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POLARIZATION-INDEPENDENT METAMATERIAL ABSORBER FOR SINGLE BAND AND MULTI-BAND FREQUENCY

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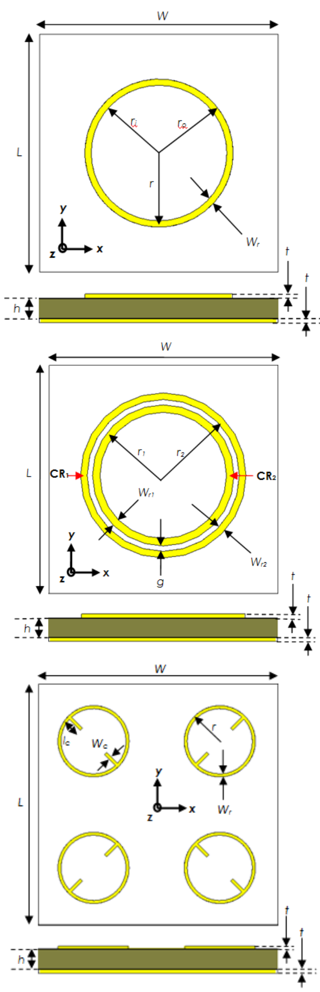
Graphical abstract



Abstract

This paper presents the design and simulation of polarization-independent type of metamaterial absorbers (MMAbs) at X-band frequency. The advantage of polarization-independent MMAbs is it can absorbs incident electromagnetic (EM) wave in all polarization states. It can be achieved by applying circular ring shape in a unit cell of MMAbs because the shape is very symmetry. The simulation is done in a unit cell for each proposed MMAbs structures. The FR4 substrate is used for MMAbs structure designs. The designed MMAbs structures can be divided into two parts which is circular ring and modified circular ring. The characteristics of both structure are studied through simulation process using CST software. Parametric study is conducted to observe the effect of each parameters in unit cell on the absorbing magnitude and frequency. It is observed that circular ring structures can achieve high EM wave absorbance for single band and multi band frequency. Since frequency separation distant limitation occurred, the modified circular ring structure is proposed by adding copper lines on the original circular ring structure. Thus, dual band frequency with close separation distant between two resonant frequencies is obtained as close as 1 GHz compared to the original dual band circular ring which is 2 GHz.

Keywords: Metamaterial absorber, polarization-independent, electromagnetic wave absorption

Abstrak

Kertas kerja ini membentangkan reka bentuk dan simulasi penyerap bahan-meta (MMAbs) pada frekuensi X-band. Kelebihan MMAbs jenis polarisasi-bebas adalah ia boleh menyerap gelombang elektromagnetik yang datang dalam semua bentuk polarisasi. Ia boleh dicapai dengan menggunakan bentuk cincin pekeliling dalam sel unit MMAbs kerana bentuknya sangat simetri. Simulasi ini dibuat dalam unit sel untuk setiap struktur MMAbs yang dicadangkan. Substrat FR4 digunakan dalam mereka bentuk struktur MMAbs. Struktur MMAbs yang direka boleh dibahagikan kepada dua bahagian iaitu cincin perkeliling dan cincin perkeliling terubahsuai. Ciri kedua-dua struktur yang dikaji melalui proses simulasi menggunakan perisian CST. Kajian parametrik dijalankan untuk melihat kesan setiap parameter dalam unit sel ke atas magnitud penyerapan dan frekuensi. Adalah diperhatikan bahawa struktur cincin bulat boleh mencapai penyerapan gelombang EM kuantiti tinggi untuk jalur tunggal dan jalur berbilang frekuensi. Oleh sebab berlaku perpisahan jalur frekuensi yang jauh, struktur cincin pekeliling terubahsuai dicadangkan dengan menambah baris tembaga pada struktur cincin bulat yang asal. Oleh itu, dua jalur frekuensi dengan pemisahan dekat jarak di antara dua frekuensi salunan diperolehi serapat 1 GHz berbanding cincin perkeliling dua-jalur iaitu 2 GHz.

