Electrical, Electronics and communications, and Computer Engineering

Ultra-broadband Thin Metamaterial Absorber for Ku and K Bands Applications

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ABSTRACT

In this paper, a design of the broadband thin metamaterial absorber (MMA) is presented. Compared with the previously reported metamaterial absorbers, the proposed structure provides a wide bandwidth with a compatible overall size. The designed absorber consists of a combination of octagon disk and split octagon resonator to provide a wide bandwidth over the Ku and K bands' frequency range. Cheap FR-4 material is chosen to be a substate of the proposed absorber with 1.6 thicknesses and 6.5×6.5 overall unit cell size. CST Studio Suite was used for the simulation of the proposed absorber. The proposed absorber provides a wide absorption bandwidth of 14.4 GHz over a frequency range of 12.8-27.5 GHz with more than %90 absorptions. To analyze the proposed design, electromagnetic parameters such as permittivity (ε) permeability (μ), reflective index (n), and impedance (z) were extracted and presented. The structure's working principle is analyzed and illustrated through input impedance, surface current, and the electric field of the structure. The proposed absorber compared with the recent MMA presented in the literature. The obtained results indicated that the proposed absorber has the widest bandwidth with the highest absorption value. According to these results, the proposed metamaterials absorber is a good candidate for RADAR applications.

Keywords: Octagon resonator, Metamaterial, Broadband absorber, RADAR absorber, High absorption.

المادة الرقيقة الخارقة الماصة ذات النطاق الترددي الفائق لتطبيقات حزمتي Ku و K

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الخلاصة

في هذا البحث ، تم تقديم تصميم لمادة رقيقة خارقة ماصة للموجات الكهرومغناطيسية Metamaterial absorber وذات نطاق ترددي فائق بالمقارنة مع المواد الماصة الأخرى . يوفر الهيكل المقترح لهذه المادة نطاق ترددي واسع مقارنة مع حجمه الكلي . يتكون هيكل المادة المصممة من طبقة اولى تتكون من مزيج من قرص معدني مثمن الشكل ورنان ذو شكل مثمن ايضا ومقسم لغرض توفير نطاق ترددي عريض يشمل حزمتي Ku و K من الطيف الكهرومغناطيسي. تبنى الطبقة الأولى للهيكل المقترح على مادة عازلة من نوع FR-4 الرخيصة لتمثل الخلية الأساسية له بأبعاد ×1.6 6.5 × 6.5 مللمترتكعيب . يوفر التركيب المقترح للمادة الماصة نطاقًا واسعًا للامتصاص يبلغ 14.4 جيجاهرتز عبر نطاق ترددي يتراوح بين 12.8 الى 27.2 جيجاهرتز حيث يعطي نسبة امتصاص أكثر من 90%. لغرض تحليل التصميم المقترح ، تم استخراج وعرض المعلمات الكهرومغناطيسية له مثل السماحية (ε) , النفاذية (μ) , معامل الانعكاس (n) والمقاومة (z) , وتم تحليل مبدأ العمل للهيكل المقترح وتوضيحه من خلال مقاومة المدخل والتيار السطحي والمجال الكهربائي للهيكل. وفقًا للنتائج التي تم الحصول عليها ، يعتبر التركيب المقترح للمادة الماصة مرشحًا جيدًا لتطبيقات الرادار.

الكلمات الرئيسية: رنان مثمن, المادة الخارقة , لنطاق العريض, تطبيقات الرادارية, امتصاص عالي.

1. INTRODUCTION

Metamaterials (MMs) are artificial media characterized by constitutive parameters. They are generally not found in nature. Their values can be engineered to specified values such as having negative permittivity, permeability, and negative refractive index (**Shelby, et al., 2001**) and (**Smith, et al., 2000**). Metamaterials were investigated for the first time by Victor Veselago in 1968 (**Veselago, 1968**). The first structure that has been used to prove the existence of metamaterial was a Split Ring Resonator SRR structure (**Shelby, et al 2001**). So far, several Microstrip resonator shapes have been used for different modern applications (**Hamza, and Al-Hindawi, 2021**). Many different applications have used this artificial material for the fields of wireless communication and other Electromagnetic applications. The Applications of Metamaterials includes sensors (**Abdulkarim, et al., 2020**) **and** (**Abdulkarim, et al., 2020**), antennas (**Bai, et al., 2020**) and (**Aziz and Al-Hindawi, 2016**)**,** polarization converters (**Cheng, et al., 2019**)**,** cloaking (**Ramaccia, et al., 2018**)**,** beamformer (**Mohammed, and Hasan, 2018**), and absorbers (**Zhang, et al., 2018**).

Recent developments of radar technologies draw scientific researchers' attention to provide aircraft with more safe and reliable flights through enhancing stealth technology (**Chen, et al., 2017**). Shaping is one of the most utilized techniques in stealth technology to reduce Radar cross-section (RCS). Shaping requires further improvements because of its frequency dependence and has narrow bandwidth (**Winson, et al., 2019**). During the last decade, absorber material was used in aircraft construction to increase invisibility(**Yin, et al., 2018**). This lets the researchers investigate material with special properties in terms of practical use. However, conventional natural materials like wedge absorbers or ferrite (**Gau, et al., 1997 and Michielssen, et al., 1993**) are limited due to their large size, complex structure, expensive, and difficult for integration(**Wang, et al., 2019**). Recently, many metamaterial-based absorbers proposed to be worked in the microwave (**Jain, et al., 2020**)**,** terahertz (**Huang, et al., 2018**)**,** optical (**Vafapour, 2019**), and infrared (**Ai, et al., 2018**) range with unique electromagnetic properties in comparison to conventional absorbers. Metamaterials are topological designs that provide specific characteristics and cannot be found by natural materials such as having negative permittivity, permeability, and negative refractive index (**Shelby, et al., 2001**) and (**Smith, et al., 2000**).

