Polarization-Independent Metamaterial Based Dual Band Absorber For Stealth Applications In Mıcrowave Bands

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Abstract: Metamaterials have drawn a great attention in recent years because of their unnatural electromagnetic properties such as backward wave propagation, negative refractive index and phase velocity. Therefore, they introduce a different perspective on lenses, antennas, sensors and electromagnetic wave absorber applications. Due to their simple design, easy fabrication process, perfect and broadband absorption features as well as tunable and controllable absorption characteristics, they become a good candidate for stealth applications. In this paper, design, simulation, fabrication and measurement of a dual-band polarization independent metamaterial absorber are presented in the microwave regime. The proposed metamaterial absorber has two distinct absorptive peaks 7.90 GHz and 8.90 GHz with top absorption levels of 99.9 % and 99.3 %, respectively. The measurement results are good agreement with the simulations for different polarizations of electromagnetic waves. Depending on these results, it is possible to say that, metamaterial absorbers can find a promising future in stealth technology applications.
Keywords: Stealth technology, radar cross section reduction, metamaterial, dual band absorber, polarization insensitive absorber.

1. Introduction

Metamaterials are artificial subwavelength structures composed of metal and dielectric materials. They can be defined as effective materials characterized by a complex electric permittivity $\varepsilon_r=\varepsilon_1+i\varepsilon_2$ and magnetic permeability $\mu_r=\mu_1+i\mu_2$. Having simultaneosly negative real parts of both ε_r and μ_r, metamaterials exhibit unusual electromagnetic (EM) responses to incident radiation such as backward wave propagation, negative refractive index and phase velocity. With these properties, metamaterials give a different point of view to many practical applications like super lenses [1], antennas [2], sensors [3] and electromagnetic wave absorbers [4]. Metamaterials are also geometrically scalable and applicable over a significant range of the electromagnetic spectrum. Because of these unusual and tunable features, they have been implemented successfully in every technologically relevant spectral range from microwave and optical region [5-7].

The initial promising studies about metamaterials have looked at its simultaneously negative ε_r and μ_r with the creation of negative refractive index [8]. Afterward, the negative index of refraction was experimentally achieved by Pendry *et al* [9]. In conjunction with confirming the negative index of refraction theoretically and empirically, there has been a great interest in metamaterials over EM spectrum. Moreover, by carefully designing the unit cell structures, both the real and imaginary parts of metamaterials could be adapted to exhibit desired electromagnetic features. This property has been successfully utilized to realize metamaterial based electromagnetic wave absorbers with nearly perfect absorption over a significant range of EM spectrum in recent years. Due to the ultra-thin nature with respect to the wavelength, perfect absorption, simple design and fabrication process, metamaterial absorbers are good candidate for radar absorbing materials in stealth technology in microwave region. The first metamaterial based absorber experiment was realized by Landy *et al* [5] in 2008. In this study, a highly absorptive metamaterial absorber was demonstrated by manipulating of its effective ε_r and μ_r to minimize both transmission and reflection at a resonant frequency. The transmission and reflection are minimized by providing impedance matching with free space and large losses owing to imaginary parts of its effective parameters in the absorber, respectively. After that, many different absorbers have been designed in single, dual, triple and multi band absorptions with having several characteristics like wide-angle and polarization-insensitivity [10-15]. Studies are also carried on many methods of broadening the absorption band such as a

single-layer planar absorber [16], a wideband absorber based on lumped resistors [17], a multilayer stacked absorber [18]. Compared to the conventional millimeter wave absorbers which are physically thick and their frequency performance is limited, metamaterial based absorbers can be used for suppressing microwaves reflected from metallic structures, due to their ultra-thin nature, near-unity absorptivity and increased effectiveness [19, 20].

