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Design of A Perfect Metamaterial Absorber for Microwave Applications

تصميم ممتص موجات كهرومغناطيسية باستخدام الميتامتيريال لتطبيقات ترددات المايكروويف

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ABSTRACT

In this manuscript, a multi-band and low-profile metamaterial absorber with polarisation independence from 0^0 to 45^0 is presented. The proposed metamaterial structure is composed of a single ring with a rectangular patch, consisting of periodic unit cells with a size of 150mm × 250mm × 1.5mm. The structure exhibits three absorption peaks under normal incidence, which cover the X-band. According to the results, the desired material can excellently absorb the electromagnetic wave signal, with an outstanding absorption rate of about 95% at the microwave x-band frequency. The proposed structure shows three absorption bands where two of them exceed 90% absorption level. The results displayed a high Q-factor of 103.5 at a resonance frequency of 8.58 GHz and the figure of merit (FOM) is 98.4, which can be used to enhance the sensor sensing, narrowband band filter and image sensing. The proposed structure is fabricated, and experiments are carried out to validate the design principle. Strong agreements are observed between the measured and the corresponding simulated results.

الملخص

صمم النموذج المقترح من المواد الخارقة (metamaterial) الذي يتكون من خلايا متراصفة بحجم 150 ملم ×250 ملم ×1.5 ملم، تتكون كل واحدة منها من حلقة نحاسية و قطعة مستطيلة. لدراسة مدى تأثر النموذج المعرض للموجة الكهرومغناطيسية الساقطة عموديا على مستوى التصميم التي تغطي حزمة التردد X. أوضحت نتائج التجربة ظهور ثلاث قمم امتصاص غير حساسة للاستقطاب من 00 إلى 450 إذ يفوق اثنان منهما مستوى امتصاص 90%. فضلاً عن ذلك تقدم النتائج عامل جودة Q الذي يبلغ 103.5 عند تردد الرنين 8.58 جيجاهرتز ومعامل الجدارة FOM الذي يبلغ 98.4 الذي يمكن استخدامه لتحسين أداء المستشعر ومرشّح النطاق الضيق واستشعار الصورة. فضلاً عن ذلك أجريت دراسة بارامترية لإظهار قابلية التعديل الميكانيكي للتصميم. وتم تصنيع النموذج المقترح ثم أجريت التجارب المختبرية للتحقق من نتائجه التي أظهرت تطابقاً جيداً بين المقاسة والمحاكاة.

KEYWORDS
الكلمات المفتاحية
Absorber, high Q-factor , metamaterials, microwave, multi-band, sensor
المواد الخارقة (الميتامتيريال)، عامل جودة Q مرتفعًا، مايكروويف، متعدد الحزم، مستشعرات، مُمتَصّ

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1. Introduction

METAMATERIAL (MTM) are materials that are not directly found in nature and exhibit unusual electromagnetic properties. In 1967—1968, the metamaterial was first proposed by Veselago (1968) but has not received much interest from scientists for many years. Pendry et al., (2001) theoretically proposed that metamaterial can be done experimentally. In the following years, many studies were carried out on this subject. Today, metamaterial has a wide range of applications such as medical (Smith et al. 2004), imaging (Papaioannou et al. 2017), signal absorption (Shawkat et al. 2020; Al-badri 2020), invisibility cloak (Kanté et al. 2009; Al-Badri 2019), absorption tuning (Hameed et al. 2020; Ekmekci et al. 2016), antenna (Luo et al. 2019), sensor (Abdulkarim et al. 2020; Ksl et al. 2018), etc. However, metamaterial with the extra-electromagnetic properties of materials provides an increase in electromagnetic applications (Sabah et al. 2015).

