Design of a five-band polarization-insensitive terahertz metamaterial absorber

A. ELAKKIYA[a,*], S. RADHA[a], E. MANIKANDAN[b], B. S. SREEJA[a]
[a]SSN College of Engineering, Chennai – 603110, India
[b]Department of ECE, B. S. Abdur Rahman Crescent Institute of Science and Technology, Chennai-600048, India

---

A novel five band polarization independent terahertz metamaterial absorber is proposed. Three small equilateral triangle-shapes are etched from a star-shaped metallic structure in which the pattern was placed on the top of the absorber structure and the metallic ground plane was separated from the polyimide dielectric substrate. The proposed absorber was a resonance at five different frequencies for the absorptivity of 98.7% at 0.3288 THz, 96% at 0.4068 THz, 97% at 0.4228 THz, 99% at 0.4472 THz, and 92% at 0.462 THz. The physical properties of the structure were analyzed by an electric field, magnetic field and surface current distribution mechanisms. This can be used the material sensing, optoelectronics, terahertz imaging.

(Received November 19, 2018; accepted August 20, 2019)

Keywords: Polyimide, Terahertz, Metamaterial, Five-bands

---

1. Introduction

Electromagnetic metamaterials have unique properties which are artificially produced [1] for different purposes from microwave [2], optical [3-6], and infrared [7] also in terahertz [8-10] frequencies. A single band absorbance of microwave metamaterial was first designed in 2008 by Landy et.al [11] with absorptivity of 88%. Then different kinds of devices such as switches [12], transparent absorbers [10], polarization conversions [13-15], filters [16], split ring resonators [17], modulators, sensor [18] etc. based absorbers have been designed by many researchers. The study of a higher absorption in natural materials is very difficult to find but the terahertz artificial absorbers provide the chance to increase the absorption rate. The terahertz system mostly prefer the multiband absorbers. But, initially, single band absorbers have demonstrated their unsuitability for some practical applications [19] but, the multiband absorbers used in martial detecting, increase the imaging resolution also in frequency selective detection etc. [20]. Achievement of the multiband absorber, requires designing multiple resonators in the single unit cell and multilayer stacked structures. But unfortunately, both have some disadvantages. The first method provides the disarrangements area consumption and the second method has problems in fabrication [21]. Moreover, many dual bands, quad-band and also five band absorbers have also demonstrated the multiband absorbers further developed by metal-dielectric layer-metal sandwiched structure [22-23].

In this paper, a novel five band polarization independent terahertz absorber has been designed. It is based on a star-shaped absorber structure from three equilateral triangles etched for improving the resonance which is placed on the top of the absorber and the ground plane is separated from the dielectric layer. The optical properties of the structure were obtained using analysing resonance and absorption strength levels and the physical mechanisms of the absorber structure is analysed by surface current distribution, electric and magnetic field distribution. The absorber resonance was at 0.3288THz, 0.4068THz, 0.4228THz, 0.4472THz and 0.462THz frequencies with the absorptivity of 98.7%, 96%, 97%, 99% and 92% respectively.

2. Structure and design

The proposed terahertz metamaterial absorber, consisted of a single star-shaped absorber from three equilateral triangles etched and placed on the top metal layer. A ground plane was at the bottom metal layer separated by a polyimide dielectric substrate. This is shown in Fig. 1. The electromagnetic characteristics, resonance and absorption mechanisms can be characterized by using a CST Microwave studio software which is based on the Finite difference time domain method.