Metamaterials were investigated for the first time by Victor Veselago in 1968 (**Veselago, 1968**). Since, This engineering material applied to many different applications including sensors (**Abdulkarim, et al., 2020) and (Abdulkarim, et al., 2020**), antennas (**Bai, et al., 2020**) and (**Aziz and Al-Hindawi, 2016**), polarization converters (**Cheng, et al., 2019**), cloaking (**Ramaccia, et al., 2018**) and absorbers (**Zhang, et al., 2018**). The first design and practical verification of a perfect metamaterial absorber were back in 2008 by Landy (**Landy, et al., 2008**). Since then, different metamaterial absorbers introduced with single (**Abdulkarim, et al., 2019**), dual (**Wang, et al., 2018**), multi (**Wang, et al., 2020**), and broadband properties (**Hoa, et al., 2019**).

In (**Zuo, et al., 2019**), broadband metamaterial absorbers presented providing 90% absorptions over the frequency range 8.3 -11.8 GHz. The structure consists of double split-ring resonators printed on an FR-4 substrate with 2 mm thickness. Due to the symmetry of the used resonators, the designed absorber provides polarization-insensitive property. (**Hoa, et al., 2019**) proposed a compact broadband MMA for C-band applications. In the design, circular disk and modified circular disk are used to form the absorber with 1.5 mm of FR-4 substrate. Authors in (**Sood and Tripathi, 2017**) proposed another broadband metamaterial absorber for X-band, Ku-band applications. The absorber, based on asymmetric folded shapes resonator, printed an FR-4 substrate with 1.6 mm thickness. The structure achieves 7.19 GHz absorption bandwidth from 10.45 GHz to 17.64 GHz with more than 90 absorptions.

Furthermore, a hexagon shape resonator with four circular slots was introduced as a wideband wide-angle MMA (**Sood and Tripathi, 2015**). The absorber substrate is made of 1.6 mm thickness of FR-4 to cover the frequency range of 5.05- 6.99 GHz with an absorption of more than 90%. A bidirectional bandwidth, enhanced MMA based on special copper patterns resonator with 1.6 mm FR-4 substrate proposed for Ku-band applications (**Stephen, et al., 2019**). After resonator dimensions are tuned well, the designed absorber provides 90% absorption between 13.40 GHz and 14.25 GHz. In another study, two different sizes of closed Square Ring Resonators (CSRR) were utilized to form wideband MMA to be operated in the Ku band frequency regime (**Barde, et al., 2020**). The resonators printed on FR4 material with 1.6 mm thickness and cover the frequency range of 11.39 to 20.15 GHz with more than %90 absorptions.

In the present study, a compact octagon-shaped broadband thin metamaterial absorber was designed based integration of resonators. The absorption bandwidth was effectively broadened by the combination of octagon disk resonator with split octagon resonator. The proposed absorber achieves 90% absorptions over the wideband frequency range of 12.8-27.5 GHz. The proposed absorber substrate is made of Fr-4 material with 1.57 mm thickness and 4.3 dielectric constants. The proposed absorber's fundamental absorption mechanism is explained by demonstrating and analyzing the surface current and electric field distribution. Electromagnetic parameters (permittivity, permeability, refractive index, and impedance) of the absorber are presented and explained.

2. DESIGN OF UNIT CELL STRUCTURE

To design near-perfect absorption, the reflection of the structure should be reduced by matching absorber impedance with free space impedance $Z(w) = Z_0 = 377\Omega$. Intrinsic impedance $Z(w)$ Any metamaterial absorber can be defined by the effective permittivity (ε) permeability (μ) of the medium (**Edries, et al., 2020**):

$$Z(w) = \sqrt{\frac{\mu_0 \mu_r(\omega)}{\varepsilon_0 \varepsilon_r(\omega)}} \tag{1}$$

The reflection coefficient $\Gamma(\omega)$ will be zero, and there is no reflected wave when $Z(w)$ is equal to Z_0.

$$\Gamma(\omega) = \frac{Z(\omega) - Z_0}{Z(\omega) + Z_0} \tag{2}$$

The absorption $A(\omega)$ of the absorbers can be calculated by

$$A(\omega) = 1 - R(\omega) - T(\omega) \tag{3}$$

Where $R(\omega) = |S_{11}|^2$, $T(\omega) = |S_{21}|^2$ are the reflection and transmission coefficient, respectively. The transmission coefficient is assumed to be zero due to a metallic ground plate at the absorber's backside. This makes equation 3 to be $A(\omega) = 1 - R(\omega)$.

