Circuit Model Analysis of a Polarization and Wide Angle Independent Hexagonal Shaped Metamaterial Absorber

M. Bahdorzadeh Ghandehari [1], N. Feiz [1], and M. Alipoor [2]

[1] Department of Electrical Engineering
College of Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran
m.bahadorzadeh@mshdiau.ac.ir, Nooshin.feyz@gmail.com

[2] Department of Electrical Engineering
International University of Imamreza, Mashhad, Iran
mehdialipour70@yahoo.com

Abstract **─** This paper presents an equivalent circuit model of metamaterial absorber (MA) based on triple hexagonal shaped resonators. This metamaterial unit cell absorber possesses a nearly wide angle perfect absorption of incidence wave and polarization independence. The absorption is occurred in three different frequencies. The absorptivity is as high as 98%, 93% and 94%, at 3.5 (GHz), 4.7 (GHz) and 6.6 (GHz), respectively. The equivalent circuit model of a single hexagonal ring has been extended to the triple band absorber structure. The simulation of the circuit model agrees well with the full-wave simulation, regarding to return loss and absorption. The important features of this method are simple fabrication of metamaterial absorber and maximum absorption in three frequencies. The proposed metamaterial absorber has wide applications such as thermal detector, stealth technology and imaging. Moreover, a very good agreement between simulation and measurement results has been observed.

Index Terms **─** Circuit model analysis, metamaterial absorber, triple band, wide angle independent.

I. INTRODUCTION

Electromagnetic metamaterials (MTMs) are defined as artificial and effectively homogeneous electromagnetic structures with unusual and unique properties that do not exist in the nature. Metamaterials were first introduced theoretically by Veselago [1]; his research was continued by Pendry, et. al. and Smith, et. al. [2-4].

These constructed engineered electromagnetic materials are composed of natural materials such as highly conductive and shaped metals and dielectric materials that will be selected according to the frequency range and the application. The advantage of the variability of the structural parameters has been implemented to create the resonant metamaterial absorbers. Basically, to design an absorber, we have to maximize the absorption coefficient. It is equivalent to minimize both the transmission (T) and reflection (R) coefficients in the equation:

$$A = 1\text{-}T\text{-}R, \qquad (1)$$

where A is absorption coefficient [5].

In this paper, we propose a novel planar metamaterial absorber which absorb the electromagnetic wave at nearly 3.5 (GHz), 4.7 (GHz) and 6.6 (GHz) with absorption rate 98%, 93% and 94%, respectively. It is observed that the metamaterial absorber is polarization insensitive for both transverse electric (TE) and transverse magnetic (TM) waves. Also, measured and simulated results are compared. Accordingly, it can be concluded that these results are very close to each other. The proposed metamaterial absorbers in many articles have only one absorbtion frequency [10]-[12]; also, some of them do not have the feature of simple construction and the absorption is not close to the maximum value [13], but the proposed metamaterial absorber in this paper has the advantage of simple fabrication and the maximum absorption at three absorber frequencies.

II. DESIGN AND SIMULATION

As shown in Fig. 1, the proposed metamaterial unit cell is considered as a hexagonal shape. The metallic structures on the top and bottom layers of the substrate are chosen as copper, the electrical conductivity and thickness is $5.8\times10^{7}(s/m)$ and 0.036 (mm), respectively. The substrate of absorber is FR4 ($\varepsilon_r = 4.3, \tan\delta = 0.025$) with 1.6 (mm) thickness.

The simulation is done by Ansoft HFSS and CST software's with periodic boundary conditions. The boundary surfaces perpendicular to the incident electrical field (E) are defined as perfect electric conductor (PEC) surfaces, while the surfaces perpendicular to the incident magnetic field (H) are

Submitted On: September 10, 2014
Accepted On: June 14, 2015

1054-4887

defined as perfect magnetic conductor (PMC) surfaces. Finally, the surfaces perpendicular to propagation vector (k) are defined as open ports.