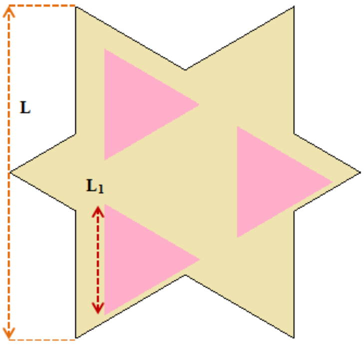

Fig. 1. Proposed terahertz metamaterial absorber structure (Three small equilateral triangle-shapes are etched from the star-shaped absorber L=346 μm, L_1=115μm)

Actually, the authors did a different analysis in the initial unit cell. The analysis helped fixing the final structure as shown in table 1. To start with, the authors took a star shaped only and obtained three bands at 0.4068 THz, 0.4228 THz and 0.4472THz frequencies with the absorption rates of 98%, 99.6% and 99.5% respectively. In order to improve the absorption, three equilateral triangles were etched out from the star-shaped absorber structure. Fig.1. Table 1.clearly shows the improving stages of the proposed absorber. The geometrical values of the proposed structure are given as follows: L=346 µm, L_1=115µm. L is the length of each side of a big triangle and L_1 is the length of each side of a small triangle which implies all were equilateral triangles. The length and the width of the polyimide substrate were 400µm and the thickness was 500 µm. The periodicity size of the proposed terahertz metamaterial absorber structure was 115 µm. EM wave was the source of excitation and the boundary conditions for the unit cell was applied towards the x and y directions. The open boundary condition was applied to the z-axis direction [24-27]. The absorption rate for this was calculated using the formula, A (ω) =1-T (ω)-R (ω), A, T, R represent absorbance, transmittance, and reflectance of the proposed absorber. The skin depth value was high compared to a bottom plane thickness. Hence the transmittance value was zero. The absorbance value could be calculated using the equation A (ω) =1- R (ω). When the impedance value was perfectly matched to the outer space, the reflectance value was approximately zero.

3. Results and discussions

The absorption curves of the proposed terahertz metamaterial absorber are shown in Fig. 2 (a), which helps identification of the five bands and their corresponding absorptivity. Absorber is a resonance seen at each of five different frequencies at 0.3288THz, 0.4068 THz, 0.4228 THz, 0.4472THz and 0.462 THz frequencies with the absorptivity of 98.7%, 96%, and 97%, 99%, and 92% respectively. Also, variations were made in three etched triangles lengths to improve the absorption rate. Maximum absorption occurred at the length of the small triangle 115 µm whose absorptivity is shown in Fig. 3 (a) also the corresponding values are shown in Table 1.

Table 1. Absorptivity corresponding to Length of the each etched Small triangles

Length of the each etched Small triangles	Absorptivity	Number of bands
Without Triangles	98%,99.6%,99.5%	3
81µm	98.8%,99.7%,99.6%	3
92µm	99.8%,99.6%,99.5%	3
104µm	97.5%,98%,99.6%	3
115µm	98.7%,96%,97%,99% ,92%	5
127µm	98.5%,92%,92%,98.6% ,89%	5

Using these results, the authors identified a frequency selectivity of the multiband absorber arising from a narrow bandwidth. Coupling of the magnetic and electric resonances provided a high absorption structure.

It also required the provision of polarization insensitive to the incident light. Analysis of polarization independent behavior was done from changing different theta values of the proposed absorber. Resonance occured in the same frequencies for different polarization angles. Hence the absorber in a polarization was insensitive by nature.

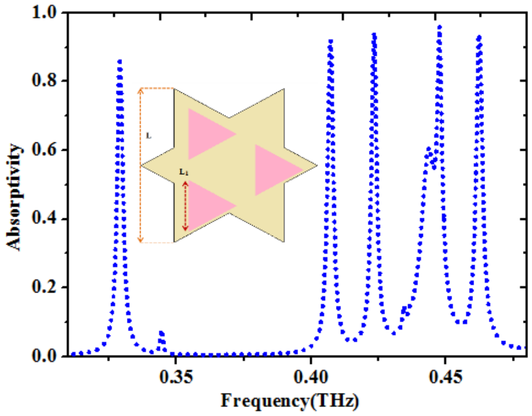

Fig. 2. Simulated absorption curves of the five-band absorber

This is shown in Fig. 3 (b). Also in the 90^0 angles of incidence provides a resonance in the same frequencies. This is shown in Fig. 4. The electromagnetic characteristics of the absorber were demonstrated by surface current distribution and electric and magnetic field distribution analysis. The electric and magnetic field distributions for five different frequencies were analyzed using CST Microwave studio software. This is shown in Figs. 4 and 5. The maximum electric field occured at the edges of the star patterned metallic absorber structure. The dielectric layer mostly had a high current distribution. The frequencies of 0.4068 THz and 0.4472THz maximum electric field distribution were seen at the dielectric layer and inside the star-shaped structure. Also, this structure was magnetically resonated compared to electrical nature.