The proposed structure is formed by combining two basic resonators to cover a wide frequency range over Ku and K bands. The configuration of the proposed absorber is presented in **Fig.1** (a), (b), and (c). The basic model 1 and model 2 are illustrated in figure 1 (d) and (e), respectively. The single unit cell of the proposed broadband metamaterial absorber consists of a dielectric substrate sandwiched with a top metallic layer and the bottom ground plane. The dielectric layer is made of an FR4 substrate (relative permittivity $\varepsilon r = 4.4$ and dielectric loss tangent $\tan \delta = 0.02$) with 1.57 mm thickness. The top layer is formed by an integration of octagon disk with split octagon ring resonators in orthogonal location along the diagonals of the unit cell structure. The splits introduced both at the top patch and the bottom ground, are made of copper material with a conductivity of $\sigma = 5.8 \ast 10^7$ S/m and 0.035mm thickness. It is optimized based on a genetic algorithm to control the impedance matching over the desired frequency range. The optimized geometric dimensions are shown in **Table 1.**
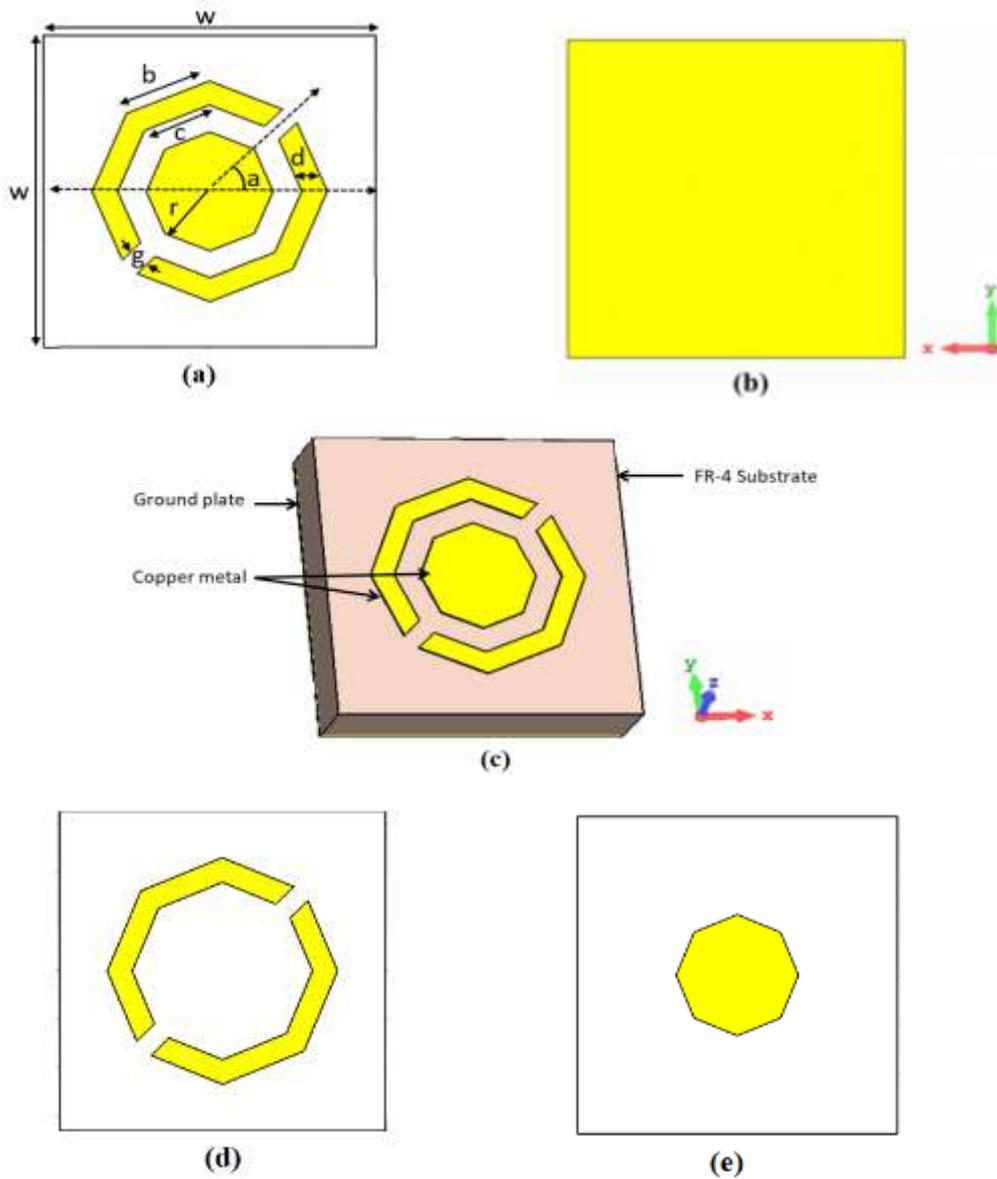
Figure 1. (a) Dimension size with the front view (b) back view and (c) perspective view of the broadband metamaterials absorber (d) model 1 (e) model 2.

Table 1. Optimum dimensions of the proposed MMA absorber.

parameters	W	d	b	c	G	a	R
Unit(mm)	6.5	0.5	1.75	1.38	0.4	450	1.24

The proposed metamaterial absorber was simulated by the CST microwave studio with Floquet ports 1 and 2, as shown in **Fig 2.**
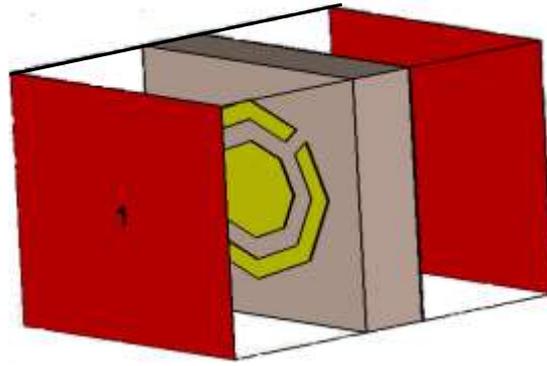
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Figure 1. The simulation setup of the proposed metamaterial absorber.