Kata kunci: Penyerap bahan-meta, polarisasi-bebas, penyerap gelombang elektromagnet

1.0 INTRODUCTION

Researches on metamaterial absorbers (MMAbs) have been increased rapidly since the first experimental results was published by Landy. et al in 2008 [1]. To obtain a perfect electromagnetic (EM) absorber, a electric field driven LC (ELC) structure was printed on the top surface of dielectric substrate with printed cut wire on the opposite surface of the dielectric substrate. However, the proposed structure can only working on single absorbing frequency while the polarization behavior was not being observed. Tao et. al proposed another ELC based MMAbs working in Terahertz frequency [2]. The proposed structure had a wide angular bandwidth. But, the structure was thick since two dielectric layer used in the design. In the same time, the structure suffers polarization-dependent. There were many other works on MMAbs from radio up to the optical frequency [3-9].

Since polarization-dependency is the main concern for designing MMAbs, many works had been done by researches to maintain the polarization behavior of MMAbs for any polarization angle [10-16]. Moreover, operating frequency is also considered in designing MMAbs. The MMabs absorbers are normally working in single frequency band. Many designs were also proposed to improve the operating frequency from single band to multiband or wideband frequency [17-20].

The concept of absorbing the incident EM wave is based on the matching impedance between MMAbs and free space. When the impedance of MMAbs is same with free space impedance, the reflection of incident wave will be minimized and the EM wave is absorbed within the structure. However, the structure should be lossy enough to attenuate the EM wave. To achieve that, the imaginary part of refractive index, $n_2(\omega)$ which is contribute to losses should be very high. The refractive index is given by equation (1) while the relative impedance is given by equation (2).

$$n(\omega) = \sqrt{\varepsilon(\omega).\mu(\omega)} = n_1(\omega) + jn_2(\omega) \quad (1)$$

$$Z(\omega) = \sqrt{\frac{\mu(\omega)}{\varepsilon(\omega)}} \quad (2)$$

In can be seen in equation (2) that the permeability and permittivity of the MMAbs should be the same magnitude to achieve Z(ω) = 1. From literature, a lot of works have been done to design high absorbing EM wave structure using the matching impedance method.

This paper proposed MMAbs that can work at single band and multi band frequency which is polarization-independent with the incident EM waves. Parametric study is also done to observe the absorbing behavior of the proposed MMAbs when vary a specific parameters.

2.0 CIRCULAR RING METAMATERIAL ABSORBER

The first part of this work is to propose a MMAbs using only circular ring structure as resonating element. Initially, the work started with rigorous parametric study on a single element of circular ring MMAbs (CRMMAbs) at different resonant frequencies. Then, a dual band and triple band CRMMAbs are proposed using combination of circular rings with different sizes in a unit cell. The latter part of this work is to propose a dual band using circular ring structure with copper lines that can overcome the limitation of the combined circular ring structures. All MMAbs are designed in X-band frequency.

The material used for all design is FR4 substrate. It has a thickness, *h* of 0.8 mm, relative permittivity, ε_r of 4.6 and loss tangent, ẟ of 0.019. There is a copper layer printed on top and bottom surfaces of the FR4 substrate which has electric conductivity, σ of 5.96 × 10^7 S/m. The thickness of copper layer, *t* is 0.035 mm.

Since the resonating elements are printed on the top surface of dielectric layer and having full metal plane at the bottom dielectric surface, the equivalent circuit of this kind of structure can be represented using simple parallel L-C circuit as given in Figure 1.

