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Triangular Split Ring Resonators for X-Band Applications and Operations

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Metamaterial absorber (MA) is of particular interest due to its numerous potential applications in sensing, microwave detection, energy harvesting, miniaturized electronic components, bolometers, and thermal detectors. In this paper, a new MA has been provided. The proposed MA is a microwave structure consisting of a network of four split ring resonators (SRRs) of magnetic resonance and negative permeability ($\mu < 0$): one central SRR has a triangular shape and three other SRRs have a square shape and the same dimensions. All SRRs are printed on the upper surface of the FR_Epoxy substrate ($\varepsilon_r = 4.4$; tg$\delta = 0.02$), its dimensions are chosen to obtain the resonance at the X-band frequency. To eliminate transmission, we add a copper conductive metal plate that will be etched on the upper face of the same substrate. The main advantage of this study based on the proposed structure is that it is possible to control its absorption percentage for X-band radar applications.

Keywords: Absorber, Metamaterial, Permeability, Split ring resonators (SRRs), Transverse electric polarization.

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1. INTRODUCTION

During the last decade, wireless communication systems using microwave devices have undergone remarkable development. The study of most microwave devices requires considerable knowledge of the physical characteristics of electromagnetic waves when they propagate in structures. These electromagnetic characteristics are reflection, transmission, refraction, radiation, diffraction and also absorption [1-3]. Absorption of electromagnetic (EM) waves has been the subject of several recent studies [4-6], the control of the absorption percentage is becoming more and more essential to meet the needs of absorber performance. Nowadays, metamaterial absorbers (MAs) occupy a prestigious position in the area of telecommunications, especially for antennas [7] and radars [8].

Metamaterials are artificially designed materials with different properties than natural materials. This kind of medium was introduced for the first time by Victor Veselago [9] in 1967 after the Second World War. He showed that the propagation of electromagnetic waves in metamaterials is carried out in the opposite direction to that of natural materials. Previously, left-handed metamaterials, whose permittivity and permeability are negative [10], have been a favorite topic for millimeter-wave and microwave applications because of their unique unusual phenomena, such as negative-index refraction [11] and surface plasmon generation.

In this work, we propose a new MA consisting of four split ring resonators (SRRs). The overall shape of our MA is based on a central SRR of a triangular shape surrounded by three SRRs of a square shape and also of the same dimensions (engraved on the upper face of the used substrate) in order to obtain resonances in the X-band. These square SRRs are spaced apart by an inter-resonator distance (e), one of these three SRRs is coupled to an etched copper conductive plate to prevent transmission of the overall structure. The polarization of our MA is transverse electric (TE) for different incidences, and the study is based on the EM coupling of the triangular SRR to square SRRs to have different absorption levels at the same X-band frequency.

The rest of the paper is organized as follows. In section two, the design procedure of the proposed MA is presented based on a detailed description with the impact of different design steps, while the simulation results and discussion are described in section three. Conclusions are included in section four.

2. MA DESIGN PROCEDURE

2.1. Depiction

SRR is a metamaterial resonator proposed for the first time by J. Pendry and his research team [12]. Geometrically, SRR is formed by two outer and inner split rings with two opposing interrupts to create a capacitive effect. Physically, SRR can support too small wavelengths of the order of a few microns [13].

2.1.1. Triangular SRR

Triangular SRR of period P_1 is a metamaterial resonator formed by two inner and outer rings. The two rings have a triangular shape (equilateral triangle) of a and b ribs for the outer and inner rings, respectively. All interruptions of the rings have the same value, which is g_t, the width W is the same for both rings. The proposed triangular SRR is represented in Fig. 1, its dimensions are given in Table 1.

The study of the elementary components of the metamaterial resonator shows that the origin of the resonance comes mainly from the Lorentz dispersion [14], which led us to propose an equivalent electrical scheme for each resonator, this scheme is based on a

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resonant circuit. The equivalent electrical circuit of the triangular SRR is composed of three resonators, each formed by inductance L_1 and capacitance C_1, these three resonators represent the outer ring of our triangular SRR. The inner ring corresponds to the resonator formed by inductance L_2 and capacitance C_2. Capacitance C_p represents the coupling between the two inner and outer rings of the triangular SRR.