In this study, design, simulation, fabrication and measurement of a polarization independent dual-band metamaterial absorber is presented. Initially, a known structure [9] is taken as a unit cell. Then, a new design is performed to get dual resonances by adding new structure. Moreover, the dimensions of the metamaterial absorber is optimized to have resonances at X-band. It is observed that the RF simulation results are in good agreement with the measurements such that perfect absorption occurs at 7.90 and 8.90 GHz. Absorptions under different polarizations of incident EM waves are measured with magnitude of over 99 % at low and high frequency peak. The design and analysis are carried out with using a commercial electromagnetic solver CST Microwave Studio, which is based on the finite integration tecnique [21].

In section 2, the design, simulation and fabrication of the metamaterial absorber are described. In addition, the simulation and measurement results are presented and discussed. Moreover, a radar cross section (RCS) of metamaterial absorber is demonstrated under normal incidence of electromagnetic wave. To better understand the mechanism of the RF absorption, the electric and magnetic current field distribution results are presented in section 3. Finally, a conclusion is drawn in section 4.

2. Design, Simulation and Fabrication of the Metamaterial Absorber

The presented metamaterial absorber is based on three layers structure. The first layer is periodically shaped metallic layer which is copper, second layer is a dielectric layer which is FR-4 and third layer is a continuous metallic layer which is also copper. The top layer consists of 2x2 array of unit cells oriented in different directions. Coppers has 35 μm thickness and its frequency independent conductivity (σ) is 5.8×10^7 S/m. FR-4 has 1.6 mm thickness and which has 3.6 relative dielectric permitivity (ε_r) and 0.03 loss tangent.

One unit cell on the first layer consists of two square rings which are separated by a gap. The inner ring is electric ring resonator (ERR), while the outer ring is split ring resonator (SRR). The unit cell's geometrical parameters are specified as follows : L_1 is unit cell's width and lenght, L_2 is the lenght and width of outer ring which is divided vertically to two U-shaped parts and d is the closest distance of these two U-shaped parts and split width in inner ring, L_3 is the lenght and width of inner ring which is divided horizontal and connected with a vertical bar, g is the gap between inner and outer ring, w is copper width. A perspective view of unit cell shown in Figure 1(a). The

proposed unit cell's parameter's values are defined, in mm, as follows : L_1=7.5, L_2=6.4, L_3=3.9, w=0.6, g=0.4 and d=0.65. The direction of radiating wave vector is perpendicular to top surface of unit cell with electric and magnetic field vector and their direction are also shown in Figure 1(a). The proposed unit cell is polarization dependent. To overcome this problem, the unit cell is rotated 90º and added next to the other one. Thus, a polarization independent metamaterial absorber is achieved by comprising of 2x2 array of unit cells oriented in different directions.
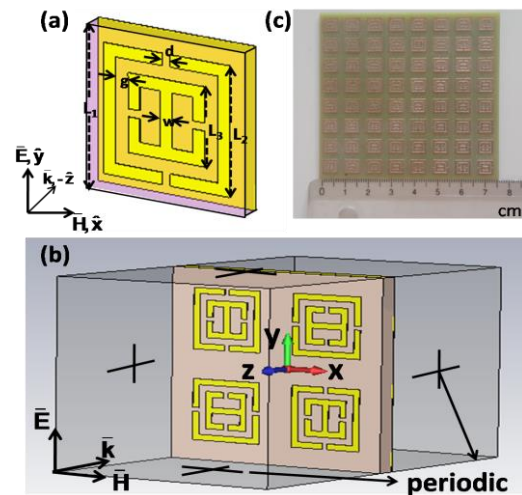

Figure 1. (a) Perspective view of the metamaterial absorber. (b) Perspective view of the simulation. (c) Photograph of the fabricated metamaterial absorber sample.

