Design And Analysis of Miniaturized Polarization And Incident Angle Insensitive Quad-Band Terahertz Metamaterial Absorber

Manpreet Kaur

Thapar Institute of Engineering and Technology

Hari Shankar Singh (✉ harishankar1990@gmail.com)

Thapar Institute of Engineering and Technology <https://orcid.org/0000-0002-3486-8989>

Research Article

Keywords: Absorber, metamaterial, polarization-independent, quad-band, and terahertz

Posted Date: February 7th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1316767/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Design and Analysis of Miniaturized Polarization and Incident Angle Insensitive Quad-Band Terahertz Metamaterial Absorber

Manpreet Kaur¹ and Hari Shankar Singh^{1,2}

¹Department of Electronics and Communication Engineering, Thapar Institute of Engineering and Technology, Patiala-147004, Punjab, India

²TIET-VT Center of Excellence for Emerging Materials (CEEMS), Thapar Institute of Engineering and Technology, Patiala-147004, India

E-mail: preetsmanu94@gmail.com and harishankar1990@gmail.com

Corresponding author:

Dr. Hari Shankar Singh, Ph.D.

Email: harishankar1990@gmail.com

Phone: +91-8090143992

ABSTRACT- *This paper presents a miniaturized polarization and incident angle independent quad-band terahertz metamaterial absorber for sensing applications. The geometrical structure of the proposed design consists of one circle enclosed within two square rings. The design is etched on a low-cost FR-4 substrate having a thickness of $2\mu\text{m}$. The size of the proposed unit cell is $20\mu\text{m} \times 20\mu\text{m}$. It provides 94.9%, 95.4%, 98.7%, and 97.8% absorption at 2 THz, 3.8 THz, 8.9 THz, and 10.8 THz, respectively. The polarization and incident angle independence is also checked to validate the stability of the structure. Additionally, the design evolution and the surface current distribution of the design is provided to have better insight into the structure.*

Keywords- Absorber, metamaterial, polarization-independent, quad-band, and terahertz.

1. Introduction

Metamaterials are categorized as artificial materials as they are formed by blending metals and dielectrics together. They exhibit some unique properties like negative permittivity, negative permeability, negative refractive index, and phase velocity [1]. Metamaterial has achieved a considerable amount of attention in fields like antennas [2], cloaking [3], lensing [4], absorbers [5], and many more. Among all these fields, metamaterial absorbers have attained significant attention because of their broad application potential. Metamaterial absorbers through their structures can easily control the THz waves and can be freely applied in fields like sensing [6], communication [7], imaging [8], detection [9], and many more. Many significant types of research have been done in the past few years providing single band [10], dual-band [11-12], multiband [13], and wide-angle [14]. Authors Kong *et al.* [10] and Wang *et al.* [11], have done the characterization of single-band and dual-band terahertz metamaterial absorbers, respectively. However, the large dimensions of the design will restrict the application in a specific area. Further, Wang *et al.* [12] in 2020, proposed a dual-band terahertz absorber having large electrical footprints. Further, the absorber is also not analyzed under different polarization and incident angles to check the stability of the structure. Furthermore, Wang *et al.* [13] and Qi *et al.* [14], presented a quad-band and wide-angle terahertz metamaterial absorber, respectively, however, the size and thickness of the structure are still under the scope of improvement.

In this paper, a miniaturized polarization and incident angle independent quad-band terahertz metamaterial absorber has been presented. The proposed design has three layers, namely, patch, ground, and a dielectric substrate (sandwiched in between the patch and ground). It provides four resonating peaks having 94.9%, 95.4%, 98.7%, and 97.8% absorptivity at 2 THz, 3.8 THz, 8.9 THz, and 10.8 THz, respectively. The polarization and incident angle independence of the structure is also checked to validate the stability of the structure. The proposed terahertz metamaterial absorber is also compared with the reference structures [10-14] and the comparison is shown in Table 1. Additionally, the design evolution and the surface current distribution of the design is provided to have better insight into the structure.

2. Absorber Configuration and Design Methodology

Apart from the complex structures, the device shown here is formed by simply combining three layers which consist of a metallic patch situated on a dielectric slab and the bottom, completely covered by a metallic board. The

Table 1 Comparison of proposed absorber with reference structures.

Ref.	No of bands	Resonance Frequency (THz)	Size (μm^2)	Thickness	Absorptivity (%)
[10]	1	0.59	150×150	$8 \mu\text{m}$	99
[11]	2	1.8	60×60	$3.7 \mu\text{m}$	98
		2.97			98
[12]	2	1.77	120×70	$4.1 \mu\text{m}$	~ 99.9
		2.45			~ 99.9
[13]	4	0.77	85×85	$16 \mu\text{m}$	99.41
		1.13			97.53
		1.53			99.06
		2.06			95.59
[14]	Wideband	0.27	900×1800	$370 \mu\text{m}$	70
		0.3			~ 99.9
		0.31			60
Proposed Absorber	4	2	20×20	$2 \mu\text{m}$	94.9
		3.8			95.4
		8.9			98.7
		10.8			97.8

(a)

(b)

Fig. 1(a) Detail dimensions of unit cell, where, $a=20\mu\text{m}$, $b=19\mu\text{m}$, $c=14\mu\text{m}$, $w_1=1.4\mu\text{m}$, $w_2=2\mu\text{m}$ and $r=4\mu\text{m}$, (b) Perspective view of the proposed metamaterial absorber.

detailed dimension unit cell of the proposed design is shown in Fig. 1(a) and the perspective view of the proposed design is shown in Fig. 1(b).