The resonant frequency of the CRMMAbs can be determined by calculating the L-C component of the resonator as given below;

$$L = \mu_o h \quad (3)$$

$$C = \frac{\varepsilon_0 \varepsilon_r \pi (r_0^2 - r_i^2)}{h} \quad (4)$$

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

When substituting equation (3) and (4) into equation (5), the final equation to determine the resonant frequency of CRMMAbs is given by equation (6):

$$f_o = \frac{1}{2\pi\sqrt{\mu_o \varepsilon_o \varepsilon_r \pi (r_o^2 - r_i^2)}} \quad (6)$$

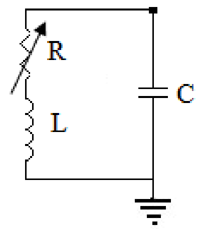


Figure 1 Equivalent circuit of simple CRMMAbs.

2.1 Parametric Study on Single Band Circular Ring Metamaterial Absorber

Circular ring shape is very symmetrical in all angle makes it the best candidate for designing polarization-independent type of MMAbs. However, to understand the relationship between the dimension of the structure with resonant frequency and absorbance magnitude, rigorous parametric study is conducted. The unit cell view of single band CRMMAbs is depicted in Figure 2 with the corresponding dimension tabulated in Table 1. The size of unit cell is roughly $\lambda_g/2$. The reference parameters yield an absorbance of 93.10% at 10 GHz through simulation.

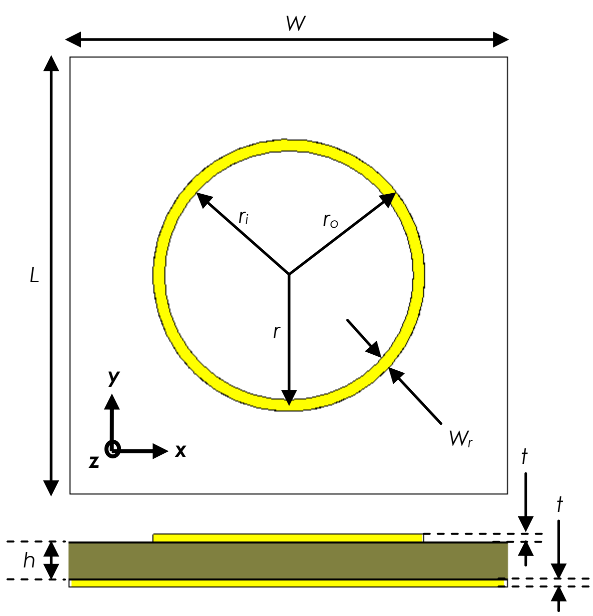


Figure 2 A unit cell view of single band CRMMAbs.

Table 1 The reference parameter of the proposed single band CRMMAbs.

Parameters	Dimension (mm)	Dimension in λ_g at resonant
W	9.00	$0.529\lambda_g$
L	9.00	$0.529\lambda_g$
r	2.68	$0.158\lambda_g$
r_i	2.80	$0.165\lambda_g$
r_o	2.56	$0.151\lambda_g$
W_r	0.24	$0.014\lambda_g$
h	0.80	$0.047\lambda_g$
t	0.035	$0.002\lambda_g$

2.1.1 Varying the Average Radius of the Circular Ring

Initially, the effect of average radius of the CRMMAbs on frequency response and absorbance are studied. The average radius, r of the circular ring is the most predominant parameter for determining the resonant frequency of the CRMMAbs. In practical, increase r will reduce the resonant frequency due to the size increment of resonating element. It can also be predicted by equation (6). In this section, the exact sizes of r are determined to resonate at five frequencies that will be used later in the next sections. Figure 3 shows the absorbance magnitudes of CRMMAbs for different r. It shows that to resonate at frequencies of 8 GHz, 9 GHz, 10 GHz, 11 GHz, and 12 GHz, the size of r are 3.32 mm, 2.96 mm, 2.68 mm, 2.43 mm, and 2.27 mm respectively. The absorbance for all cases are high which is more than 90%.