Landy et al. (2008) proved that metamaterial absorbers' structure can absorb radiation of incoming electromagnetic wave inside the absorber. They exploited the impedance matching to get perfect absorption. These interesting results opened the door for a new absorber/isolators application, which is much smaller than the traditional ones (Abdulkarim et al., 2020). Metamaterial absorbers showed that absorption rate can reach the unity absorption level or 99% at an overall structure thickness of 1/30 or more (Hameed et al. 2019). Thus, electromagnetic metamaterial absorbers became a topic of interest in science and technology. In principle, metamaterial absorption develops from the E-field and/or the H-field resonance, which may lead to a narrow bandwidth absorption band. Consequently, to satisfy the practical requirements of the rapid development of sensors nowadays, it is necessary to enhance sensor sensitivity. A lot of metamaterial structures have led to a broken structure symmetry (Abdulkarim et al. 2020; Ksl et al. 2018).

In this study, the signal absorption of metamaterial was discussed. As the electromagnetic signal is applied to the material, it is expected that the incoming signal will not be transmitted and absorbed in the resonance frequency range so that the signal is absorbed by the material. Since there will not be a 100% absorption, this value is supposed to be at least 90% after the losses are released. Such can also be referred to as materials that produce excellent signal absorption. For this case, the back of the material is covered with metal. Thus, the transmission value $S_{21,}$ which is very close to zero. With the resonator design and the dielectric used, the reflection value S_{11} obtained can be very close to zero (Mohammed et al. 2019). Material structure, thickness, dielectric value, loss tangent value, structure of resonator, etc. are the parameters directly affected by the absorption of the signal.

There are various metamaterial signal absorption studies published (Watts, et al. 2012; Cui et al. 2014; Lim et al. 2016; He et al., 2018.). The dual-band absorption, in particular, is the most frequently discussed multi-band absorption structure and has subsequently been widely studied and reported. Some studies focused on the dual-band absorption based on coplanar structural (Zhang et al. 2018;

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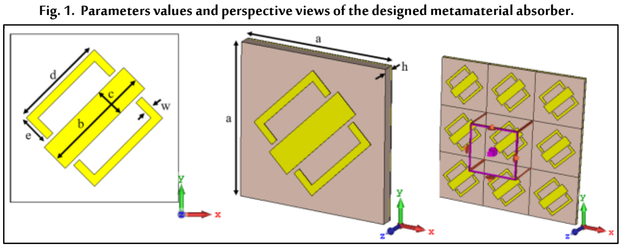
Song et al. 2018), implementation using the sandwich design (Wang et al. 2019; Xing Jian, 2018), and other designs presented by circular sector resonator (Luo and Chen, 2018), graphene–SiC (Qing et al. 2019) and cylinder MoS2-dielectric array (Qiu et al. 2019). In this study, the metamaterial is aimed to be absorbed in two bands in the x-band and to be an example of the recent studies by obtaining close to excellent absorption values at different bands. To achieve good absorption at different frequencies, the signal is absorbed by the simulation at multiple frequencies. This work can apply to many areas, such as medical, thermal imaging, military and so on.

2. Material and Method

The design of the material-based signal-absorbing dielectric material is FR-4 with a layer thickness of 1.5 mm. FR-4 is made of glass fibre reinforced laminate and is composed of epoxy structure. It can be manufactured with double or single surface copper plating and can be used easily at high frequencies. Regarding the FR-4 structure, the relative dielectric permeability is 4.3 and the loss tangent value is 0.025. To keep the reflection value near zero, the back of the structure is covered with copper having a metallic property of 5.8 $x10^7$ S/m and a thickness of 0.035mm. Similarly, the resonator on the front is made of copper. The dimensions of the given resonator structure are as follows: a = 17 mm, a = 10 mm, b = 6.7 mm, c = 1.75 mm, d = 5.75 mm, e = 1.76 mm, g = 0.25 mm, h = 1.45 mm, w = 0.5 mm. To obtain these values, a parametric study was performed, and the structure was optimised. When constructing the structure, Figure 1 shows the parameters and perspective views of the structure.

Fig. 1. Parameters values and perspective views of the designed metamaterial absorber.