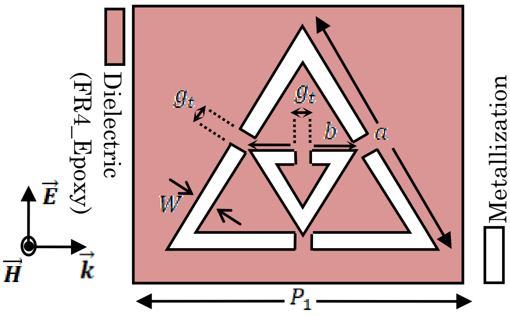


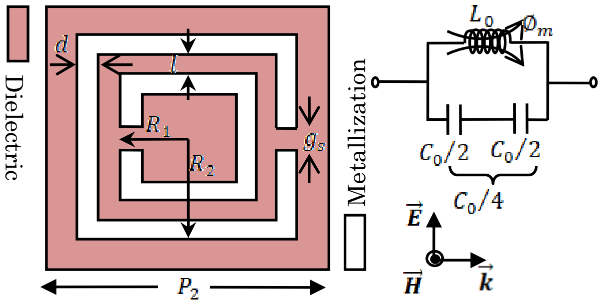
Fig. 1 – Representation in rings of the proposed triangular SRR

Table 1 – Triangular SRR dimensions

Parameter	a	b	g_t	W	P_1
Value (mm)	6.4	2.64	0.2	0.2	7.2

2.1.2 Square SRR

As triangular SRR, the square SRR is also formed by two rings: inner of radius R_1 and outer of radius R_2 for a square shape. The period of the proposed square SRR is P_2, l represents the spacing between the two rings that have the same width d, interruption gaps g_s have the same value as the interruption g_t for the triangular SRR. The proposed square SRR and its equivalent circuit model are illustrated in Fig. 2, the SRR dimensions with $l = d$ are shown in Table 2.



a b

Fig. 2 – Square SRR: (a) representation in rings, (b) equivalent circuit model

Table 2 – Square SRR dimensions

Parameter	g_s	d	R_1	R_2	P_2
Value (mm)	0.2	0.2	2.8	3.2	6.8

A square SRR can be mainly considered as a magnetic dipole, its equivalent circuit model behaves like an L_0C_0 resonator excited by a magnetic field perpendicular to the plane of the rings [15].

2.2. Proposed MA

Our proposed MA consists of four metamaterial SRRs; three SRRs of a square shape (with dimensions shown in Table 2) are centered on a triangular SRR (with dimensions shown in Table 1) and are separated from each other by an angle $\varphi = 120^{\circ}$. These resonators (square and triangular) are engraved on the upper face of the used substrate, a metal plate (made of copper) is etched on the upper face of the same substrate to prevent transmission of the overall structure.

The dimensions of this plate are optimized at $a_1 = a = 2R_2 = 6.4$ mm and $W_1 = 1.5$ mm. We polarize the proposed MA to have TE polarization and we will study the absorption as a function of the inter-resonator EM coupling distance (e) between each square SRR and the central triangular SRR. Then, we will study the absorption according to the numerical values of the incidence angle (θ). The optimized dimensions of the proposed MA are $m \times n$ mm^2 with $m = 27.9$ mm and $n = 32$ mm. Fig. 3 represents our proposed MA.