The absorption is calculated as:

$$A(\omega) = 1 - |S_{11}|^2 - |S_{12}|^2 , \quad (2)$$

where

$$R(\omega) = |S_{11}|^2 , \quad (3)$$

represents the reflection, and

$$T(\omega) = |S_{12}|^2 , \quad (4)$$

represents the transmission. Due to the presence of the metallic ground plane on the bottom side of the absorber the T(ω) is zero so, the absorption can be expressed as:

$$A(\omega) = 1 - |S_{11}|^2 . \quad (5)$$

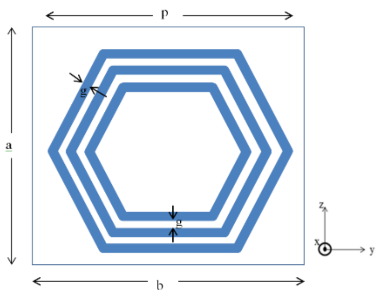


Fig. 1. Unit cell geometry and design parameters: a=b=20 mm, p=17.4 mm, and g=1.2 mm.

The absorption and reflection of the proposed structure is shown in Fig. 2. It is evident that near the frequencies of 3.5 (GHz), 4.7 (GHz) and 6.6 (GHz) the reflection reaches its minimum value and the absorption rate reaches to 98%, 93% and 94%, respectively.

The first absorption frequency is occurred due to the largest perimeter hexagonal and the medium and smallest hexagonal will result in the second and third absorption.

Figure 3 shows the surface current's distribution on the smallest hexagonal which causes the third absorption at the resonant frequency (6.6 GHz). It implies the absorption mechanism of such metamaterial absorber.

For electromagnetic wave normal incidence, the currents on the absorber are symmetrical and counter-circulated between the left and right parts, providing an electric response similar to an electric-LC resonator. There is a magnetic response associated with a circulating displacement current between the resonator and the ground plane (bottom side of substrate). The electric and magnetic response appeared simultaneously at the absorption frequency. In this resonance condition, the effective impedance is defined as [10]:

$$Z(\omega) = \sqrt{\frac{\mu(\omega)}{\varepsilon(\omega)}} . \quad (6)$$

In order to make the minimum reflection, the effective impedance has to be matched to free space impedance. This phenomenon is happening in the resonance frequency.

Moreover, due to the resonant loss in the metallic resonator and the dielectric loss of substrate, the transmission in the metamaterial absorber is effectively reduced.

So, the metamaterial absorber proposed in this paper can absorb both the incident electric and magnetic fields. This absorption mechanism is similar to the common published metamaterial absorbers as shown in [6-9].

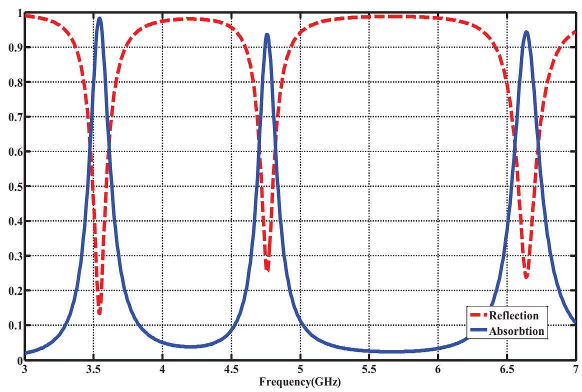


Fig. 2. Simulated reflection and absorption of the proposed metamaterial absorber.

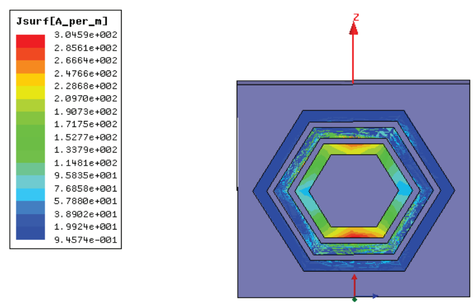


Fig. 3. Current distribution on the metamaterial unit cell at third resonance frequency (6.6 GHz).