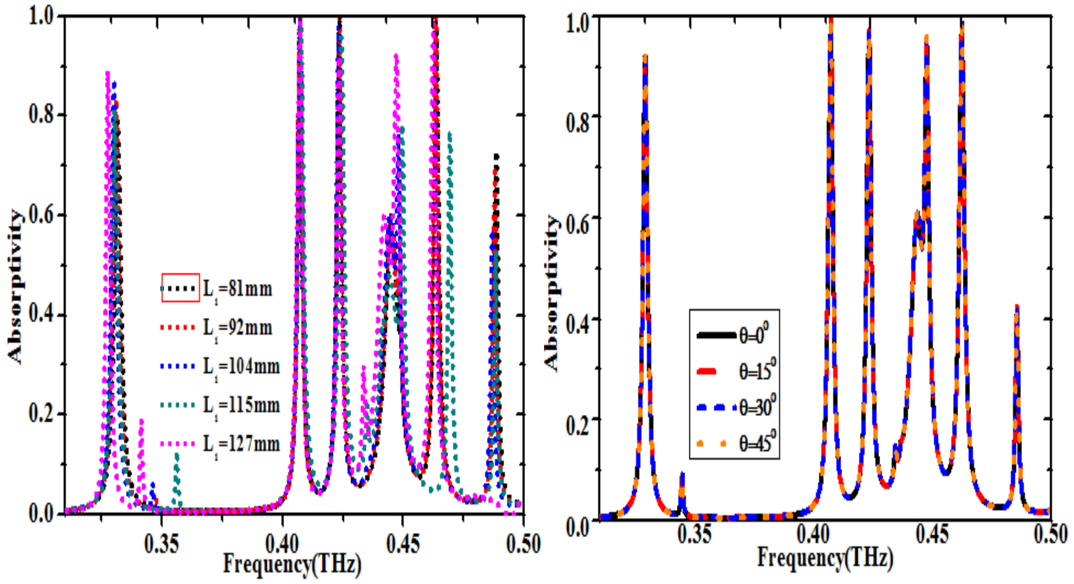

Fig. 3. (a) Dependence of the absorption on the L_1 change; (b) Dependence of the absorption on the different polarization angles

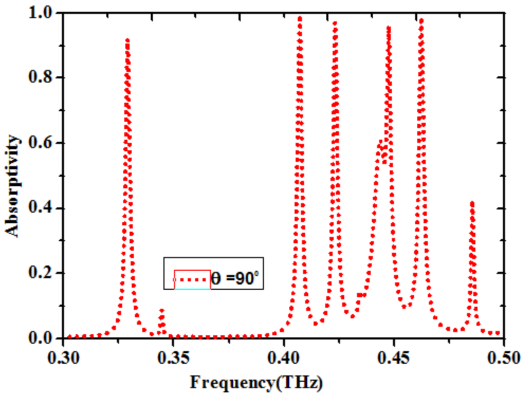

Fig. 4.Dependence of the absorption of 90^0 polarization angle

Fig. 5 shows the magnetic field distribution for all the five frequencies. For frequency of 0.3288THz the magnetic response was maximum that occurred at the small triangles and the dielectric layer. With the frequency of 0.4068 THz the maximum field distribution was maximum at the dielectric layer. The frequency of 0.4228 THz resonance was due to the field distribution in the inside of the metallic resonator. Dielectric layer and 0.4472THz frequency magnetic field existed at the inside small triangles and the dielectric layer. Finally, the magnetic field distribution was high compared to other modes and occurred at the dielectric layer and inside the star-shaped absorber completely.