3. SIMULATED RESULTS AND DISCUSSION

The absorption response of design 1 is presented in **Fig. 3**. It is observed that the absorber cover frequency range 13-21 GHz with absorption more than 90% except 15 to 15.7 GHz in which the absorption reduced to 87%. **Fig. 4** presents the absorption curve of model 2, which provides a single absorption peck at 27 GHz with a 95% absorption value.
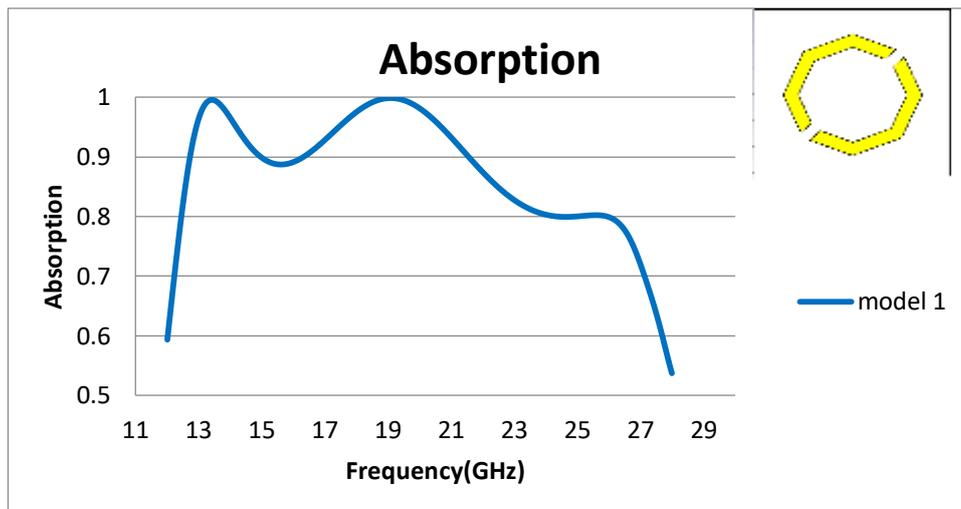

Figure 2. Simulated absorption response of model 1.
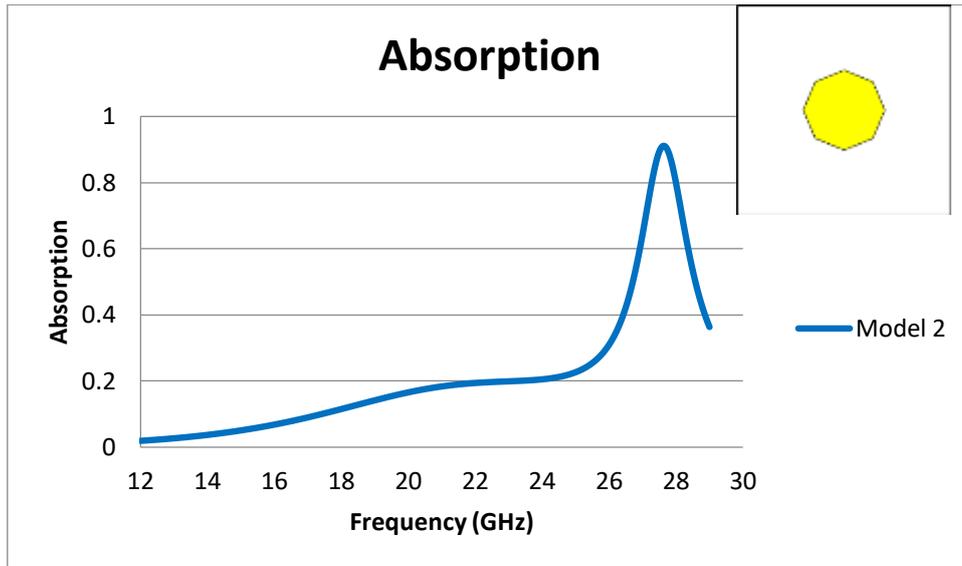
Figure 3. Absorptivity versus frequency for model 2.

Integration of both models 1 and 2 into a single absorber (proposed absorber) widens the achieved bandwidth and the absorption level enhanced within the Ku band around 15 GHz and K band from 21 to 25.5 GHz.This is due to the coupling between the resonators. Therefore, the distance between resonators is accurately optimized to achieve optimum results. The reflection coefficient and of the proposed absorber demonstrated in **Fig.5.** The reflection coefficient is less than -10 dB from 12.8 GHz to 27.5 GHz with four resonance frequencies at 13.7GHz, 17.9 GHz,24.45 GHz and, 27.2 GHz. The corresponding absorption peaks obtained at the four resonance frequencies, are %99, %99, %99, and %97.3 respectively, as shown in figure 6.
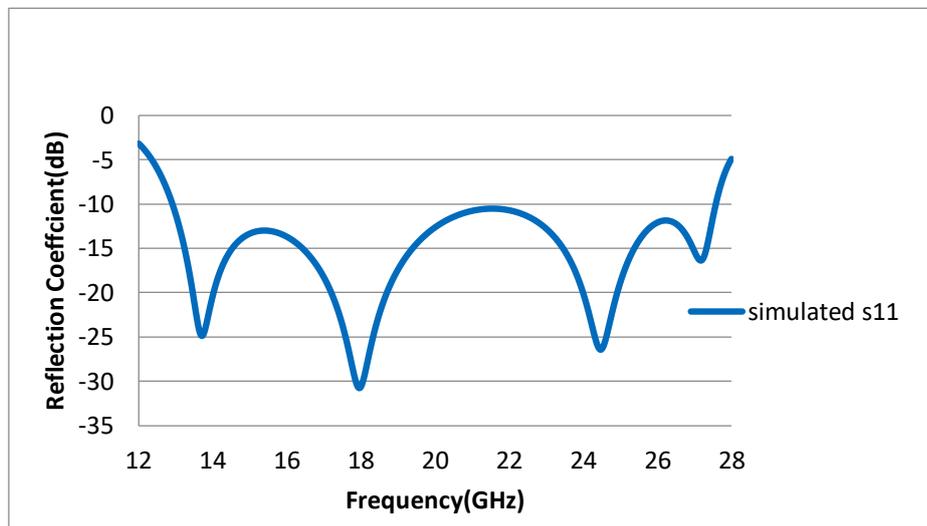

