DESIGN, SIMULATION AND MEASUREMENT OF A DUAL LINEAR POLARIZATION INSENSITIVE PLANAR RESONANT METAMATERIAL ABSORBER

S. Fallahzadeh[*], K. Forooraghi, and Z. Atlasbaf

Department of Electronic and Computer Engineering, Tarbiat Modares University, Jalal Ale Ahmad Highway, Tehran, Iran

Abstract—In this paper, we introduce a highly electric-field-coupled (ELC) metamaterial planar absorber in microwave frequency range. The structure is a one layer dual linear polarization insensitive absorber, which is designed by utilizing properly arranged resonant structure with orthogonal polarization sensitivity. In addition, this metamaterial absorber operates over a wide angular range, from 0° to 65° with more than 95% absorption peak. Absorption peak occurs at the frequency of 10.05 GHz with 98% magnitude with FWHM about 5%. In addition to simulation, the theoretically results are verified by measurement, and test results generally agree with simulation ones. The dielectric spacer loss tangent for higher absorption peak and broader bandwidth has been investigated too, and the optimum value for the best absorber structure performance has been obtained.

1. INTRODUCTION

Electromagnetic metamaterials (MTMs) are defined as artificial and effectively homogeneous electromagnetic structures with unusual and unique properties not easily available in the nature. Metamaterials were first introduced theoretically by Veselago in 1968 [1], but became a hot research topic since Pendry et al. and Smith et al.'s works were published [2–4].

These construct engineered electromagnetic materials are composed of natural materials such as highly conductive and shaped metals (like gold or copper), and dielectric materials that will be selected according to the frequency range and the application. These materials

are usually arranged in a periodic array. An effectively homogeneous structure is defined as a structure whose average unit cell size p is much smaller than the guided wavelength λ_g. If the condition of effective homogeneity is satisfied, the metamaterial structure behaves as a real and integrated material in the electromagnetic waves incidence, which means that it can be characterized by a complex electric permittivity as $\varepsilon(\omega) = \varepsilon_1(\omega) + i\,\varepsilon_2(\omega)$ and a complex permeability as $\mu(\omega) = \mu_1(\omega) + i\mu_2(\omega)$, where both the real and imaginary parts of these parameters can be adjusted, depending on the nature and geometry of the unit cell [5]. Metamaterials are scalable and can operate from the visible to the microwave bands [6–15].

The advantage of variability of the structural parameters of metamaterial has been implemented to create resonant metamaterial absorbers. Basically, to design an absorber, we have to maximize the absorption coefficient. This is equivalent to minimizing both the transmission (T) and reflection (R) coefficients in the equation $A = 1 - T - R$, where A is absorption. The fundamental idea in designing a metamaterial absorber is to simultaneously tailor electric and magnetic resonators to achieve suitable permittivity and permeability that cause minimum transmission and reflection from the absorber structure.

Many works have been done about metamaterial absorber structures design in terahertz and microwave frequency bands. In 2008, two metamaterial resonant absorbers were proposed with two different ELC structures. One suggested by Tao et al. in the terahertz frequency band with two dielectric layers, an ELC and a metallic layer that had a wide angular bandwidth [8]. Another was suggested by Landy et al. with two dielectric layers, an ELC structure on top side and a cut wire, between which a dielectric spacer layer insulates them. This structure was implemented in microwave x-band and terahertz frequency band [7, 9]. Both of these structures were polarization sensitive and had large thicknesses. In 2009, a one layer metamaterial absorber was proposed that had a polarization insensitive absorbance but with a smaller frequency band width [11].

In this paper, a novel design of the planar metamaterial absorber using an ELC resonator is presented. We will show that this new structure can almost completely absorb the incident electromagnetic waves for two perpendicular linear polarizations. Furthermore, the absorber has high absorption within a wide range of incident angle. However, the significance and advantage of this structure are due to its broader bandwidth than previous planar absorbers [9, 11, 13].