In order to find the influence of polarization and incident angle on the performance of the proposed metmaterial absorber some simulations were performed. The structure was simulated by a 3D full wave electromagnetic simulator CST based on the FDTD method as shown in Fig. 4. The result of the absorption under different incident angles for TE and TM polarizations have been demonstrated in Figs. 5 and 6 respectively. As shown in these figures, the strength of the absorption is close to maximum for all incident angles from 0° to 45° regardless of the mode. This fact represents the independence of metamaterial absorber to the angle of incident for a wide range.

It is evident that the main peak of the absorption is above 90% for both TE and TM cases at different angles. Also, the resonant frequencies for both TE and TM polarization are the same implies the polarization independence of the absorber.

So, the proposed metamaterial unit cell is flexible and has multi directional structure. It is evident that a very small and negligible difference is observed between the TE and TM modes by changing the polarization angle. The simulated results show that the proposed metamaterial absorber can be operated for a wide range of incident angles with arbitrary polarizations.

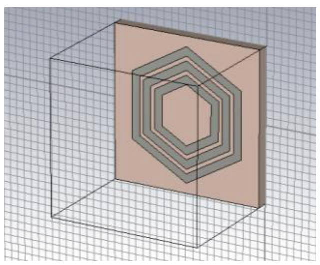


Fig. 4. The simulated structure by CST.

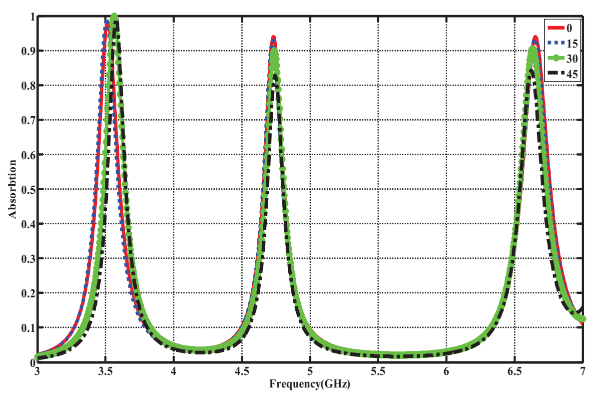


Fig. 5. Absorption at the different incident of polarization angles ranging from 0° to 45° for TE mode.

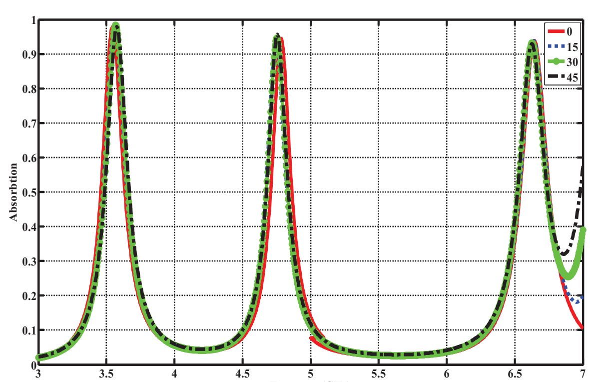


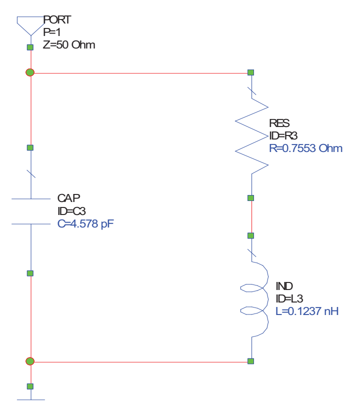
Fig. 6. Absorption at the different incident of polarization angles ranging from 0° to 45° for TM mode.

III. CIRCUIT MODEL ANALYSIS

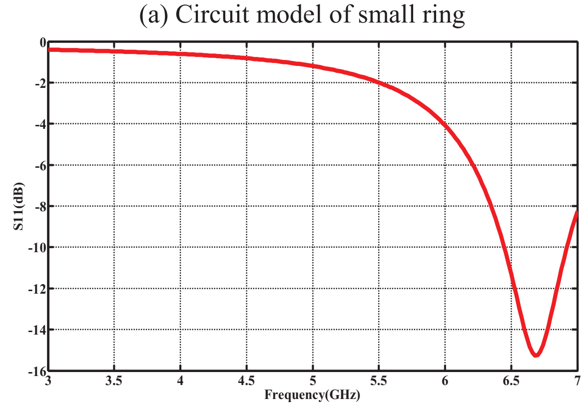
A circuit model for an individual closed ring resonator (CRR) based structure backed by copper lamination is proposed in [14]. A closed ring could be modeled by the circuit model which is presented simply in Fig. 7 (a).