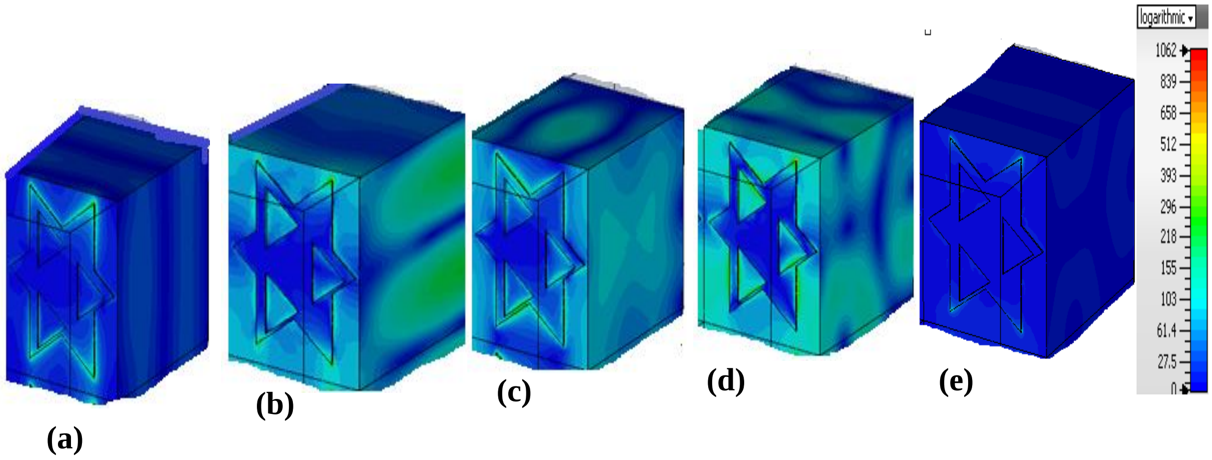

Fig. 4.Electric field distribution for all the frequencies (a) 0.3288THz, (b) 0.4068 THz, (c) 0.4228 THz, (d) 0.4472THz and (e) 0.462 THz

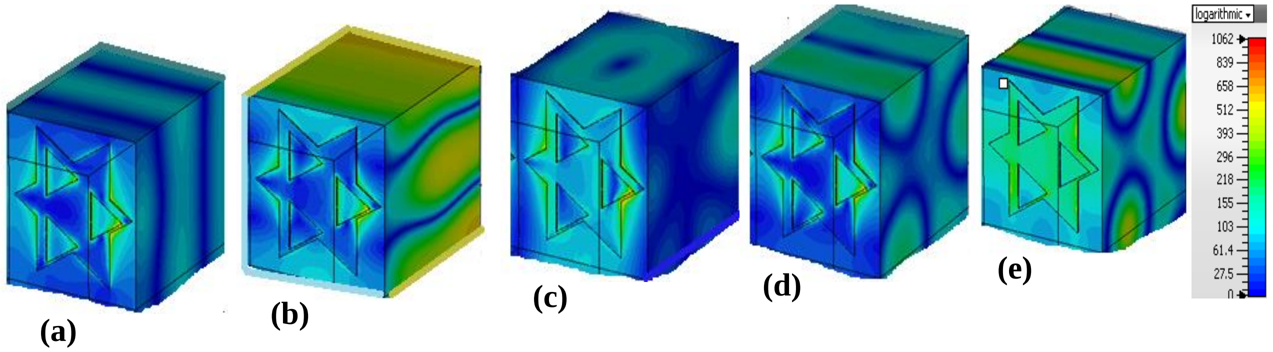

Fig.5. Magnetic field distribution for all the frequencies (a) 0.3288THz, (b) 0.4068 THz, (c) 0.4228 THz, (d) 0.4472THz and (e) 0.462 THz