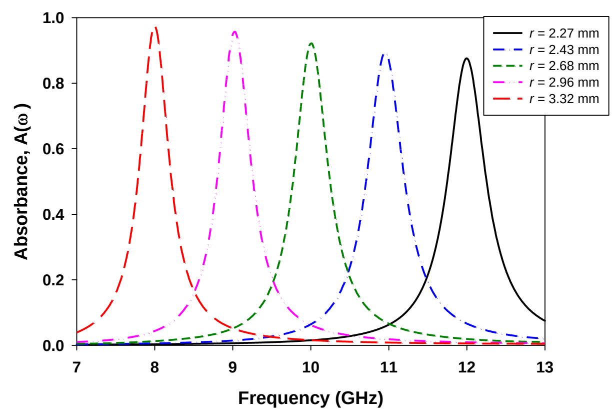


Figure 3 Absorbance for various r of CRMMAbs.

2.1.2 Varying the width of the Circular Ring

Next, the effect of varying the width of the CRMMAbs is studied. The width, W_r is varied with r = 2.68 mm and other parameters which is tabulated in Table 1 unchanged. The result is plotted in Figure 4. The CRMMAbs is simulated with W_r of 0.12 mm, 0.24 mm, 0.48 mm, 0.96 mm, and 2.00 mm. The calculated absorbance are 96.13%, 93.10%, 89.50%, 78.74%, and 65.39% respectively. It shows that as the W_r increased, the magnitude of absorbance decreases. The resonant frequency is also decrease to lower frequency even though the average radius of the circular ring is the same. This is due to the increment of capacitance value. It is expected that further increasing W_r will reduce the absorbance more and the structure will not be an absorber anymore but it will be transformed to EM reflector which is known as AMC structure. The narrow W_r will helps circular ring structure to drive the currents upside and downside more efficient compared to the wider W_r.

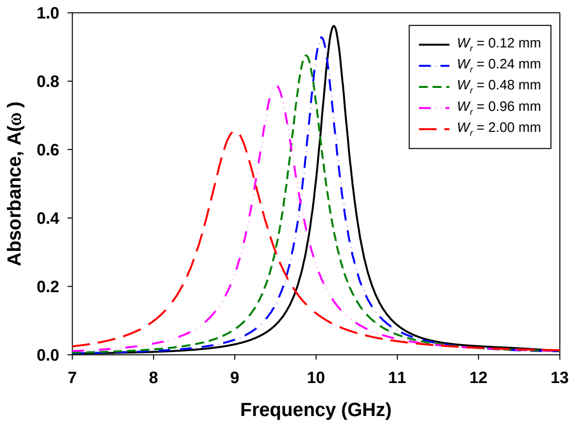


Figure 4 Absorbance for various W_r of CRMMAbs.

2.1.3 Varying the Substrate Thickness

Then, the effect of varying the substrate thickness, *h* of the CRMMAbs is studied. Five different substrate thicknesses are simulated and the result is presented in Figure 5. Start with *h* = 0.2 mm, the absorbance is around 52.18% only. Increase *h* to 0.4 mm and 0.8 mm, high absorbance are observed with magnitudes of 90.74% and 93.10% respectively. When further increase *h* to 1.2 mm and 1.6 mm, the absorbance are dramatically dropped to 68.28% and 49.27% respectively. The substrate thickness is affecting the capacitance and inductance value simultaneously. Once the substrate thickness is optimized, the formation of circulating current is also optimized. The magnetic flux that is formed in the substrate is high so that high EM loss can be obtained. The resonant frequency for all thickness is almost the same because when refer to equation (6), the substrate thickness is not considered for determining the resonant frequency.