2. DESIGN PROCEDURE

As described, absorber design is based on minimizing transmission and reflection. The transmission and reflection coefficients for a structure according to S-parameters are defined as $|S_{21}|^2$ and $|S_{11}|^2$. Normalized impedance of a structure is defined as

$$z = \sqrt{\mu_r(\omega)/\varepsilon_r(\omega)} \tag{1}$$

If we make the absorber normalized impedance match with the impedance of the free space, then

$$z = z_0 \quad (\text{i.e., } \varepsilon_r(\omega) = \mu_r(\omega)) \tag{2}$$

whereupon, the reflection from the structure surface will be slaked. The continuous partial reflections of the absorber structure will be minimized via total structure loss increment, too [16]. The index of refraction is defined as

$$n(\omega) = \sqrt{\mu_r(\omega)\varepsilon_r(\omega)} = n_1 + in_2 \tag{3}$$

and the imaginary part of it describes total losses in a structure. In addition, loss increment can minimize the transmission from the structure, but metallic sheet existence in the back side of the absorber
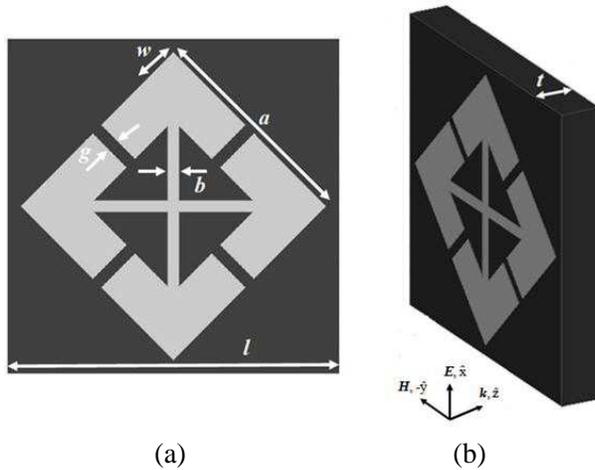

(a)   (b)

Figure 1. (a) Top view of the absorber unit cell structure, all dimensions are in millimeter: $l = 5.5$, $a = 3.6$, $b = 0.2$, $g = 0.2$, $w = 0.8$, $t = 0.74$. (b) Perspective view of structure with showing the vectors of incident EM incident wave. The ELC structure is shown in gray and substrate layer is black.

structure makes it almost equal to zero. So, as mentioned, designing an absorber can be possible using tailor the structural parameters of a metamaterial structure [7–13].

Figure 1 shows the proposed unit cell of the absorber. It is a combination of an Electric-LC (ELC) resonator structure in the front of the unit cell, a dielectric spacer layer made of a lossy FR4-epoxy, and a metal layer on the back side of the dielectric spacer as a ground plate.

Since the ELC structure is an electric resonator, it couples strongly to the incident electric field and has a weak coupling to the incident magnetic field. Therefore, the existing gaps in the structure are coupled with the electric component of electromagnetic incident wave and act as capacitors [17, 18]. Moreover, the center branch of the ELC structure and the metal layer in the back side of the dielectric spacer can strongly couple to the flux of the incident magnetic field and produce antiparallel surface currents. With these two electric and magnetic resonances, we can tune $\varepsilon(\omega)$ and $\mu(\omega)$ to achieve the equality of $\varepsilon(\omega) = \mu(\omega)$ and much content of losses, simultaneously [11, 13].

3. SIMULATION AND MEASUREMENT RESULTS

The absorber structure has been simulated and optimized by Ansoft HFSS. The optimizations of the unit cell structure were made upon the geometric dimensions of the ELC and the dielectric thickness. We set a proper periodic boundary condition (PBC) with the wave vector perpendicular to the unit cell plane at $\hat{z}$-axis where the electric and magnetic fields were parallel to $\hat{y}$-axis and $\hat{x}$-axis, respectively.