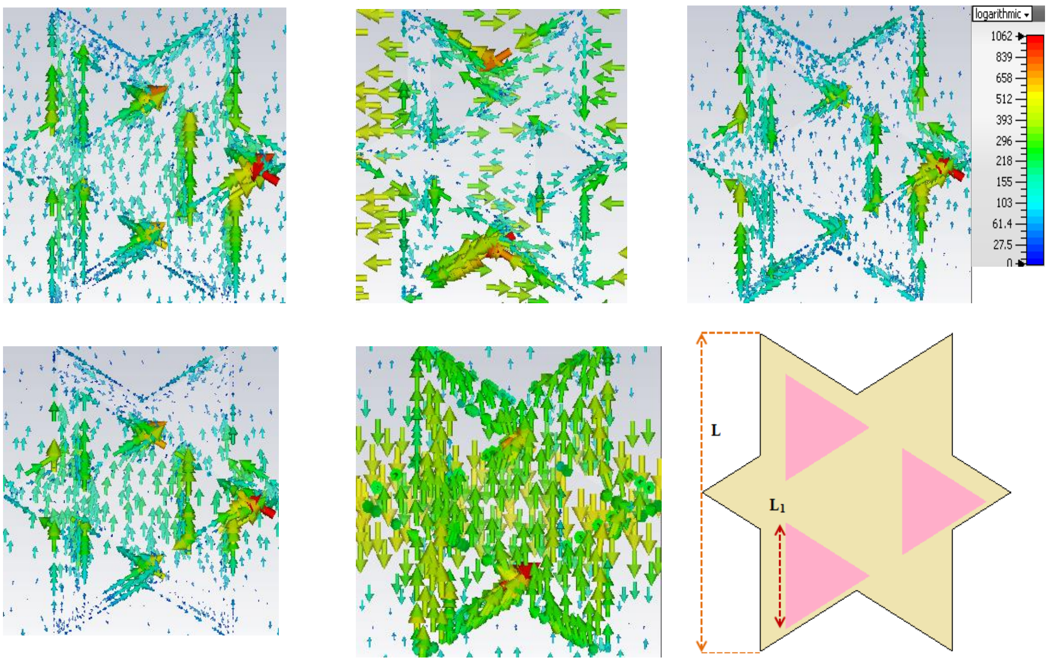

Fig. 6. Surface current distribution for all the frequencies: (a) 0.3288THz, (b) 0.4068 THz, (c) 0.4228 THz, (d) 0.4472THz and (e) 0.462 THz

Magnetic field distribution was high compared to the electric field distribution.

The absorption is understood by surface current distribution mechanisms. Fig. 6 shows the surface current distribution plots for all the five frequencies. For the frequency of 0.3288 THz the small current distribution was in three etched triangle edges. The right side edge of the star-shaped absorber and the frequency of 0.4068THz were identified at the top and bottom edges of a star-shaped absorber.

The frequency of 0.4228THz was identified at the left and right edges of the star-shaped absorber. The frequency of 0.4472THz occurred at the right side of small triangle edges and also at right side edge of the star-shaped absorber. Finally, the fifth frequency of 0.462THz provided the current distribution in an inner and right side of the metallic absorber.

4. Conclusion

In conclusion, the authors have designed a novel five band metamaterial absorber in the terahertz regime. Apart from the simple shape, the five band structure provides the chance to reduce the number of stacked layers. The absorber resonated at 0.3288THz, 0.4068 THz, 0.4228 THz, 0.4472THz and 0.462 THz frequencies had the absorptivity of 98.7%, 96%, 97%, 99%, and 92% respectively and the understanding of the absorber was done by an electric field, magnetic field and surface current distribution. Those proposed terahertz absorbers and optical properties found applications in detection, selective thermal emitters, sensing, and imaging.

References

[1] Y. Ra'di, C. R. Simovski, S. A. Tretyakov, Physical Review Applied **3**, 037001 (2015).