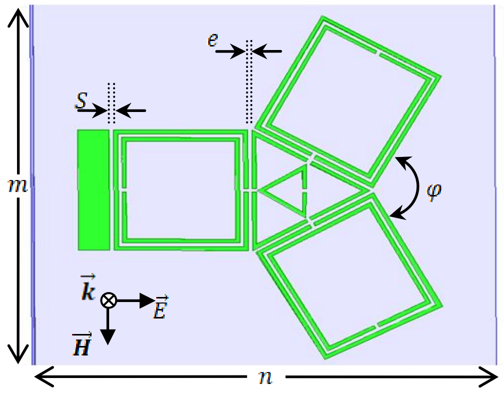


Fig. 3 – Top view of the proposed MA

3. RESULTS AND DISCUSSION

3.1. Triangular SRR Behavior

In [16, 17], M. Berka et al. have done a comparison between three types of the dielectric substrate, while FR_Epoxy is the most suitable for our design (high absorption coefficients for various designs). On the upper surface of this substrate ($\varepsilon_r = 4.4$, tg$\delta = 0.02$) of thickness $h = 1.53$ mm, a triangular metamaterial SRR is printed for a metallization thickness $t = 15$ µm.

On the simulator, we polarize the three triangular SRRs in the OZ direction and fix the boundary conditions for the electric and magnetic fields. The boundary conditions for the simulation of our triangular SRR on HFSS are maintained in our configuration (polarization along the OZ axis) as follows. For the electric wall, we place PEC 1 and PEC 2 (two perfect electrical conductors) on the two faces perpendicular to the electric field E. For the magnetic wall, we place PMC 1 and PMC 2 (two perfect magnetic conductors) on the two faces perpendicular to the magnetic field H. For the two faces perpendicular to the direction of propagation, we place WAVEPORT1 and WAVEPORT2, respectively.

The module and phase of the reflection coefficient (S_{11}) are shown in Fig. 4.

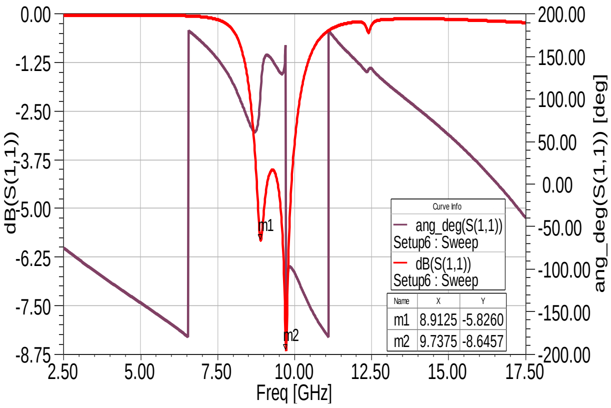


Fig. 4 – Reflection coefficient of the triangular SRR: amplitude and phase

Fig. 4 shows the behavior of the triangular SRR based on its S_{11} parameter (amplitude and phase). By the amplitude of this parameter, we note that it is about two resonance frequencies in the X-band [8-12]: frequency $f_{r1} = 8.91$ GHz of the low resonance associated with the inner ring of the triangular SRR and frequency $f_{r2} = 9.73$ GHz of the high resonance associated with the outer ring.

For the S_{11} argument, we notice that the values vary in the interval $[-\pi, +\pi]$ for the same resonance frequencies.

The triangular SRR has a characteristic impedance $Z(\omega)$ defined by the relation:

$$Z(\omega) = \sqrt{\frac{\mu_r(\omega)}{\varepsilon_r(\omega)}} Z_0, \tag{1}$$

where $\mu_r(\omega)$ and $\varepsilon_r(\omega)$ are the relative permeability and the relative permittivity of the triangular SRR, respectively, and Z_0 represents the characteristic impedance of vacuum ($Z_0 \approx 377\ \Omega$.) We note that the triangular SSR is adapted for $Z(\omega) = Z_0$.

The effective reduced impedance of the triangular SRR is defined by

$$Z_{eff}(\omega) = \frac{Z(\omega)}{Z_0} = \sqrt{\frac{(1+S_{11}(\omega))^2 - S_{21}^2(\omega)}{(1-S_{11}(\omega))^2 - S_{21}^2(\omega)}}. \tag{2}$$

For zero transmission $S_{21}(\omega) = 0$, then

$$Z_{eff}(\omega) = \frac{Z(\omega)}{Z_0} = \sqrt{\frac{(1+S_{11}(\omega))^2}{(1-S_{11}(\omega))^2}} \tag{3}$$

and also

$$Z(\omega) = \mathrm{Re}\{Z(\omega)\} + i\,\mathrm{Im}\{Z(\omega)\} = Z'(\omega) + iZ''(\omega). \tag{4}$$

In HFSS simulator, we directly select both parts, namely the real with $Z'(\omega) > 0$ and the imaginary characteristic impedance. Fig. 5 shows the variation of these two impedance parts.