Numerical studies of a 3D electromagnetic solution have been realized for the numerical results of the designed and optimised structure. Periodic boundary conditions are used to demonstrate the periodic arrangement of the proposed design, which are applied to the x- and y-axes, while the perfectly matched layers for absorbing unnecessary scattered light are applied to the z-axis. The electric field direction is applied along the x-direction and magnetic field is along y-direction and propagation wave is along the z-axis. The reflectance and transmission values of the structure were first determined. The metal plate behind the structure allows the transmission to be very close to zero, and the highest value of the signal absorption at the linear value is at the point where the reflection is the smallest in the signal absorption calculation. The signal absorption (Ekmekci et al. 2016)

$$A\,(w) \;=\; 1 - \;(R\,(w)\;+\;T\,(w)) \qquad (1)$$

is calculated according to the formula and the results are given in Figure 2 and 3. Here the $R\,(w) = |S_{11}|^2$ and $T\,(w) = |S_{21}|^2$, where $A\,(w)$ the absorption rate can be calculated from the and reflection coefficient ($R\,(w) = |S_{11}|^2$) and the transmission coefficient ($T\,(w) = |S_{21}|^2$). The transmission coefficient of the absorber with the metallic ground is zero. Therefore, A is determined by the reflectivity of the absorber.

3. Result

The CST Microwave Studio based on Finite Integration Technique (FIT) is used for numerical analysis founded on the frequency domine solver. According to the result in Figure 2, the lowest obtained value of S11 was 0.18 in the frequency of 11.07 GHz. In addition, it is seen that the structure shows signal absorption at around 8.58 GHz and 10.24 GHz frequency values, and S11 values are below 0.7. Even though the frequency is absorbed by the signal at these frequency values, the best, perfectly resonant frequency at which the signal is absorbed is at 11.07 GHz. At this frequency, it can be seen that the structure performs 95.98% of signal absorption.

Fig. 2. Numerical S11, S21 and absorption spectrum for the proposed Metamaterial absorber.

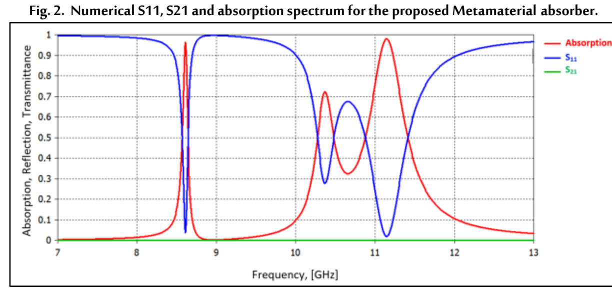
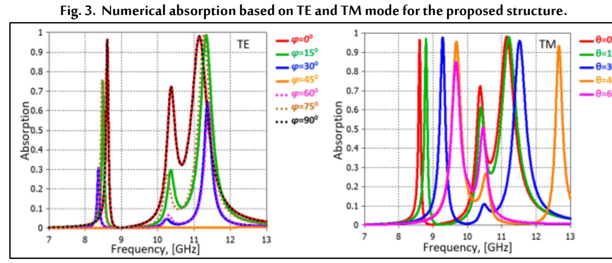


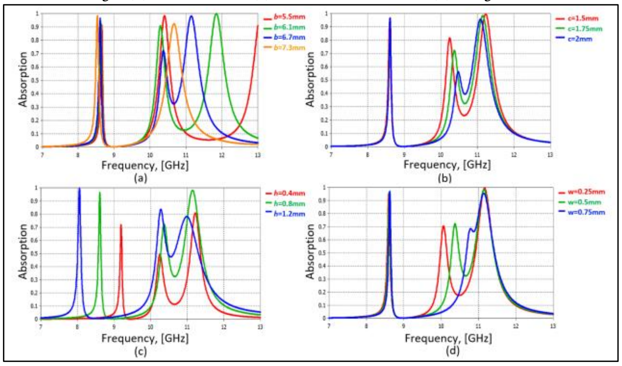
Fig. 3. Numerical absorption based on TE and TM mode for the proposed structure.