The resonance is modeled by the parallel inductance and capacitance. A single band absorber can be considered as a parallel LC circuit. The resistive part in series with the inductive part models the resonator losses. The magnetic and electric excitations give rise to the effective inductance and capacitance respectively in the circuit model. The result of s parameter simulation with AWR has been presented in Fig. 7 (b) shows a good agreement with the EM simulation.

When the electromagnetic plane wave impinges the proposed absorber all the three CRRs will be excited simultaneously. The complete circuit model of the absorber with all three coupling resonator circuits has been shown in Fig. 8. The extra capacitances were used to model the mutual coupling effects between resonators. The reflection coefficient of the complete circuit model is presented in Fig. 9, which represents a good agreement with EM simulation. Through this circuit model the resonance frequencies could be tuned easily.



(a) Circuit model of small ring



(b) CRR reflection coefficient based on circuit model

Fig. 7. CRR unit cell circuit model and simulated S-parameter.

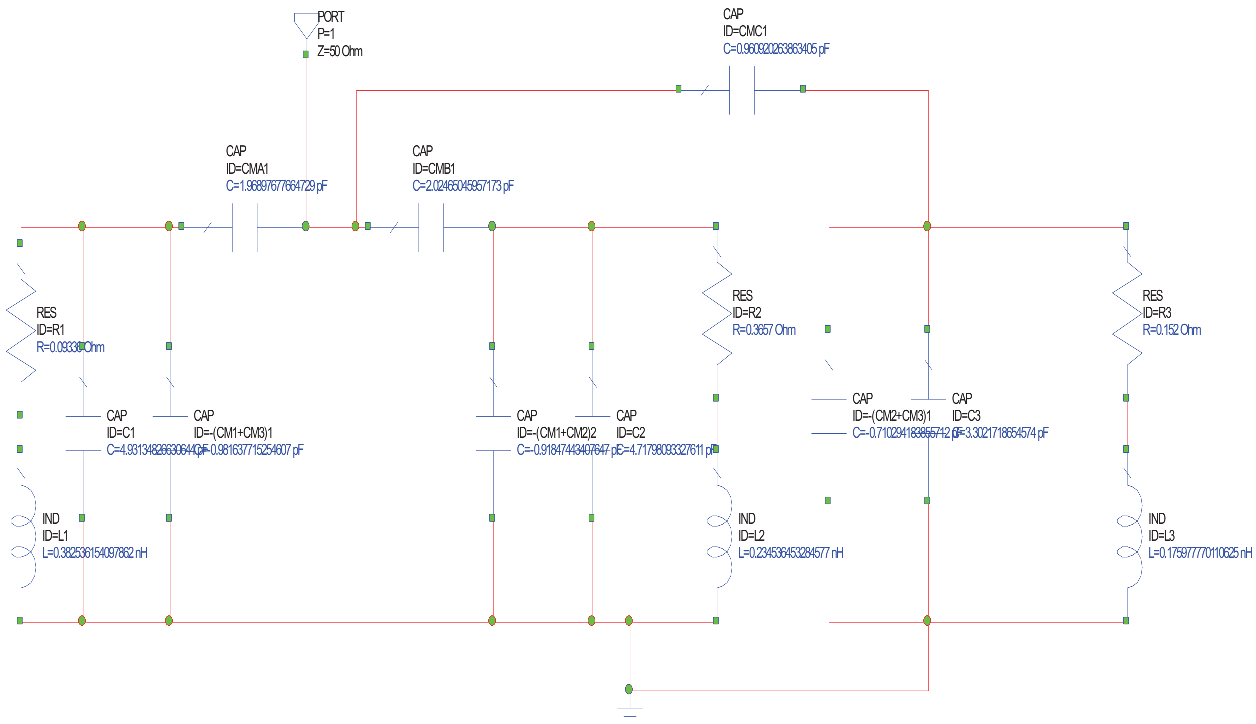


Fig. 8. Circuit model of triple band absorber.