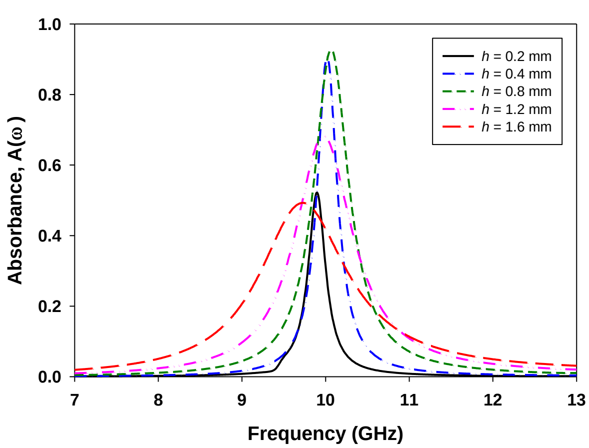


Figure 5 Absorbance for various *h* of CRMMAbs.

2.1.4 Varying the Relative Permittivity of Substrate

Finally, the effect of relative permittivity, ε_r is studied. The ε_r is simulated between 2 and 8 with constant loss tangent. The result is shown in Figure 6. It shows that the resonant frequency is shifted to lower frequency if the ε_r is increased. For ε_r of 2, 4, 4.6, 6, and 8, the absorbance are 80.30%, 89.44%, 93.10%, 97.97%, and 99.75% at 12.00 GHz, 10.63 GHz, 10.00 GHz, 8.83 GHz, and 7.77 GHz respectively. The magnitude of absorbance however increases for lower resonant frequency. This is because substrates with lower permittivity will form more electric flux that yield to EM loss.

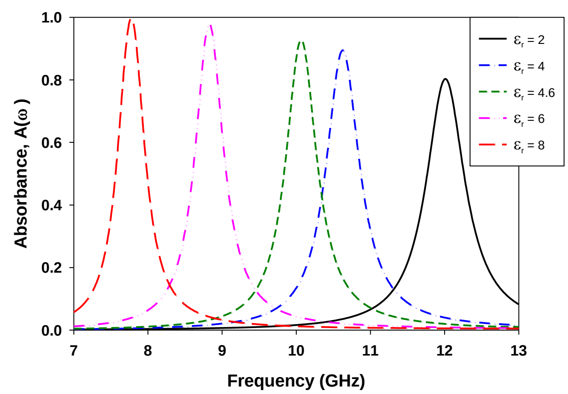


Figure 6 Absorbance for various ε_r of CRMMAbs.

2.2 Dual Band Circular Ring Metamaterial Absorber

From parametric study, it is observed that a single element of circular ring structure can achieves high EM wave absorbance at single resonant frequency. Next, this section propose a design of dual band CRMMAbs using two circular rings, CR_1 and CR_2 in a unit cell to resonate at 9 GHz and 11 GHz respectively. The proposed structure is illustrated in Figure 7. Two circular rings have average radius of r_1 and r_2 respectively. All the labeled parameters are tabulated in Table 2.

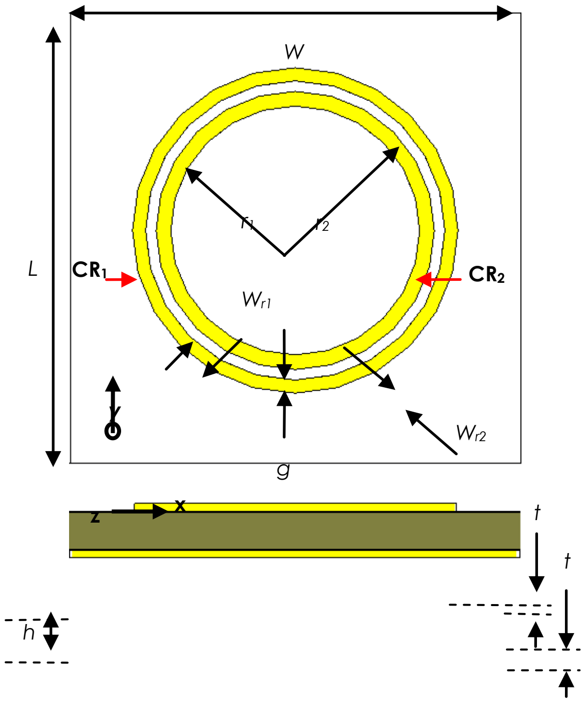


Figure 7 A unit cell view of dual band CRMMAbs.