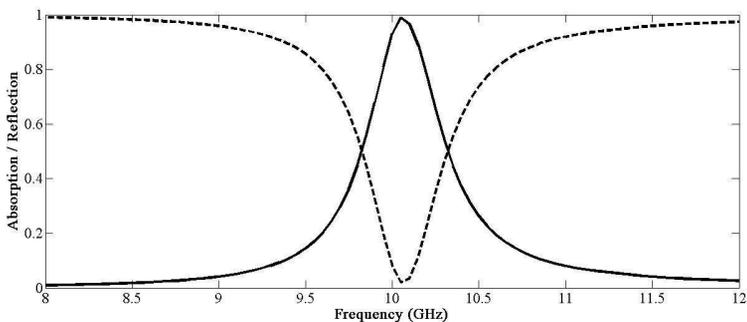The metal elements were modeled with $10\,\mu\mathrm{m}$ thickness copper

Figure 2. Simulation results for Absorption (solid line) and Reflection (dash line) in response to normal electromagnetic incident wave.

with an electric conductivity of $\sigma = 5.8 \times 10^7$ (S/m). As mentioned earlier, FR4 was selected as the dielectric spacer with thickness $t = 0.74\,\text{mm}$ and frequency independent permittivity of $\varepsilon = 4.4 + i0.088$.

    With full wave simulation, the complex frequency dependent S-parameters were obtained. Simulated and experimental results are shown in Figure 2. Here, due to the presence of metal layer in the back side of the spacer layer, S_{21} is equal to zero. The reflection is minimized at the $\omega_0 = 10.05\,\text{GHz}$ that leads to almost complete absorption with a FWHM of 4.8% compared with ω_0. In this frequency, the absorption peak leads to more than 98%.

    The electric field distribution in the unit cell structure at $\omega_0 = 10.05\,\text{GHz}$ is shown in Figure 3(a). It is clear that a strong resonance in ELC gaps due to electric component of incident EM wave has occurred. The surface current density on the ELC and metal plate is shown in Figures 3(b) and (c). The surface currents density on the branch of the ELC and on the central part of metal plate are strong and antiparallel,
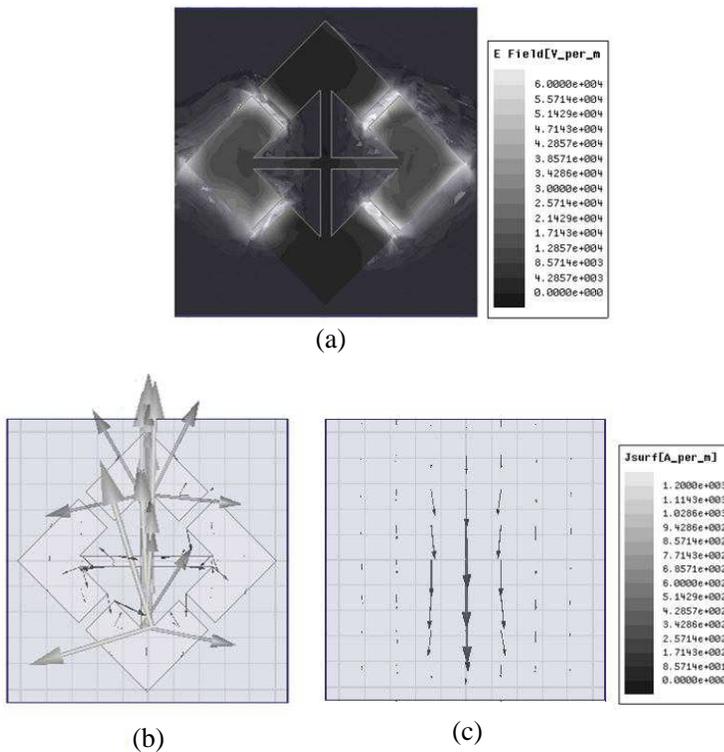

(a)

(b)   (c)

Figure 3. (a) Electric field distribution in the proposed structure and surface current density in (b) ELC resonator and (c) metal layer.