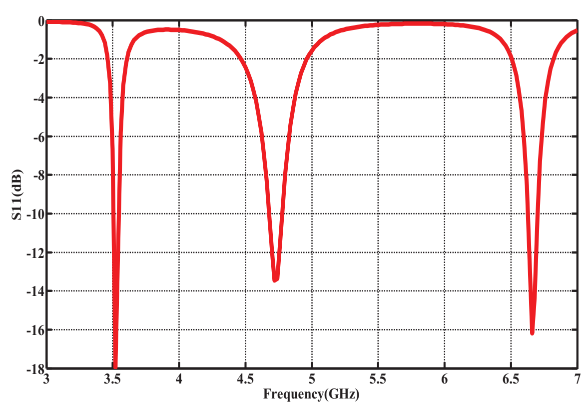
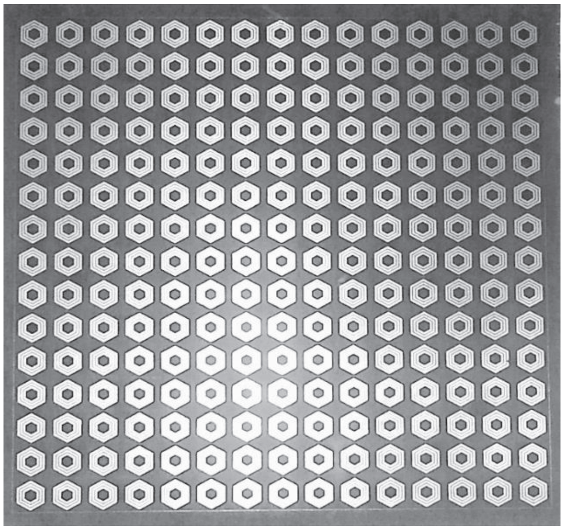


Fig. 9. S-parameter of simulated circuit model.

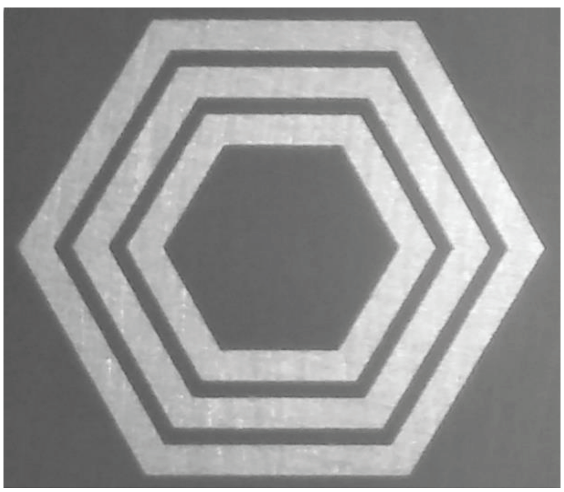
IV. FABRICATION AND EXPERIMENT RESULTS

To verify the full-wave simulations, a 15×15 unit cells sample (300 mm × 300 mm × 1.5 mm) was fabricated by printing a planar array of designed hexagonal shaped structure on the front side. A complete ground plate was placed on the back side of a FR-4 substrate. The thickness of the substrate is considered 1.5 mm and printed-circuit-board (PCB) technology was used for fabrication. The photograph of the experimental sample of proposed MA is shown in Fig. 10. A vector network analyzer Agilent E8363C and two linear polarized horn antennas were used to transmit TEM waves in the range from 3 GHz to 7 GHz to sample and receive the reflected signals. The location of the absorber was far enough from the horn antennas so that the incidence could be recognized normal to the sample. As demonstrated in [11], the experimental measurement is carried out in two steps. In the first step, the reflection measurements should be calibrated using a copper sample-sized sheet as a reflecting mirror. The measurement is done by a ground copper plane with the same dimension as the sample used for measurement and this is used as measurement reference.