In the simulation setup, the proposed metamaterial absorber is illuminated with different angle (θ) of polarized plane wave in 7-10 GHz frequency band. The plane wave propagates along -z direction. The polarization of the electric field vector is along the y-axis and the polarization of the magnetic field vector is along the x-axis. Periodic boundary conditions are used in the yz and xz-plane, as seen in Figure (1)b. To experimentally verify the absorption limits of the proposed metamaterial absorber, the metamaterial absorber structure which has the dimensions of 7.5 x 7.5 cm (i.e., 8 unit cells along x-axis and y-axis) is fabricated using printed circuit board (PCB) technique as shown in Figure 1(c). To obtain an ideal metamaterial absorber in other words to achieve the full absorption, there should be no reflection and no transmission. But in practice, to produce an efficient and reliable metamaterial absorber, reflection and transmission of the incident waves should be minimized, exploiting the complex interactions of the metamaterial with the impinging radiation. The absorption is calculated and expressed in terms of the S-parameters:

$$A(\omega) = 1 - T(\omega) - R(\omega) \qquad (1)$$

where $A(\omega)$ the absorption, $T(\omega) = |S_{21}(\omega)|^2$ is the transmission and $R(\omega) = |S_{11}(\omega)|^2$ is the reflection of the metamaterial absorber at an angular frequency ω. $T(\omega)$ is zero due to the shielding of the bottom continuous metal

plate. Thus, the total absorption is calculated only by the reflection and modifying (1) as:

$$A(\omega) = 1 - R(\omega) \qquad (2)$$

In the experimental setup, as shown in Figure 2(a), a vector network analyzer (Net Rohde & Schwarz ZVL, 9 KHz-13.6 GHz) and a pair of double-ridged waveguide horn antennas (HF907 800 MHz-18 GHz) are used. The distance between the horn antennas is set to 60 cm in order to prevent the near field effects on the reflection and the metamaterial absorber is located 115 cm away from the antennas to satisfy the basic far-field condition. Many absorbers are also placed around the metamaterial absorber sample and between the horn antennas to eliminate the electromagnetic interference. The horn antennas serving as the transmitter and receiver are connected to the network analyzer by using low loss flexible cables in order to measure the reflection coefficient. The copper sheet in the same size is measured to define the standard reflection response as the first phase.
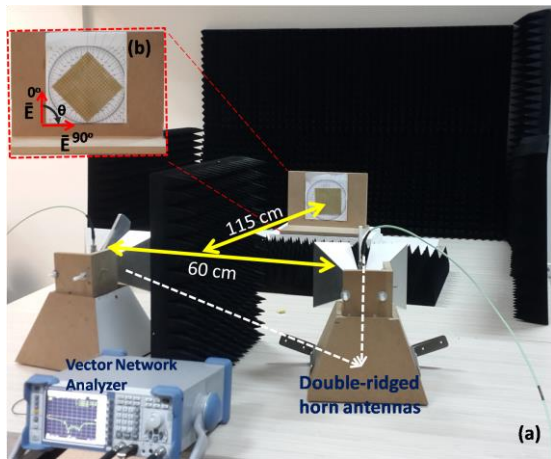

Figure 2. (a) The experimental setup. (b) The mechanism of absorption measurement for different polarization angles under normal incidence.

In the second phase, the reflection coefficient of the metamaterial absorber is measured by replacing the copper sheet. The disparity of the reflection responses between the copper sheet and the metamaterial absorber are defined as the absorption. By rotating structure at intervals of 10° from vertically polarized plane wave to the horizantally one without changing the transmitting and receiving antenna location, polarization-insensitive behavior of the metamaterial absorber is examined. The mechanism of absorption measurement for different polarization angles under normal incidence is seen in Figure 2(b).