which is an indication of a magnetic coupling. Hence, we can ensure that the structure can be coupled with the electric and magnetic-field components of the EM incident wave.
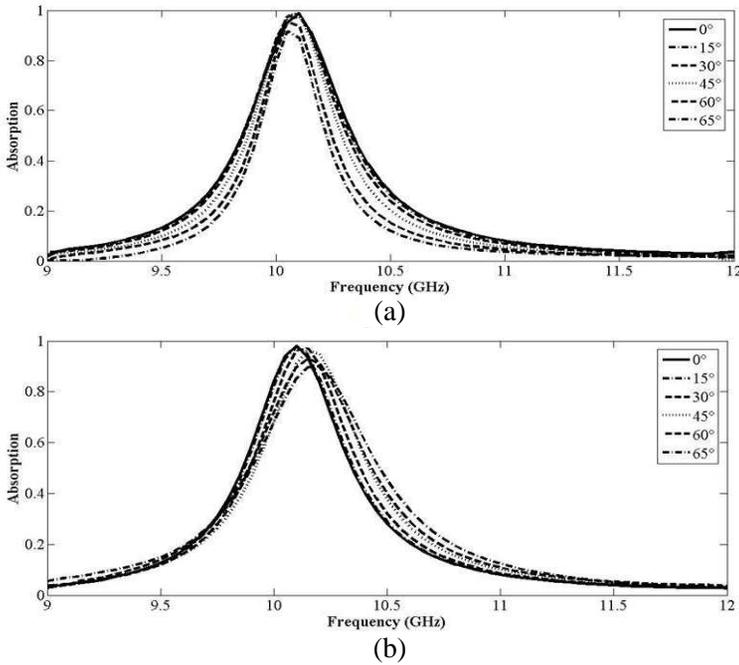

(a)

(b)

Figure 4. The absorption for various values of the incident electromagnetic wave angles for (a) TE and (b) TM polarizations.
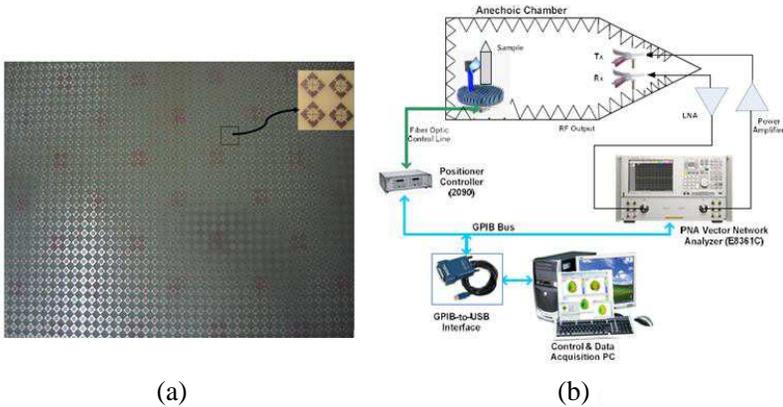

(a)

(b)

Figure 5. (a) Top view of the fabricated sample and (b) test setup.

One important aspect about absorber behavior is to evaluate the sensitivity of the absorption to the change in the incident wave angle. To study this concept, the proposed absorber structure has been simulated for different angles of the electromagnetic incident wave for both TE and TM polarizations, from 0° to 65°, and the results are shown in Figure 4. Good absorptions, over 90%, from 0° to 65° incident wave angle can be observed, which means broad angular bandwidth for the absorber structure.

Based on the simulation results, we have manufactured a 305 mm × 305 mm planar array of the unit cell structure, using printed circuit board (PCB) technique, as a measurement sample. This array is shown in Figure 5(a). In production, the metallic layers were fabricated on both sides of a 0.74 mm thickness FR4 dielectric substrate with frequency independent permittivity of $\varepsilon = 4.4 + i0.088$. Metallic elements, consisting of ELC structure and metal plate, are fabricated with copper film with 0.01 mm thickness.

The experiment setup was performed in an anechoic chamber with two horns. One horn is used to transmit the electromagnetic wave to the sample and another to receive the reflected echoes. The illustrated test set up is shown in Figure 5(b). Normal incident electromagnetic waves with polarization along $\hat{y}$ axis have been established to realize the experiment. The microwave beams reflectance has been collected from 8 to 12 GHz in a PNA vector network analyzer (E8361C) that connected to the two horns. The experimental and simulated reflectance results are shown in Figure 6.