In the second step, the fabricated sample of the metamaterial absorber is tested and the S-parameters are recorded. The differences between the measured results of the first and second steps represent the modified reflection coefficient from the proposed MA [11]. The reflection coefficient and the absorption of the experimental proposed metematerial absorber is shown in Fig. 11. The measured and simulated absorption of TE and TM modes as a function of the frequency are shown in Fig. 12 and Fig. 13, respectively. It is observed that the simulation and experimental results are in a good agreement.



(a) Fabricated metamaterial absorber



(b) An isolated unit cell

Fig. 10. Photograph of fabrication of proposed metamaterial absorber.

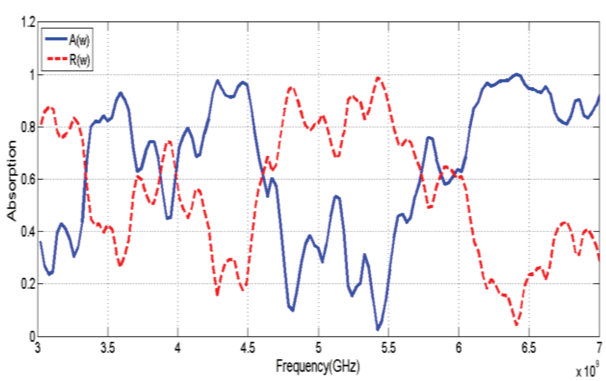


Fig. 11. The reflection coefficient and absorption of the experimental proposed metematerial absorber.

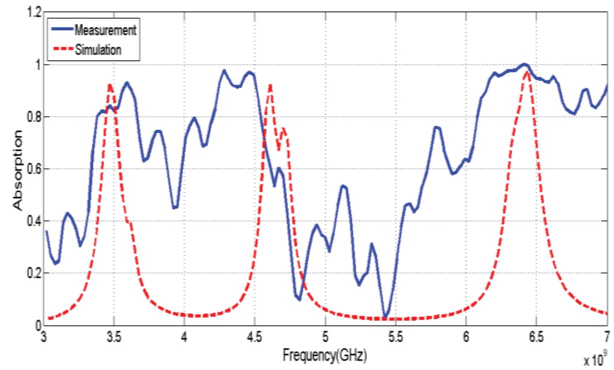


Fig. 12. The measured and simulated absorption of TE mode as a function of the frequency.

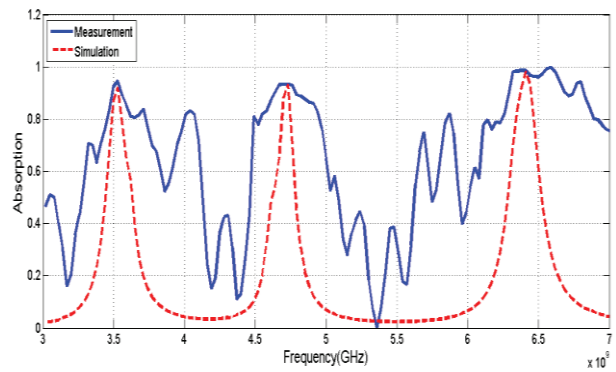


Fig. 13. The measured and simulated absorption of TM mode as a function of the frequency.

V. CONCLUSION

In this paper, a novel metamaterial unit cell absorber based on triple hexagonal shapes has been presented. Simulations demonstrated that due to the hexagonal with different perimeters, absorption occurs at three different frequencies. Metamaterial absorbers that were used in many articles have only one absorption frequency, but in this paper, maximum absorption is observed in three frequencies. Compared to other researches, absorption is very close to its maximum value. It could be found that the absorber is polarization independent and could be worked for a wide angle of incidence. An equivalent circuit model was represented for modeling the absorber. The results are in a good agreement with simulation and measurement results. The geometric parameters that influence the resonance of the absorber were further discussed, which shows that the absorbing frequency could be shifted by adjusting the space of hexagonal. Also, the fabrication results of the proposed metamaterial absorber are demonstrated that the simulation and experimental results are in a good agreement.