The frequency characteristic of the absorption is presented in different polarizations, as seen in Figure 3. It is noted that the reflection of the absorber drops to a minimum at 7.90 and 8.90 GHz denoting impedance

matching with the free space. These results show that the RF simulation results are in good agreement with the measurements such that near-perfect and polarization independent absorption occurs at 7.90 and 8.90 GHz, with peak absorption levels of 99.9 % and 99.3 %, respectively.
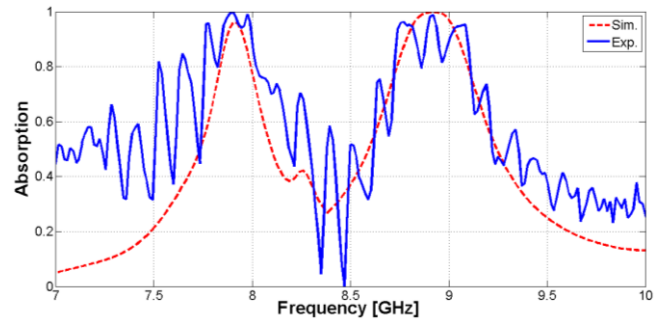

Figure 3. The simulated and measured absorption of the metamaterial absorber for vertical polarization (Ē field perpendicular to the ERR splits)

The quality-factor (Q) value around the resonant frequency can be calculated from the resonance spectra in Figure 3 by the following equation:

$$Q = \frac{f_o}{\Delta f_{FWHM}} \qquad (3)$$

Here, f_o is the resonance frequency and Δf_{FWHM} is its half maximum width. From the simulation and experimental results; f_o, Δf_{FWHM}, Q-factor related to Equation 3 and absorption levels for low and high absorption peaks are given in Table I. As seen in Table I, the Q-factor at 8.9 GHz is lower than the 7.9 GHz's value for both simulation and measurement results. An increase of the bandwidth of absorption peak means the reduced Q-factor, which is very important for the broadband response of metamaterial based absorbers.

TABLE I.

	Low Absorption Peak		High Absorption Peak	
	Sim.	Exp.	Sim.	Exp.
f_o (GHz)	7.91	7.90	8.92	8.92
Δf_{FWHM} (MHz)	360	450	660	630
Q factor	19.9	17.6	13.5	14.1
% $A(f_o)$	96.0	99.9	99.7	99.3

* Units; GHz: gigahertz, MHz: megahertz

Absorption for different angles of polarization (θ) are also investigated. To achieve polarization independent absorption characteristics, the proposed absorber is obtained by placing the unit cell and its 90° rotated counterpart diagonally. The simulated and measured absorptivity of the metamaterial absorber shows almost identical absorption peaks for different polarizing angles up to 90° under normal incidence, as shown in Figure 4 (a, b). These results verify the the polarization-insensitive behavior of the dual band metamaterial absorber.
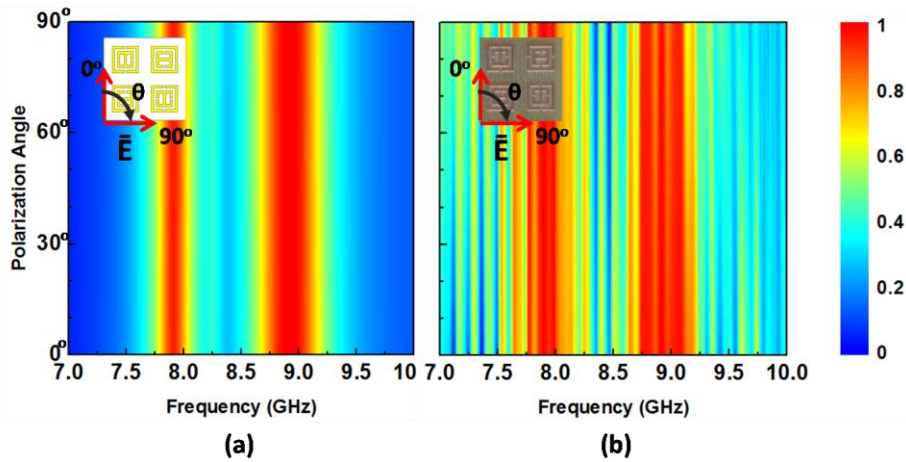
Figure 4. Polarization angle dependence of (a) the simulated absorption (b) the measured absorption results. θ corresponds to the polarization angles.