Table 2 The reference parameter of the proposed dual band CRMMAbs.

Parameters	Dimension (mm)	Dimension in λ_g at resonant
W	9.000	$0.584\lambda_g$
L	9.000	$0.584\lambda_g$
r_1	2.510	$0.163\lambda_g$
r_2	2.975	$0.158\lambda_g$
W_{r1}	0.280	$0.018\lambda_g$
W_{r2}	0.250	$0.016\lambda_g$
g	0.200	$0.013\lambda_g$
h	0.800	$0.052\lambda_g$
t	0.035	$0.002\lambda_g$

The simulated reflectance, transmittance, and absorbance of the propose dual band CRMMAbs is shown in Figure 8. The transmittance, T(ω) is zero for all frequency due to the full copper layer at the bottom of the substrate. The absorbance, A(ω) is determined by reflectance, R(ω) magnitude only. For normal incident wave, R(ω) are 4.41% and 8.65% so that A(ω) are 95.59% and 91.35% at 9 GHz and 11 GHz respectively. The corresponding FWHM bandwidths are 5.12% and 3.08%. The absorbance at two resonant frequencies are above 90% indicates that high EM wave absorbance is achieved at the designed frequencies.

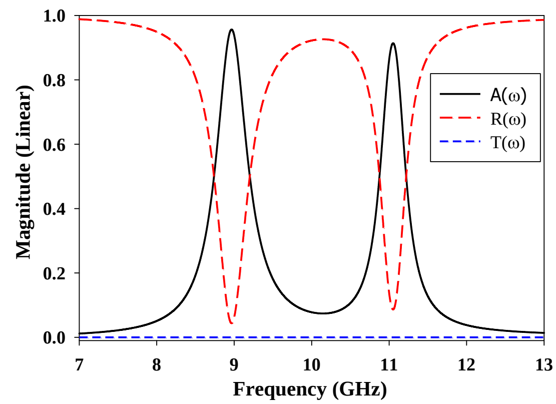


Figure 8 Absorbance for dual band CRMMAbs.

2.3 Triple Band Circular Ring Metamaterial Absorber

The design can further extended to achieve triple band resonant frequency. Thus, this section proposes a triple band CRMMAbs design using three circular rings namely CR_1, CR_2, and CR_3 to achieve resonant frequencies of 8 GHz, 10 GHz, and 12 GHz respectively. The proposed structure is illustrated in Figure 9. The corresponding parameters are tabulated in Table 3

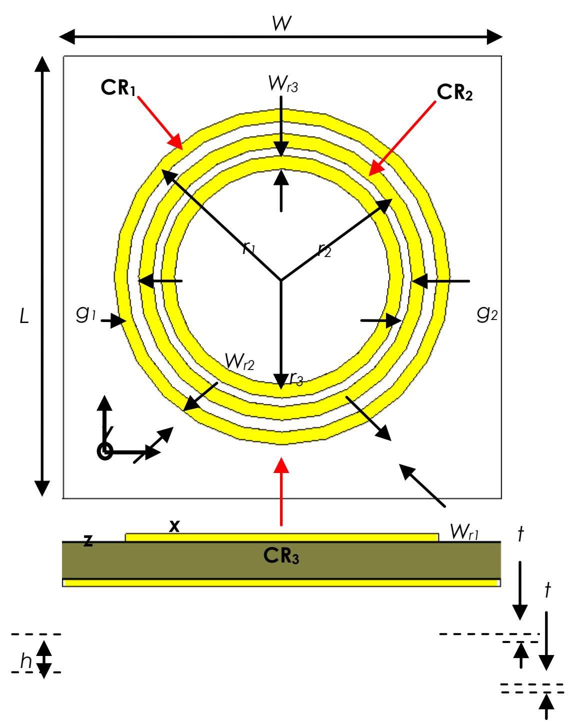


Figure 9 A unit cell view of dual band CRMMAbs.