Figure 5. Simulated reflection coefficient of the proposed broadband absorber.
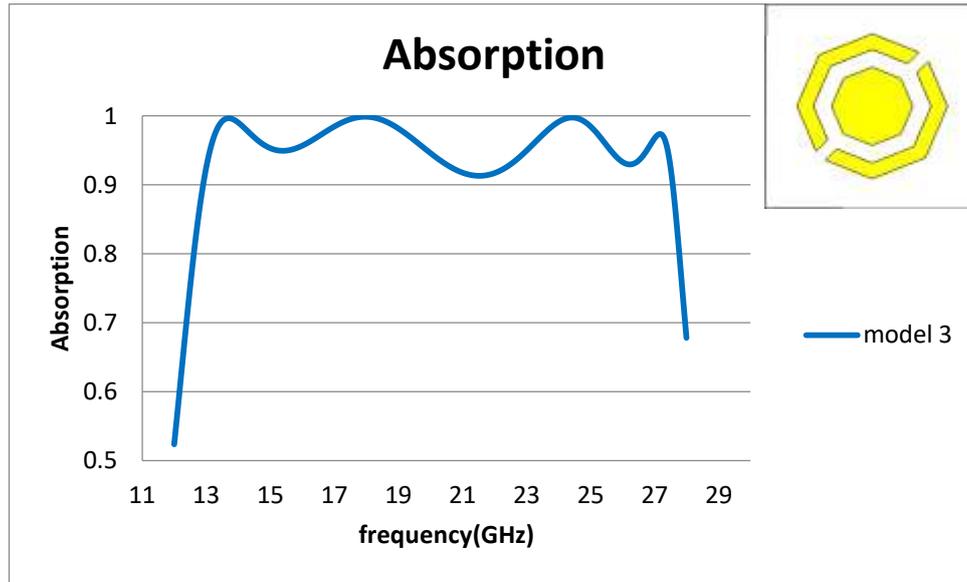
Figure 6. simulated absorption curve of proposed Broadband metamaterial absorber.

To examine the proposed broadband metamaterial absorber's polarization behavior, the propagating wave's direction was kept constant perpendicular to the absorber surface. In contrast, E-Field and H-field's direction changed at different polarization angles (φ) from 0^0 to 90^0 with each step angle size of 150, as illustrated in figure 7. The figure shows that the absorptivity gradually declined with higher polarization angles, reaches a minimum of 450, and then increased until a return to maximize value at 90^0. Also, the absorptivity is almost the same with the polarization angle of 0^0 and 90^0, 15^0 and 75^0, 30^0 and 60^0, respectively

Further, to investigate the effect of incidence angle variation on the absorption value, the incidence angle (θ) changed from 0 to 45 degrees in 4 steps while the polarization angle kept constant at zero degrees. It is noted that the absorptivity of the proposed absorber decreased with an increment of incidence angle, and the absorber provides triple-band absorption in the case of 45^0.
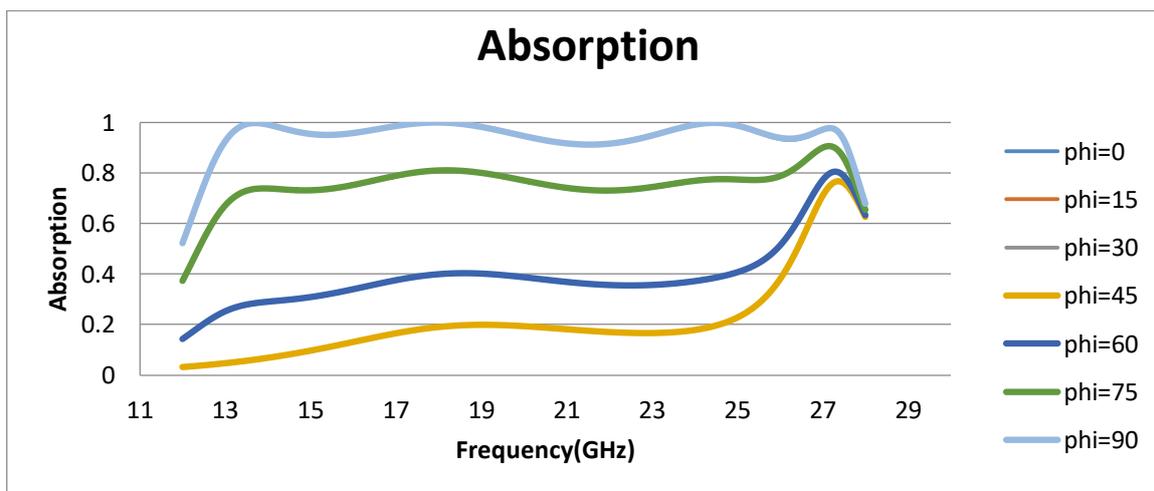

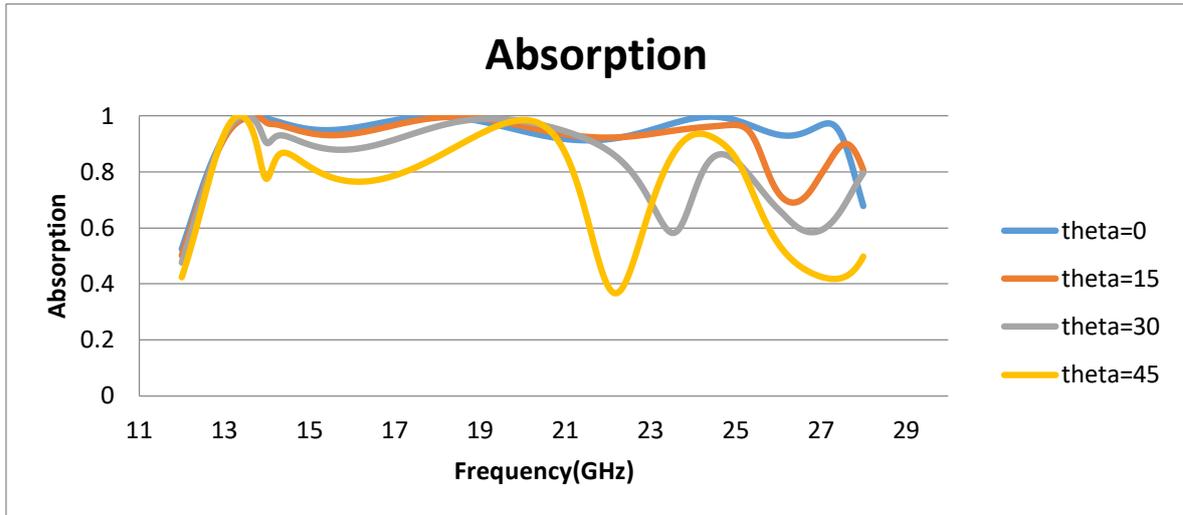**Figure 7.** Simulated Absorption response at different angles of polarization (φ).