4. Analysis and Discussion

Figure 3 presents the characteristic of TE-polarisation and TM-polarisation responses. Due to the symmetry of the proposed design at a high 45^0 of sensitivity, from 0^0 to 45^0 angles for the TE mode of the dual-band absorption spectrum, the proposed absorber is polarisation sensitive. However, it can also be gathered from the TM-polarisation simulated results that the absorption spectrum presents a high degree of insensitivity under different polarisation angles from 0^0 to 45^0. In some cases, the cross-sectional areas of the structure are designed for the best absorption value to be produced. It is also adjusted depending on the frequency being kept constant at a certain band (i.e. x-band). Thus, the cross-sectional area from which the best result is obtained is determined. In other words, optimisation works are carried out to give the best result. To better understand the reason behind the results of the proposed design, a parametric analysis of the b cut wire length, c cut wire width, h substrate thickness and w ring width is carried out with respect to the design variables. It can be seen that the absorption spectrum for the two high frequencies changes straight to high frequencies with an increase in the b cut wire length and an increase in the absorption rate. However, only the absorption level increases when the c cut wire width increased. Moreover, the three absorption bands decreased in level when the h substrate thickness increased. When the width of the ring increases, the second absorption band shifted right until it merged with the third absorption band.

Fig. 4. (colour online) Dependence of the absorption spectrum on the changes of (a) b cut wire length, (b) c cut wire width, (c) h substrate thickness and (d) w ring width



It is seen that outstanding absorption resulted in different frequency values where the b value increased. When the frequency range is kept between 8 and 12 GHz, the best absorption rate produced is 95% and the parametrical value is 6.1 mm. Similarly, when the applied frequency value is taken from 8 to 9 GHz, the best absorption rate outcome is 99.03% and the b cross-sectional area is 7.3 mm. In addition, when the frequency range falls between 10 and 12 GHz, the best absorption rate is 99.98% and the b cross-sectional area is 6.1 mm. This result indicated that the best absorption rate that can be produced depends on the frequency range applied. In previous studies examined in the introduction section, it was found that there are very few structures that provide excellent absorption at different frequencies. Satisfactory results were obtained in the simulation studies in the medical, image processing, military fields and so on, showing that it can be applied to many areas of work. In addition, the results of changing the c cut wire width, h substrate thickness and w ring width show excellent absorption when the frequency range is kept between 8 and 12 GHz for all parameters. It is confirmed that the best absorption rate is 99.89% at c=1.5mm, while the best absorption rate based on substrate thickness is seen at h=0.8mm. Finally, w=0.25mm has shown perfect absorption compared to other w ring width.

Figure 3 also shows a satisfactory Q-factor result of 103.5 at a resonance frequency of 8.58 GHz. Where

$$Q_{factor} = \frac{f_{res}}{FWHM} \quad (2)$$

f_{res} resonance frequency, $FWHM$ is the full width at a half maximum of the resonance peak (He et al. 2018). Additionally, the FOM is 98.4, where:

$$FOM = A_{max} \times Q\_factor \quad (3)$$

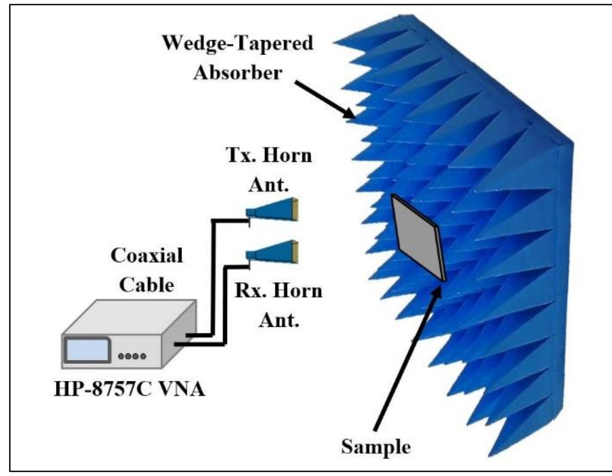
A_{max} is the height amplitude of absorption at the resonance frequency. Meanwhile, the high Q-factor and FOM can be used to enhance the sensor sensing, narrowband band filter and image sensing (Abdulkarim et al. 2020).