After that, RCS reduction of metamaterial absorber is demonstrated under normal incidence of electromagnetic wave in Figure 5. For monostatic RCS under normal incidence compared with a PEC plate with comparable dimensions can be defined by [22]:

$$\Delta_{\mathrm{RCS}}(\omega) = -10\log(1 - A(\omega)) \quad \text{(dBsm)} \tag{4}$$

The simulated result given in Figure 5 is calculated by putting the absorption of simulated result in Figure 3 (red dashed line) into Equation (4). As seen from the simulation and experimental results, the RCS reduction is above 10 dB at both absorption peaks under normal incidence.
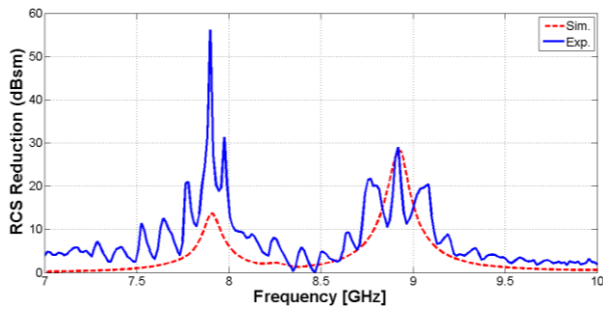

Figure 5. Comparison of simulated and measured RCS reduction for vertical polarization ($\bar{E}$ field perpendicular to the ERR splits)

3. Absorption Mechanism of The Metamaterial Absorber

To better understand the physical mechanism of the dualband metamaterial absorber, electric field and surface current on metals with power loss distribution are plotted in Figure 6 and Figure 7, respectively. Electric field and surface distribution are investigated for both absorption peaks. For vertical and horizontal polarization, the electric field is strongly concentrated diagonally between the gap of the outer ring splits and

inner ring structure at 7.90 GHz, as shown in Figure 6(a, c). However, at the 8.90 GHz, electric field distribution is observed in all ERR splits as seen in Figure 6(b, d). It can be seen clearly that opposite charges are concentrated for both polarization case at absorption peaks. The magnetic field distribution is strongly concentrated on the vicinity of the the inductive ring parallel to the split-wire in ERR [14].
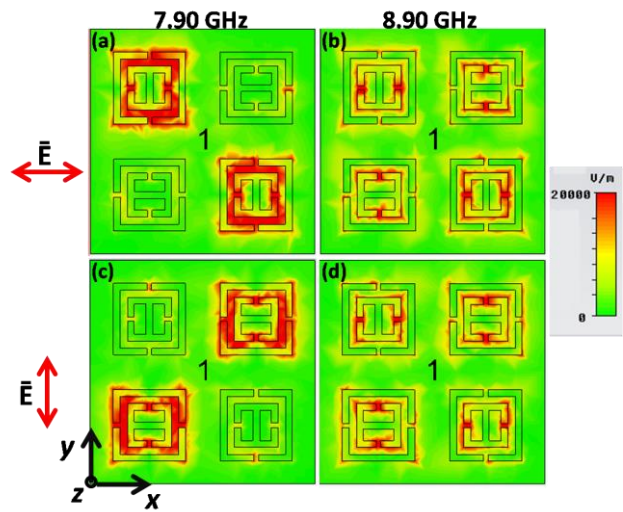

Figure 6. Electric field distribution of the MA, $|\bar{E}|$ field.