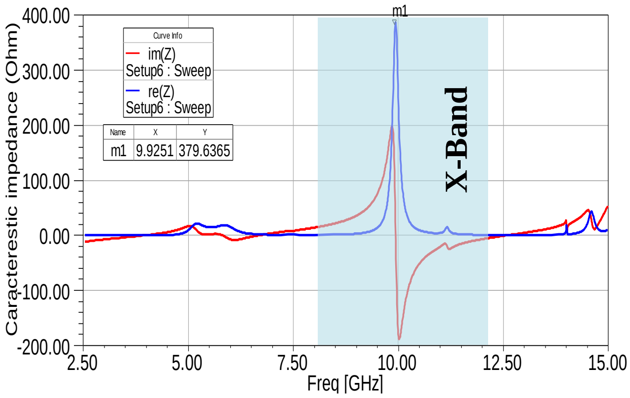


Fig. 5 – Real and imaginary parts of the characteristic impedance for the triangular SRR

As shown in Fig. 5, at the resonance frequency, the real part of the characteristic impedance of the triangular SRR has a value of 379 Ω. So, it approaches the vacuum impedance (i.e., approximately 377 Ω), while the imaginary part tends to 0. So, energy that is not reflected is trapped and absorbed in the resonator. The triangular SRR absorption is given by [18]:

$$A_b = 1 - R - T - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2, \tag{5}$$

where $R = |S_{11}(\omega)|^2$, $T = |S_{21}(\omega)|^2$.

So,

$$\begin{cases} S_{11} = \dfrac{\sqrt{Power\ reflected\ port\ 1}}{\sqrt{Power\ incident\ port\ 1}}, \\ S_{21} = \dfrac{\sqrt{Power\ reflected\ port\ 2}}{\sqrt{Power\ incident\ port\ 1}}. \end{cases} \tag{6}$$

$$A_b = 1 - |S_{11}(\omega)|^2. \tag{7}$$

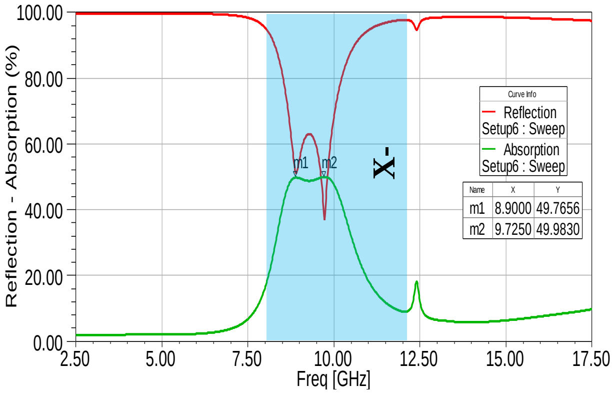


Fig. 6 – Reflection and absorption of the triangular SRR

Fig. 6 shows the absorption (A_b) and reflection (R) of the triangular SRR. We note that at two magnetic resonances of the triangular SRR ($f_{r1} = 8.91$ GHz and $f_{r2} = 9.73$ GHz), we have two absorptions $A_{b1} = 49.76$ % and $A_{b1} = 49.98$ %, respectively. It can also be noted that the absorption of this SRR is modest, where the largest is associated with the smallest reflection of – 8.64 dB.

3.2. Square SRR Behavior

On the upper surface of the same substrate used for the triangular SRR, the square metamaterial SRR is etched for the same thickness (t = 15 μm). For the same boundary conditions, the reflection and absorption of the square SRR are shown in Fig. 7.