[2] Wen-Chen Chen, Andrew Cardin, Machhindra Koirala, et al., Opt.Express **24**, 6783 (2016).

[3] Jeremy A. Bossard, Lan Lin, Seokho Yun et al., ACS Nano **8**(2), 1517 (2014).

[4] Mulin Huang, Yongzhi Cheng, Zhengze Cheng, Haoran Chen, Xuesong Mao, Rongzhou Gong, Optics Communications **415**, 194(2018).

[5] Yongzhi Cheng, Haijun Zou, Jiaji Yang, Xuesong Mao, Rongzhou Gong, Opt. Mater. Express **8**, 3104 (2018).

[6] Yongzhi Cheng, Haoran Chen, Jingcheng Zhao, Xuesong Mao, Zhengze Cheng, Opt. Mater. Express **8**, 1399 (2018).

[7] K. Chen, T. D. Dao, S. Ishii, M. Aono, T. Nagao, Adv. Funct. Mater. **25**(42), 6637 (2015).

[8] H. Tao, N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, W. J. Padilla, Opt. Exp. **16**, 7181 (2008).

[9] R. Yahiaoui, J. P. Guillet, F. D. Miollis, P. Mounaix, Opt. Lett. **38**, 4988 (2013).

[10] E. Manikandan, B. S. Sreeja, S. Radha, Ravi Nathuram Bathe, Mater. Lett. **229**, 320 (2018).

[11] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, W. J. Padilla, Phys. Rev. Lett. **100**, 207402 (2008).

[12] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, R. D. Averitt, Nature **444**, 597 (2006).

[13] J. He, P. Ding, J. Wang, C. Fan, E. Liang, Opt. Exp. **23**, 6083 (2015).

[14] J. Kaschke et al., Adv. Opt. Mat. **3**, 1411 (2015).

[15] Yongzhi Cheng Rongzhouong, Jingcheng Zhao, Optical Materials **62**, 28 (2016).

[16] Yong Zhi Cheng, Mu Lin Huang, Hao Ran Chen, Zhen Zhong Guo, Xue Song Mao, Rong Zhou Gong, Materials **10**, 591 (2017).

[17] M. Gil, J. Bonache, F. Martin, Metamaterials **2**(4), 186 (2008).

[18] J. W. Park et al., Opt. Exp. **21**(8), 9691 (2013).

[19] B.-X. Wang, X. Zhai, G.-Z. Wang, W.-Q. Huang, L.-L. Wang, J. Appl. Phys. **117**(1), 014504 (2015).

[20] D. S. Wilbert, M. P. Hokmabadi, P. Kung, S. M. Kim, IEEE Trans. Terahertz Sci. Technol. **3**, 846 (2013).

[21] B. Zhang, J. Hendrickson, J. Guo, Journal of Optical Society of America **30**(3), 656 (2013).

[22] D.-E. Wen, X. Huang, L. Guo, H. Yang, S. Han, J. Zhang, Optik - International Journal for Light and Electron Optics **126**(9), 1018 (2015).

[23] D. Xiao, K. Tao, Appl. Phys. Exp. **8**, 102001 (2015).

[24] Ben-Xin Wang, Gui-Zhen Wang, Tian Sang, Ling-Ling Wang, Scientific Reports **7**, 41373 (2017).

[25] Arnab Pattanayak, Sandipta Roy, Goutam Rana, Siddhartha P. Duttagupta, Venu Gopal Achanta, S. S. Prabhu, Scientific Reports **7**, 16961 (2017).

[26] B.-X. Wang, L.-L. Wang, G.-Z. Wang, W.-Q. Huang, X.-F. Li, X. Zhai, Journal of Light wave Technology **32**(6), 1183 (2014).

[27] E. Manikandan, B. S. Sreeja, S. Radha, R. N. Bathe, R. Jain, Journal of Infrared, Millimeter, Terahertz Waves **40**(1), 38 (2019).

---

*Corresponding author: elakkiyaa@ssn.edu.in