Figure 8. Simulated Absorption response at different incidence angles ($\boldsymbol{\theta}$).

To investigate the proposed MMA's behavior In this method, the scattering parameters reflection coefficient S_{11} and the transmission coefficient S_{21} are utilized for extraction. The normalized impedance of the proposed multiband MMA is illustrated in **Fig. 9**. It is observed from the figure that the real part of the normalized impedance is close to one while the imaginary part close to zero at an over-the-frequency range of interest. This indicates that the impedance of the proposed absorber matched with the impedance of the free space. The values of the real and imaginary parts of the proposed absorber at the four absorption peaks are presented in **Table 2.**

Table 2. Real and imaginary part of the proposed MMA at resonance peaks.

Frequency (GHz)	13.7	17.9	24.45	27.2
Impedance, Real (Z)	1.03	1.09	1.13	1.13
Impedance, Imaginary (Z)	-0.11	0.14	-0.22	-0.38

To further properties explanation of the proposed metamaterial absorber, permittivity, permeability, and reflective index are illustrated in **Fig.9.** It can be seen from the figure, both permittivity, permeability have very close dispersion to each other over the operating frequency range. In addition, the imaginary part of permittivity, permeability is over the desired frequency range, which leads to achieving a negative reflective index at the same frequency band.

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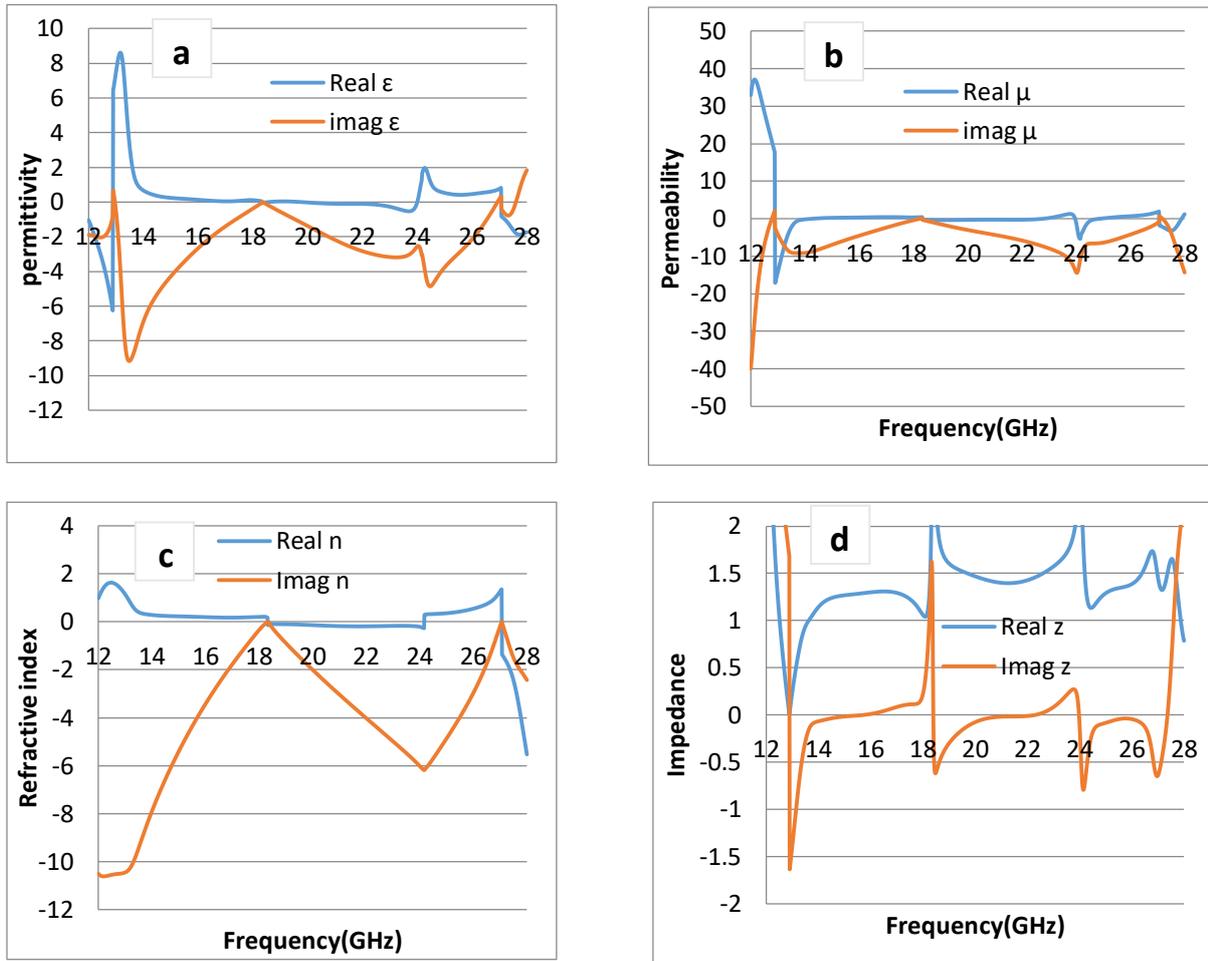
Figure 4. Extracted bulk electromagnetic properties of the proposed Multiband MMA absorber

(a) permittivity, (b) permeability, (c) reflective index, and (d) normalized impedance.