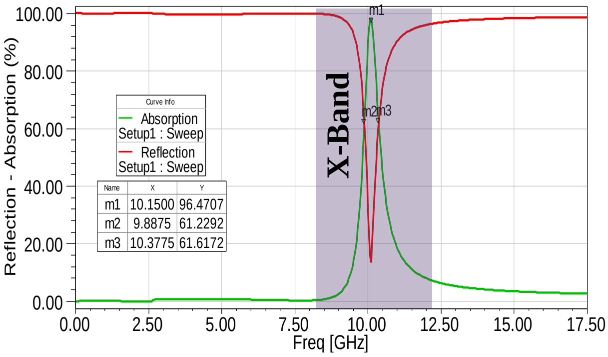


Fig. 7 – Reflection and absorption of the square SRR

In Fig. 7, we note the presence of one resonance (in the X-band) associated with frequency f_r = 10.15 GHz, the maximum absorption estimate of this SRR at the indicated resonance frequency is A_b = 96.47 % with a thickness of the order of λ/19. It is also noted that the absorption is obtained for a narrow band of the order of 0.49 GHz.

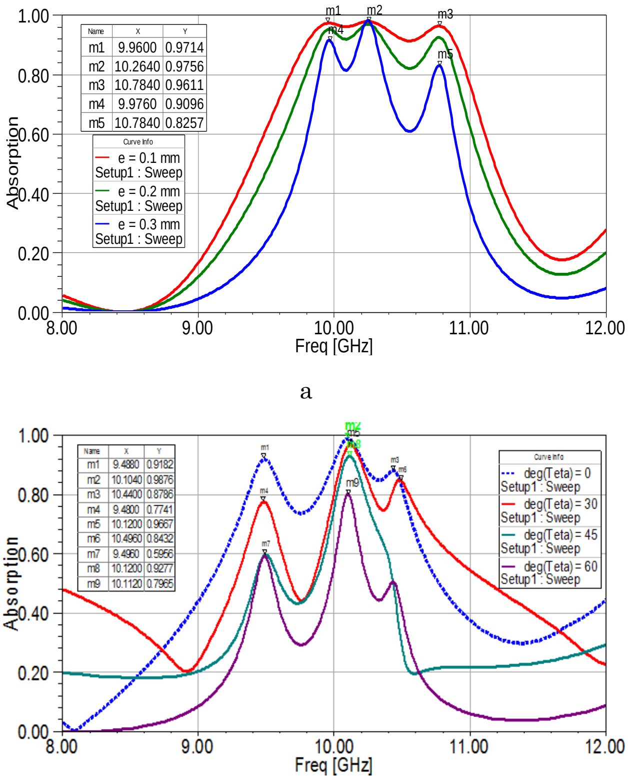
3.3. EM Characteristics of the Proposed MA

According to the inter-resonator spacing value (e = 0.1, 0.2 and 0.3 mm), we have done three simulations of the proposed MA (for normal incidence) and for a fixed value of the spacing between the metal plate and one of the three square SRRs (S = 0.2 mm). Then, we searched for the absorption of the proposed MA for TE polarization for both normal incidence ($\theta = 0^{o}$) and three oblique incidence angles ($\theta = 30^{o}$, 45^{o} and 60^{0}). The absorption of our MA according to the inter-resonator spacing and incidence angle (for TE polarization) is shown in Fig. 8.

In Fig. 8a, we note that our proposed MA has three absorption peaks in the X-band, which correspond to three square SRRs. For e = 0.1 mm, we have three absorptions of 97.14 %, 97.56 % and 96.11 % for three resonances at 9.96 GHz, 10.26 GHz and 10.78 GHz, respectively. We also note that the most important absorption among the three indicated is that which is around the resonance of the square SRR (previously estimated of the order of 96.47 % around 10.15 GHz). It is noted in the same figure that the absorption of the proposed MA increases when the value of the spacing e decreases, which proves that the absorption is greater for considerable EM coupling between the metamaterial SRRs in the absorber.