REFERENCES

[1] V. G. Veselgo, "The electro dynamics of substances with simultaneously negative value of ε and μ," *Sov. Phys. Usp.*, vol. 10, no. 4, pp. 509-514, Feb. 1968.

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

[3] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2075-2084, 1999.

[4] D. R. Smith, 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, pp. 4184-4187, May 2000.

[5] S. Jamilan, M. N. Azarmanesh, and D. Zarifi, "Design and characterization of a dual band metamaterial absorber based on destructive interferences," *Progress In Electromagnetics Reseach C*, vol. 47, pp. 95-101, 2014.

[6] M. H. Li, H-L. Yang, X-W. Hou, Y. Tian, and D-Y. Hou, "Perfect metamaterial absorber with dual bands," *Prog. Electromagn. Res.*, 108:37-49, 2010.

[7] X-J. He, Y. Wang, J-M. Wang, T-L. Gui, and Q. Wu, "Dual-band terahertz metamaterial absorber with polarization insensitivity and wide incident angle," *Prog. Electromagn. Res.*, 115:381-397, 2011.

[8] L. Huang and H. Chen, "Multi-band and polarization insensitive metamaterial absorber," *Prog. Electromagn. Res.*, 113:103-110, 2011.

[9] L. Li, Y. Yang, and C. Liang, "A wide-angle polarization-insensitive ultra-thin metamaterial absorber with three resonant modes," *J. Appl. Phys.*, 110:063702, 2011.

[10] Y. J. Huang, G. J. Wen, J. Li, W. R. Zhu, P. Wang, and Y. H. Sun, "Wide angle and polarization independent metamaterial absorber based on snowflake shaped configuration," *Journal of Electromagnetic Waves and Applications*, vol. 27, no. 5, pp. 552-559, 2013.

[11] F. Dincer, M. Karaaslan, E. Unal, E. Akgol, E. Demirel, and C. Sabah, "Polarization and angle independent perfect metamaterial absorber based on discontinuous cross-wire-strips," *Journal of Electromagnetic Waves and Applications*, vol. 28, no. 6, pp. 741-751, 2014.

[12] S. Fallahzadeh, K. Forooraghi, and Z. Atlasbaf, "Design, simulation and measurement of a dual linear polarization insensitive planar resonant metamaterial absorber," *Prog. Electromagn. Letter*, vol. 35, pp. 135-144, 2012.

[13] P. K. Singah, S. Kabiri, L. Chao, M. N. Afsar, and S. Sonkusale, "Boardband millimeterwave metamaterial absorber based on embedding of dual resonators," *Prog. Electromagn. Res.*, vol. 142, pp. 625-638, 2013.

[14] S. Bhattacharyya, S. Ghosh, and K. V. Srivastava, "Equivalent circuit model of an ultra-thin polarization-independent triple band metamaterial absorber," *AIP Advances 4*, 097127, 2014.

Mehdi Bahadorzadeh G. was born in Mashhad, Iran in September of 1981 and he received his B.Sc. from Ferdowsi University in 2003, his M.Sc. from Shahed University in 2005, and his Ph.D. from Islamic Azad University in 2009, all in Telecommunication Engineering. He also cooperates with the Iranian Telecommunication Research Center (ITRC) and Iranian Research Institute for Electrical Engineering as a Research Assistant since 2007. His main areas of interest are electromagnetic compatibility, numerical methods in electromagnetics, microstrip antenna, microwave engineering and RF circuit design.

Nooshin Feiz was born in Mashhad, Iran in 1987. She received the B.S. from Fredowsi University, Mashhad Iran, in 2009 and the M.S. degree from Shiraz University, Shiraz, Iran in 2011. Her research interest is in electromagnetic waves in complex media, metamaterial applications such as absorbers and antenna.

Mehdi Alipoor was born in Tehran, Iran, on February 16, 1992. He is now a Bachelor Student of Telecommunication Engineering at the International University of Imamreza, Mashhad, Iran. His research interest is in microwave engineering, RF circuit design, electromagnetic waves in complex media, metamaterial applications such as absorbers and antenna, etc.