The metallic patch of the structure consists of one circle which is enclosed within two square rings. The top layer i.e. patch and the bottom layer i.e. ground are made up of gold having conductivity (σ) of 4.56×10^7 S/m and thickness of $0.4\mu\text{m}$. The dielectric slab in between these two layers is made of FR4 substrate ($\epsilon_r = 4.4$ and $\tan \delta = 0.018$) having a thickness of $2\mu\text{m}$. The detailed optimized parameters of the proposed design are shown in Table 2. Full-wave simulations and optimizations of the proposed absorber design are done using finite integration technique (FIT) based computer simulation microwave studio (CST MWS) [15] by applying periodic boundary conditions. Further, the absorptivity $A(\omega)$ of the structure is calculated by Eq. (1),

$$A(\omega) = 1 - |S_{21}(\omega)|^2 - |S_{11}(\omega)|^2 \quad (1)$$

where, $S_{21}(\omega)$ corresponds to the transmission coefficient and $S_{11}(\omega)$ corresponds to the reflection coefficient. However, the transmission coefficient i.e. $S_{21}(\omega)$ is zero because the ground plane is completely covered with metal [16]. Thus, the absorptivity can be calculated by Eq. (2),

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

The proposed absorber design can be represented in three individual geometrical configurations as shown in Fig. 2(a). The absorption curve analogous to each geometry is shown in Fig. 2(b). It is observed from Fig. 2 that the outer square ring i.e. Absorber-A provides resonance at 1.96 THz and 10.92 THz, the inner square ring i.e. Absorber-B provides resonance at 3.6 THz and 10.32 THz, and the circle i.e. Absorber-C provides resonance at 8.77 THz. However, these geometries are not able to provide an adequate level of absorption, individually. Therefore, when all three geometries are combined to form one structure (proposed absorber), their absorption increases remarkably due to the strong mutual coupling between the closely placed geometries. Thus, the proposed absorber structure is able to provide good absorption at 2 THz, 3.8 THz, 8.9 THz, and 10.8 THz as shown in Fig. 2(c).

(b)

(c)

Fig. 2(a) Design evolution of the proposed metamaterial absorber, (b) Absorption curve corresponding to each individual geometry, (c) Absorption curve corresponding to the proposed structure.

In order to get a better insight into the proposed structure, surface current distribution at four resonance peaks (i.e. 2 THz, 3.8 THz, 8.9 THz, and 10.8 THz) is shown in Fig. 3. It is observed from the figure that the resonance at 2 THz is solely due to the outer square ring i.e. Absorber-A whereas the inner square ring i.e. Absorber-B is solely responsible for resonance at 3.8 THz. Further, the resonance at 8.9 THz is mainly due to the circle i.e. Absorber-C,

and with some effect of the lower edge of the Absorber-B. Furthermore, the mutual coupling between all the three geometries (Absorber-A, Absorber-B, and Absorber-C) is responsible for the resonance at high frequency i.e. 10.8 THz.

Fig. 3 Surface current distribution of the proposed metamaterial absorber at four resonating frequencies.

3. Results and Discussions

3.1 Parametric Sensitivity

In order to check the effect of geometrical parameters of the metamaterial absorber, a parametric study has been carried out. One parameter of each geometrical shape is varied, keeping all other parameters constant as shown in Fig. 4.

Initially, the width (w_1) of the outer square ring (i.e. Absorber-A) is varied, keeping all other parameters constant as shown in Fig. 4(a). It is observed that either we decrease or increase the value of the parameter, the absorption level decreases at the lower resonating frequency. Further, the width (w_2) of the inner square ring (i.e. Absorber-B) is varied, keeping all other parameters constant as shown in Fig. 4(b). It is noted that the proposed parameter is the optimized one because the absorption level at the two lower resonating frequencies decreases while we are changing the value of the parameter.

Moreover, the radius (r) of the Absorber-C is also varied (keeping all other parameters constant) to check its effect on the design as shown in Fig. 4(c). It is observed that when we are decreasing the value of the parameter from the proposed one, we are not able to get the resonating peak at 8.9 THz. Thus, we are only getting three absorption peaks while when we increase its value from the proposed one, we are not able to get a good absorption level at 3.8 THz.

(a)

(b)

(c)

Fig. 4(a) Effect of the width of Absorber-A on absorption (i.e. w_1), (b) Effect of the width of Absorber-B on absorption (i.e. w_2), (c) Effect of the radius of Absorber-C on absorption (i.e. r).