Fig. 8b shows the simulated absorption of the proposed MA in the X-band for normal incidence ($\theta = 0^{o}$) and oblique (for three values of θ). We notice in this figure that the absorption has always three peaks. For normal incidence, it is noted that the absorption is estimated by the highest percentage of 98.76 % at a frequency of 10.19 GHz (around the resonance of the square SRR), the other two peaks represent two absorptions estimated by 91.82 % and 87.86 % at resonances of 9.48 GHz and 10.44 GHz, respectively. We also note that the absorption for TE polarization decreases as the angle of incidence increases, the absorptions around the resonance of the square SRR are estimated by 92.77 % ($\theta = 45^{o}$) and 79.65 % ($\theta = 60^{o}$ 60^{0}) at frequencies of 10.12 GHz and 10.11 GHz, respectively.

In Table 3, we present a comparison between our proposed MA and proposed MA in literature.



a

b

Fig. 8 – Absorption of the proposed MA: (a) according to the inter-resonator spacing, (b) according to the angle of incidence

Table 3 – Performance comparison of the designed filter with literature

Reference	[19]	[20]	This work
Absorber shape	Asymmetric circular SRR	Gap coupled hexagonal SRR	Triangular and square SRRs
Center frequency (GHz)	4.1/11.3/13.45	4.27/12.4	9.96/10.26/10.78
Absorbance (%)	97.9	98.81	97.56
Absorber area	$0.11\lambda_0 \times 0.116\lambda_0$	$0.14\lambda_0 \times 0.14\lambda_0$	$0.92\lambda_0 \times 1.06\lambda_0$
Frequency band	C-, X-, Ku-	S-, X-	X-
Applications	multiband microwave systems	multiband microwave systems	RADAR systems

4. CONCLUSIONS

In this work, we have proposed a new microwave structure that is a MA. Our proposed MA is based on the EM coupling between three square SRRs and one central triangular SRR. All dimensions of these metamaterial SRRs are chosen to have magnetic resonances in the X-band and thus have the necessary absorption in the same band. We used a printed metal plate on the upper face of the used substrate to prevent transmission of the structure. We polarized our MA to have TE polarization (for different angle of incidence). During our study, we also varied the inter-resonator spacing. In our results, we always found three absorption peaks relative to the coupling between the triangular SRR and the three square SRRs, where the biggest peak appeared around the resonance of each square SRR for normal incidence. Based on these results, our proposed MA may represent a base cell for several future applications of RADAR systems at the X-frequency band.

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Майже ідеальний метаматеріальний поглинач з ТЕ поляризацією, що заряджається трикутними розрізними кільцевими резонаторами для додатків і операцій Х-діапазону

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Метаматеріальний поглинач (МА) представляє особливий інтерес завдяки його численним потенційним застосуванням в зондуванні, надвисокочастотній дефектоскопії, акумулюванні енергії, мініатюрних електронних компонентах, болометрах і теплових детекторах. У статті запропоновано новий МА. Він являє собою надвисокочастотну структуру, що складається з чотирьох розрізних кільцевих резонаторів (SRRs) магнітного резонансу та негативної проникності ($\mu < 0$): один центральний SRR має трикутну форму, а три інші SRRs мають квадратну форму і однакові розміри. Усі SRRs розташовані на верхній поверхні підкладки FR_Epoxy ($\varepsilon_r = 4,4$; tg$\delta = 0,02$), її розміри підібрані для отримання резонансу на частоті Х-діапазону. Щоб усунути передачу, ми додаємо мідну електропровідну металеву пластину, яка буде витравлена на верхній поверхні тієї ж підкладки. Основна перевага дослідження, заснованого на запропонованій структурі, полягає в тому, що можна контролювати відсоток його поглинання для радіолокаційних застосувань Х-діапазону.

Ключові слова: Поглинач, Метаматеріал, Проникність, Розрізні кільцеві резонатори (SRRs), Поперечна електрична (ТЕ) поляризація.