These resonance structures are very sensitive to fabrication tolerances. The frequency shift between simulated and experimental results is mainly due to the inaccuracy of the fabrication process. Further, the larger absorptivity in experiment than in simulation can
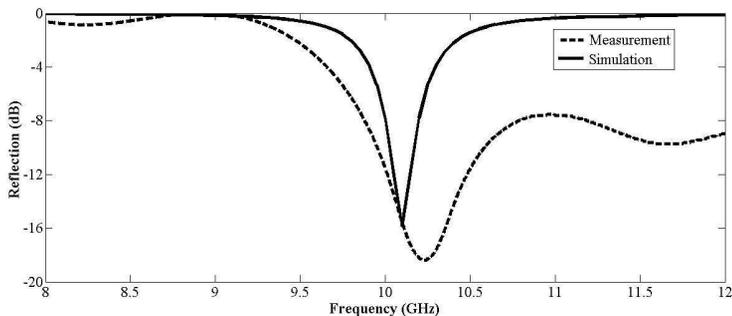

Figure 6. Simulation and measurement reflection results (dB).

be due to scattering from the structure. Mutual coupling between two horns in the test setup may cause changes in measurement results. These impressive factors can justify the difference between simulation and measurement results.

Beside geometric parameters adjustment, dielectric layer properties can improve absorber operation. As mentioned earlier, increasing imaginary part of the index of refraction is an important aspect in absorber design. This can be achieved by augmentation losses in the absorber structure. A part of losses comes from imperfect conductors. In addition, the major part of total losses in a structure is due to dielectric spacer and can be tuned with dielectric loss and thickness. In Figures 7(a) and (b), the absorption as a function of frequency for various values of the dielectric loss tangents are shown. With a constant spacer thickness, dielectric $\tan(\delta)$ enhancement from zero to a bigger value leads to increment in the absorption peak and bandwidth. We can see that via $\tan(\delta) = 0.03$, the absorption peak is more than 99.9%
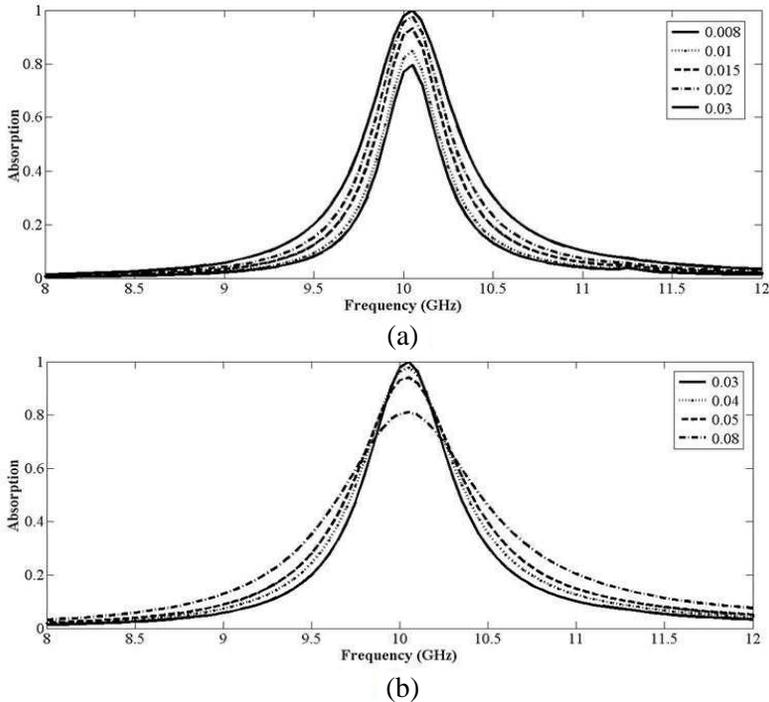

(a)

(b)

Figure 7. The absorption for various values of dielectric loss tangents $(\tan(\delta))$, (a) from 0.008 to 0.03 (optimum value) and (b) from 0.03 to 0.08.

with a FWHM of about 5.75% (Figure 7(a)). But loss tangent increment to more than this optimum value decreases the absorption peak (Figure 7(b)).