In this paper, a multi-band metamaterial absorber operating at x-band frequency is presented. The absorber suggested here is designed using simple structures of cut wire and split ring, which was placed on a 0.8mm FR-4 substrate. Three absorption peaks with two bands near 100% absorbance were obtained. Based on this, the Q-factor and FOM performance of the proposed structure is discussed. The first absorption peak shows a high Q-factor=103.5 and FOM=98.4 at a resonance frequency of 8.58 GHz, which are significantly higher than many existing absorbers reported at GHz frequency. See Table 1.

Table 1 Comparison of the Q-factor and FOM between the proposed structure and the other works

References	Q-Factor	FOM
Cong et al. 2015	11.6	2.3
Hu et al. 2016	8.5	4
Li et al. 2019	8.5	0.85
Burrow et al. 2019	15.5	17.5
Saadeldin et al. 2019	22.1	2.94
Xie et al. 2018	58	7.5
This work	103.5	98.4

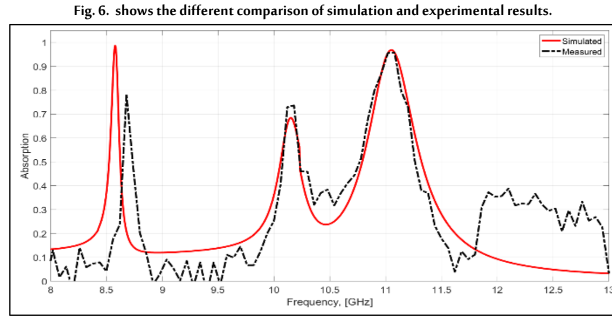
Fig. 5. Experimental setup.



5. Experimental Results

Figure 6 shows the experimental sample. It is implemented by using the traditional circuit board etching technology. A 150X250 mm sample was etched on cells on a 1.5 mm thick FR4 dielectric board. In the absorbance material reflectivity test system, there are two broadband horn antennae connected to a vector network analyser by coaxial cable, used as the source and receiver ports to test the proposed structure as presented in Figure 5. Figure 6 shows the different comparison of simulation and experimental results of the absorption rate. However, the measurement results are in strong agreement with the simulation results.

Fig. 6. shows the different comparison of simulation and experimental results.



6. Conclusion

In this study, the signal absorbing material structure, which is one of the metamaterial applications that has become the focus of attention in recent years, is designed, and the numerical data analysis is carried out. To ensure the maximum absorption of the designed structure, the back portion is covered with a metal conductor and the results are tested with the sections on the front surface. According to the obtained numerical and experimental data, the b length is changed from 6.1 mm to 7.3 mm with a stipe length of 0.3 mm in order to achieve excellent outcomes. As a result of the values obtained in the simulation results, an absorption value of 99.98% is provided in the b length of 6.1 mm at a resonance frequency of 11.07 GHz and two other perfect absorption bands. Next, at 7.1 mm and two perfect absorption bands, it demonstrates the applicability of the numerical structure, which is designed to achieve a high Q-factor of 103.5 at a resonance frequency of 8.58 GHz. The FOM is 98.4, which can be used to enhance the sensor sensing, narrowband band filter and image sensing. For this purpose, this structure, which has been designed and has achieved excellent results with its mechanical adjustability feature, is used in medical, image processing, military fields and so on. It applies to many working areas. This work done on microwave applications is also adaptable for different frequency bands.

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