3.2 Polarization and Incident Angle Independence

The proposed THz metamaterial absorber is studied under transverse electric (TE) mode as well as transverse magnetic (TM) mode to check the stability of the proposed absorber under different incident and polarization angles. It is observed from Fig. 5(a) that the proposed design provides the same level of absorption under both the modes (TE and TM). Further, the polarization sensitivity of the proposed metamaterial absorber is observed under the normal incidence angle. In order to view this, the direction of electric as well as the magnetic field is varied while keeping the direction of the wave vector constant. It is noticed from Fig. 5(b) that all the curves at different polarization angles (ϕ) are overlapping each other, thus, making the proposed design polarization insensitive in nature.

Fig. 5(a) Proposed metamaterial absorber under TE and TM mode, (b) Proposed metamaterial absorber at different polarization angles (ϕ).

Thereafter, the effect of incident angle on the absorption curve of the proposed geometrical structure is observed under both transverse electric (TE) and transverse magnetic (TM) modes as shown in Fig. 6. Initially, for TE mode, the direction of the magnetic field and the direction of wave vector are varied by an angle θ while keeping the direction of the electric field constant as shown in Fig. 6(a). Then, for TM mode, the direction of the electric field and the direction of wave vector are varied by an angle θ while keeping the direction of the magnetic field constant as shown in Fig. 6(b). It is noted from Fig. 6 that small side peaks occurred along with slight variation in the absorption curves due to the multiple reflection and interference theory which normally occurs in the case of oblique incidence of wave [17].

(a)

Fig. 6(a) Proposed absorber at different incident angles (θ) under TE mode, (b) Proposed absorber at different incident angles (θ) under TM mode.

4. Conclusion

In this paper, a miniaturized quad-band compact polarization and incident angle independent terahertz metamaterial absorber has been presented. The dimensions of the proposed metamaterial absorber unit cell are optimized to get a good absorption rate. The proposed terahertz absorber provides 94.9%, 95.4%, 98.7%, and 97.8% absorption at 2 THz, 3.8 THz, 8.9 THz, and 10.8 THz, respectively. The polarization and incident angle independence is also checked to validate the stability of the structure. Additionally, the surface current distribution analysis of the design is done to have better insight into the structure.

Data Availability

The datasets generated during current study are not publicly available due to work on the new/minituarized strcuture but are available from the corresponding author on reasonable request.

Declarations

- **Funding and/or Conflicts of interests/Competing interests**

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. Moroeover, the authors have no potential conflicts of interests/competing interests that are relevant to the content of this article.

References

- [1] D.R. Smith, W.J. Padilla, D.C.Vier, Physical Review Letters. (2000) 10.1103/PhysRevLett.84.4184
- [2] L.W. Li, Y.N. Li, T.S. Yeo, Applied Physics Letters. (2010) <https://doi.org/10.1063/1.3651481>
- [3] C. Caloz, T. Itoh, A. Rennings, IEEE Antennas and Propagation Magazine (2008) 10.1109/MAP.2008.4674709
- [4] N. Garcia, M.N. Vesperinas, Physical Review Letters (2002) 10.1103/PhysRevLett.90.229903
- [5] A. Erentok, R.W. Ziolkowski, IEEE Transactions on Antennas and Propagation (2008) 10.1109/TAP.2008.916949
- [6] H. Tao, E.A. Kadlec, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt, E.A. Shaner, X. Zhang, Opt. Express (2011) <https://doi.org/10.1364/OE.19.021620>
- [7] W. Li, Z.J. Coppens, L.V. Besteiro, W. Wang, A.O. Govorov, J. Valentine, Nat. Commun. 6(2015)
- [8] A.W. Lee, Q. Hu, Opt. Lett. (2005) 10.1364/ol.30.002563
- [9] T. Frank, O. Buchnev, T. Cookson, M. Kaczmarek, P. Lagoudakis, V.A. Fedotov, Nano Lett. (2019) <https://doi.org/10.1021/acs.nanolett.9b02094>
- [10] H. Kong, G. Li, Z. Jin, G. Ma, Z. Zhang, C. Zhang, J Infrared Milli Terahz Waves (2012) 10.1007/s10762-012-9906-x
- [11] B.X. Wang, G.Z. Wang, L.L. Wang, Plasmonics 11(2016)
- [12] B.X. Wang, Y. He, P. Lou, W. Xing, Nanoscale Advances (2020) <https://doi.org/10.1039/C9NA00770A>

- [13] B.X. Wang, X. Zhai, G.Z. Wang, W.Q. Huang, L.L. Wang, IEEE Photonics Journal (2015) 10.1109/JPHOT.2014.2381633
- [14] L. Qi, C. Liu, Journal of Applied Physics (2018) <https://doi.org/10.1063/1.5046520>
- [15] CST Microwave Studio available, www.cst.com.
- [16] M. Kaur, H.S. Singh, Microw Opt Technol Lett. (2020) <https://doi.org/10.1002/mop.32264>
- [17] T. Wanghuang, W. Chen, Y. Huang, G. Wen, AIP Adv. (2013) <https://doi.org/10.1063/1.4826522>