4. CONCLUSIONS

In this paper, we have designed, simulated and fabricated a planar dual linear polarization insensitive metamaterial absorber based on an ELC structure that works at microwave frequency band. In addition, this structure has good absorption in a wide range of incident EM wave angles. The measured results generally agree with those obtained by simulations. We demonstrate surface currents and electric field distribution in a unit cell structure to show electric and magnetic coupling. Finally, by optimizing the structural parameters of the dielectric substrate, we obtain 99.9% absorption peak.

REFERENCES

1. Veselago, V. G., "The electrodynamics of substances with simultaneously negative value of ε and μ," *Sov. Phys. Usp.*, Vol. 10, No. 4, 509–514, Feb. 1968.

2. Pendry, J. B., A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low frequency plasmons in thin-wire structure," *J. Phys. Condens. Matter*, Vol. 10, 4785–4809, 1998.

3. Pendry, J. B., A. J. Holden, D. J. Robbins, and W. J. Strewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, 2075–2084, 1999.

4. Smith, D. R., W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, Vol. 84, No. 18, 4184–4187, May 2000.

5. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications,* John Wiley & Sons, New Jersey, 2006.

6. Tao, H., A. C. Strikwerda, K. Fan, C. M. Bingham, W. J. Padilla, X. Zhang, and R. D. Averitt, "Terahertz metamaterials on free-standing highly-flexible polyimide substrates," *Appl. Phys.*, Vol. 41, Nov. 2008.

7. Tao, H., N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, and W. J. Padilla, "A metamaterial absorber for the terahertz

regime: Design, fabrication and characterization," *Optic. Exp.*, Vol. 16, No. 10, 7181–7188, May 2008.

8. Tao, H., C. M. Bingham, A. C. Strikwerda, D. Pilon, D. Shrekehamer, N. I. Landy, K. Fan, X. Zhang, W. J. Padilla, and R. D. Averitt, "Highly flexible wide angle incidence terahertz metamaterial absorber: Design, fabrication and characterization," *Phys. Rew. B*, Vol. 78, 2008.

9. Landy, N. I., S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Phys. Rew. Lett.*, Vol. 100, May 2008.

10. Wen, Q. Y., H. W. Zhang, Y. S. Xie, Q. H. Yang, and Y. L. Liu, "Dual band terahertz metamaterial absorber: Design, fabrication and characterization," *Appl. Phys. Lett.*, Vol. 95, Dec. 2009.

11. Zhu, B., Z.-B. Wang, Z.-Z. Yu, Q. Zhang, J.-M. Zhao, Y.-J. Feng, and T. Jiang, "Planar metamaterial microwave absorber for all wave polarizations," *Chin. Phys. Lett.*, Vol. 26, No. 11, 2009.

12. Tao, H., C. M. Bingham, D. Pilon, K. Fan, A. C. Strikwerda, D. Shrekenhamer, W. J. Padilla, X. Zhang, and R. D. Averitt, "A dual band terahertz metamaterial absorber," *Appl. Phys. Lett.*, Vol. 43, 2010.

13. Cheng, Y. and H. Yang, "Design, simulation, and measurement of metamaterial absorber," *J. Appl. Phys.*, Vol. 108, Aug. 2010.

14. Schuring, D., J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," *Science*, Vol. 314, 977–980, Nov. 2006.

15. Watts, C., X. Liu, and W. J. Padilla, "Metamaterial electromagnetic wave absorbers," *Adv. Mat.*, Vol. 24, OP98, 2012.

16. Pozar, D. M., *Microwave Engineering,* 2nd Edition, John Wiley & Sons, 1999, ISBN 0471170968.

17. Padilla, W. J., M. T. Aronsson, C. Highstrete, M. Lee, A. J. Taylor, and R. D. Averitt, "Electrically resonant terahertz metamaterials: Theoretical and experimental investigations," *Phys. Rew. Lett. B*, Vol. 75, 2007.

18. Schuring, D., J. J. Mock, and D. R. Smith, "Electric-field-coupled resonators for negative permittivity metamaterials," *Appl. Phys. Lett.*, Vol. 88, 2006.