To understand the absorption mechanism, the simulated surface current distribution of the proposed broadband absorber at the resonance frequencies shown in **Fig.10**. A strong current distribution can be seen at the edge of the octagon disk resonator and around the split octagon resonator's center at both inner and outer edges. This can be considered as one of the main factors in achieving high absorption. Moreover, the current circulates the octagon disk and around both parts of the split octagon resonator in the reverse direction.

(a) 13.7   **(b) 17.9**

(c) 24.45   **(d) 27.2**
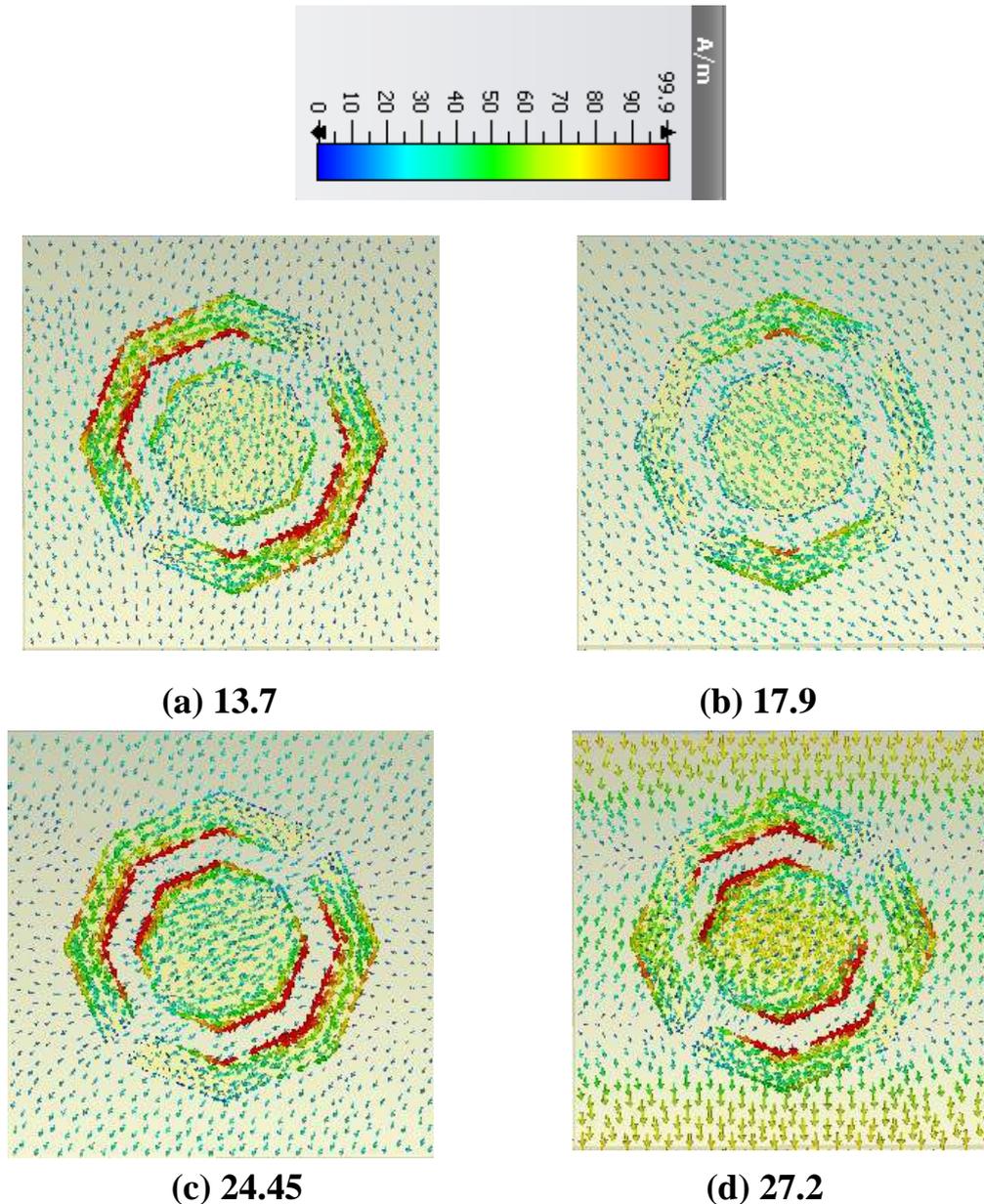
Figure 5. Simulated surface current distribution of the proposed metamaterial absorber at the six absorption peck frequencies.

Fig.11 shows the E-field distribution of the proposed broadband MMA at four absorption peaks. The figure clearly illustrated a strong electric field gathered at the outer edge and the ends of the split octagon resonator for the first three resonance frequencies, 13.7GHz, 17.9 GHz, and 24.45 GHz. This indicates that the split octagon resonator is responsible for producing absorption pecks at these frequencies. At the last resonance frequency (27.2 GHz), a strong Electric field can be seen on the octagon disk resonators, which addresses that octagon disk resonators are mainly responsible for providing absorption peaks 27.2 GHz.

