10.5GHz, (b) 17.5GHz, and (c) 21.5GHz

For the higher frequency of 17.5 GHz, electric field distribution moves on rings with smaller radius, and for higher frequency of 21.5 GHz, electric field distribution is stronger on the rings of upper layer with smaller radii. On the other hand, electric field of lower frequencies couple to outer rings with larger physical dimensions, and electric field of higher frequencies mainly couple to split rings with smaller physical dimensions. In fact, the outer rings with bigger physical dimensions, determine absorption in lower frequencies and inner rings with smaller dimensions are responsible for higher resonant frequencies absorption.

4. CONCLUDING REMARKS

A planar layered metamaterial absorber was designed and investigated numerically. The absorber is thin and composed of a copper sheet coated by two dielectric layers, a Teflon layer and a FR4 layer, each one with a thickness of 1mm. Several split rings, with different dimensions, were etched on the dielectric layers. Dimensions of the rings were designed to provide different nearby resonant frequencies so that the whole structure provides ultrbandwidth of 68% for 85% absorption. Performance of the absorber was thoroughly investigated for TE and TM incident waves, and for various incident and polarization angles. With increasing the incident angle, absorption in the whole bandwidth reduces and, instead, multiband absorption with lower bandwidths appear.

Due to the symmetry of the structure, with increasing polarization angle, φ, a different phenomenon occurs. With increasing φ, absorption of the structure reduces until φ equals to 45 degrees. Further increase of φ results in an increase of absorption either, and eventually for φ=90 degrees the ultrawibeband performance is again achieved. To better understand electromagnetic wave manipulation of the structure, electric field distribution was plotted and investigated for three frequencies. It was observed that for lower frequencies, the rings with larger radii mainly interact with the incident wave, and for higher frequencies the rings with lower dimensions have strong effects. Future work will focus on reducing sensibility of the proposed absorber on incidence and polarization angles.

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چکیده

در این مقاله یک جاذب فرامادہ و فراپهن‌باند طراحی و شبیه‌سازی شده است. جاذب پیشنهاد شده مسطح و کم ضخامت بوده و از یک صفحه مسی ساخته شده است که بر روی آن دو لایه دی‌الکتریک پوشیده شده است. هر سلول واحد جاذب فراماده از چندین حلقه شکاف‌دار فلزی تشکیل گردیده که بر روی مرزهای بالایی و میانی دی‌الکتریک‌ها شکل‌دهی شده‌اند. جاذب طراحی شده از تشدیدهای متفاوت حلقه‌های شکاف‌دار با پارامترهای نامساوی بهره می‌برد. برای دست‌یابی به جذب فراپهن‌باند، ابعاد حلقه‌ها به‌گونه‌ای طراحی شده‌اند که بسامدهای تشدید متفاوت و مجاور هم به دست آید. پهنای باند فوق وسیع ۶۷٪ برای جذب ۸۵٪ به دست آمده است. عمل‌کرد جاذب برای قطبش‌های TE و TM، و با تغییر زوایای تابش و قطبی‌شدگی بررسی شده است. با افزایش زاویه تابش، عمل‌کرد فراپهن‌باند ساختار در حالت تابش عمودی، به جذب چندبانده تغییر پیدا می‌کند. توزیع میدان الکتریکی حلقه‌ها برای سه بسامد پایین، میانه و بالا در پهنای باند جذب، شبیه‌سازی شده و با استفاده از شکل نشان داده شده است. توزیع میدان تایید می‌کند که حلقه‌های با ابعاد بزرگ‌تر به طور کاراتری با امواج الکترومغناطیسی بسامد پایین اندرکنش دارند و حلقه‌های با ابعاد کوچک‌تر اثر قوی‌تری بر امواج بسامد بالا دارند.

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