Surface current which is responsible for the low-frequency absorption is induced to the outer ring and the inductive wire of inner ring, as shown in Figure 7(a). It is observed that the currents are existing in opposite directions along x axis owing to a dipolar response which contributes to ε_r at 7.90 GHz [11]. Due to the circulating displacement current between the two metallic layers, the magnetic flux are occured, as seen in Figure 7(a, b). As Figure 7(c) shows, most of the power loss occur in between the two rings where the electric field is large [5]. However, surface current which is responsible for the high-frequency absorption is induced diagonally to the inductive wire of inner rings, as seen in Figure 7(d).
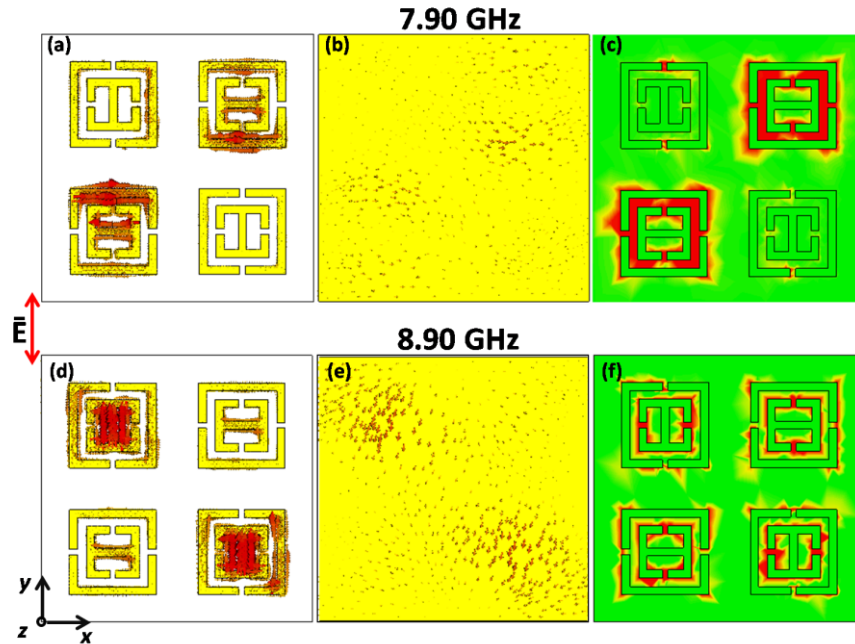
7.90 GHz

8.90 GHz

Figure 7. At 7.90 GHz, Simulation of (a) surface currents on the front unit cell and (b) back metallic plate (c) the distribution of the power-loss absorption. At 8.90 GHz, Simulation of (d) surface currents on the front unit cell and (e) back metallic plate (f) the distribution of the power-loss absorption for vertical polarization (Ē field perpendicular to the ERR splits)

A dipolar response is also occured by strong currents accumulated at the inductive wire and outer ring at 8.90 GHz. Having circulating displacement current between the two metallic layers, the magnetic flux are also occured, as seen in Figure 7(d, e). Most of the power loss occur in around the outer ring and between the splits of inner ring where the electric field is large, as shown in Figure 7(f) [5]. As mentioned above, the proposed absorber interacts with the incident electromagnetic wave field as both an electric resonator and a magnetic resonator in this way and exhibits effective electromagnetic parameters ensuring high energy absorption.

4. Conclusions

In this paper, a polarization independent dual-band metamaterial absorber has been successfully simulated, fabricated and measured. The proposed metamaterial presents absorption peaks at 7.90 and 8.90 GHz with the absorption levels of 99.9 % and 99.3 %, respectively. The measurement results are in good agreement with the simulated results under different polarizations of incident EM waves. Moreover, above 10 dB RCS reduction is achieved at both absorption peaks under normal incidence. Investigations into the electric, surface current and power loss distributions in the unit cell have exhibited the working mode of the proposed absorber. Depending on these results, it is possible to say that, metamaterials have great promise for future applications such as frequency selective surfaces, electromagnetic wave spatial filter.

With geometrical scalability, the broadband metamaterial absorber can be achieved by overlapping the absorption peaks of the proposed unit cell when their peaks are closed to each other. Due to the simple design, easy fabrication, perfect and broadband absorption as well as tunable and controllable absorption characteristics, metamaterial based absorbers have great potential of cloaking and stealth technology applications,

5. Acknowledgements

6. References

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