(a) 13.7   **(b) 17.9**

(d) 24.45   **(c) 27.2**
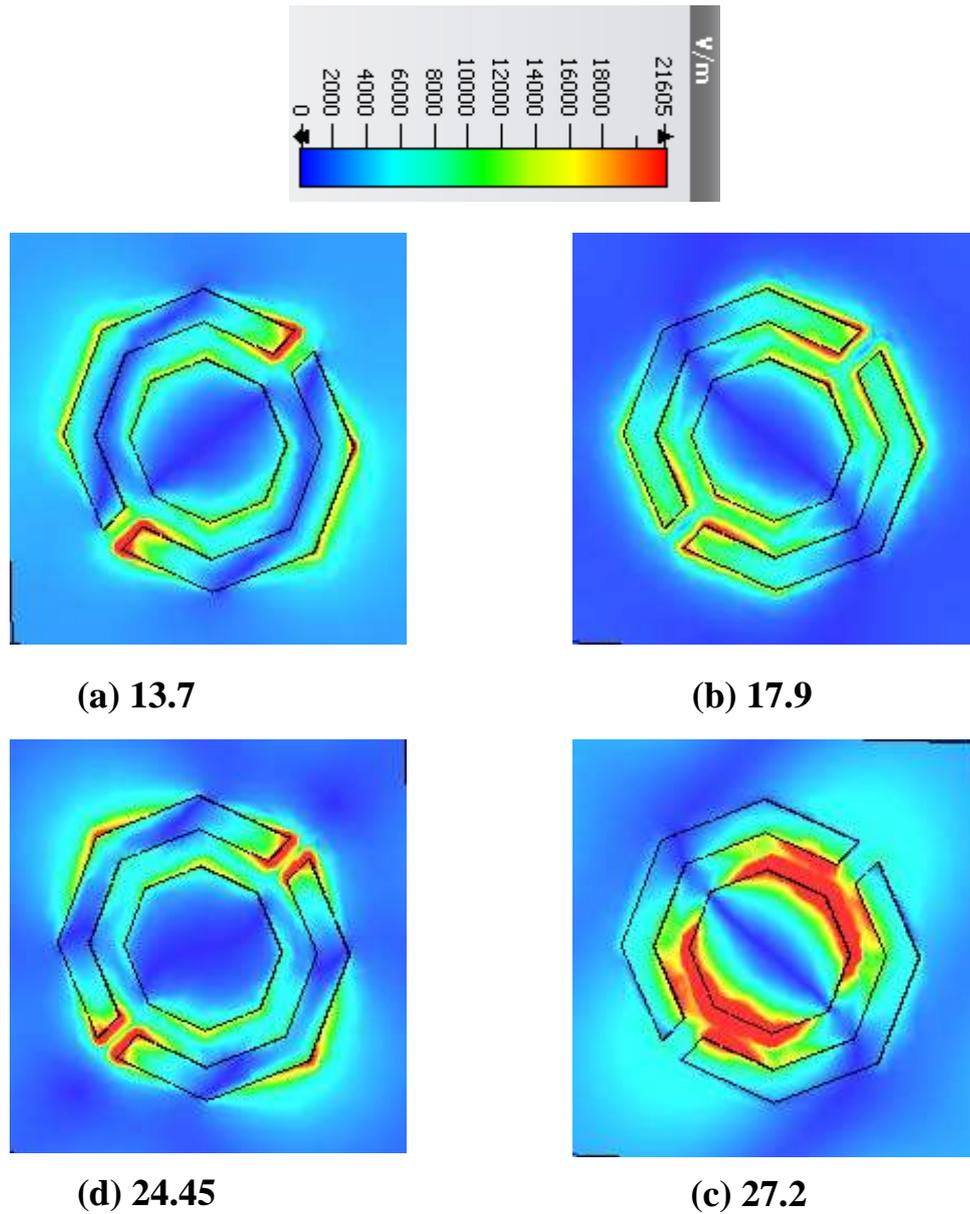
Figure 6. Electric field distribution at the four absorption peak frequencies.

For further performance evaluation, The proposed broadband metamaterial absorber compared with recently reported absorbers in the literature. The comparison is based on the unit cell dimension, thickness, maximum absorption rate, absorption bandwidth, and frequency band of interest. It is observed that our proposed design achieves the widest absorption bandwidth with the highest absorption of 100% with a competitive absorber dimension and thickness compared to the published works.

Table 3. Comparison of the proposed MMA with recently published work.

Ref.	Unit cell dimension (mm)	Thickness(lowest resonance)	Max. Absorption rate (%)	Bandwidth (GHz)	Frequency (GHz)
(Zuo, et al., 2019)	8 x 8	$0.07\ \lambda_0$	90	3	8.3 - 11.3
(Hoa, et al., 2019)	15.6 x 15.6	$0.257\ \lambda_0$		4	4.0 - 8.0
(Sood and Tripathi, 2017)	5.5x 5.5	$0.257\ \lambda_0$	90	7.19	10.45 - 17.64
(Sood and Tripathi, 2015)	9.0x 9.0	$0.031\lambda_0$	90	1.3	5.27 - 6.57
(Stephen, et al., 2019)	10×10	$0.061\ \lambda_0$	90	8.76	11.39 - 20.15
(Barde, et al., 2020)	10.3x10.3	$0.0675\lambda_0$	90	0.85	13.4 - 14.25
This work	6.5 x6.5	$0.055\ \lambda_0$	90	6.86	10.3-17.16

4. CONCLUSIONS

In this paper, a novel ultra-broadband thin metamaterial absorber based on an octagon-shaped resonator is presented. The proposed absorber is based on a combination of two basic structures, octagon disk and split octagon ring. The proposed broadband metamaterial absorber has an overall size of the size 6.5×6. 5×1.57 mm to be operated in the Ku and K bands from 12.8 GHz to 27.2 GHz with more than 90% absorptions. To verify absorptivity and further investigate the absorption mechanism, surface current, electric field distribution, and normalized impedance of the proposed absorber are presented and analyzed. The proposed broadband absorber's performance compared with recently reported absorbers in the literature, in terms of several parameters including unit cell dimension, thickness, maximum absorption rate, absorption bandwidth, and operating frequency range. The comparison shows that the proposed broadband metamaterial absorber has the widest absorption bandwidth of 6.86 GHz with the highest absorption of 100%. This obtained bandwidth and absorption are considered a novelty of this paper, which is achieved by combining the resonator technique. Due to repeated properties, the proposed broadband MMA, interested in several applications, especially RADAR applications.

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