Table 3 The reference parameter of the proposed triple band CRMMAbs.

Parameters	Dimension (mm)	Dimension in λ_g at resonant
W	9.000	$0.637\lambda_g$
L	9.000	$0.637\lambda_g$
r_1	3.290	$0.155\lambda_g$
r_2	2.780	$0.164\lambda_g$
r_3	2.330	$0.165\lambda_g$
W_{r1}	0.260	$0.012\lambda_g$
W_{r2}	0.280	$0.017\lambda_g$
W_{r3}	0.280	$0.020\lambda_g$
g_1	0.240	$0.017\lambda_g$
g_2	0.170	$0.012\lambda_g$
h	0.800	$0.057\lambda_g$
t	0.035	$0.002\lambda_g$

The simulated reflectance, transmittance, and absorbance of the proposed triple band CRMMAbs is shown in Figure 10. The absorbance, A(ω) is determined by reflectance, R(ω) magnitude only since T(ω) is zero for all frequency. For normal incident wave, R(ω) are 2.67%, 8.16%, and 9.92% so that the A(ω) are 97.33%, 91.84%, and 90.08% at 8 GHz, 10 GHz, and 12 GHz respectively. The corresponding FWHM bandwidths are 5.51%, 3.42%, and 2.65%. The A(ω) of the proposed triple band CRMMAbs achieves 90% at all resonant frequencies indicates that the structure can absorbs the incident EM waves very high.

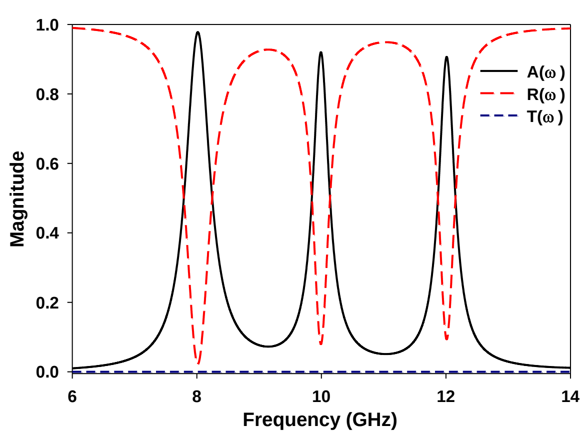


Figure 10 Absorbance for triple band CRMMAbs.

3.0 MODIFIED CIRCULAR RING METAMATERIAL ABSORBER

The design and simulation of circular ring type MMAbs has been presented in the previous section. By apply multiple circular ring elements in a unit cell, more than one absorbing frequencies can be obtained. However, to obtain the same resonant frequency, the multiple rings do not have the same dimension with the single ring operates at the same frequency. This is due to the coupling effects among the adjacent elements that give a significant contribution on the equivalent L-C circuit of the MMAbs. One drawback from the previous design is the multiple resonant frequencies cannot be designed very near to each other due to the nature of the structure in such arrangement. It is observed that the separation frequency is at least 2 GHz. So, the proposed arrangement of resonating elements is only suitable for designing multiband MMAbs that has large separation of resonant frequency.

The limitation of previous design can be improved by modify the original circular ring structure by adding copper lines. So, the resonant frequency can be controlled by adjusting the length of the copper lines. However, this new design is more suitable if two resonant frequencies need to be very near to each other.

3.1 Parametric Study

Firstly, the design started using single circular ring structure which has resonant frequency of 10 GHz. Then, copper lines are placed vertically on the circular ring structure parallel to the direction of incident E-field as illustrated in Figure 11. The dimension of W,L, r, W_c, and W_r are kept constant during simulation which are 9.00 mm, 9.00 mm, 2.68 mm, 0.24 mm, and 0.24 mm respectively.

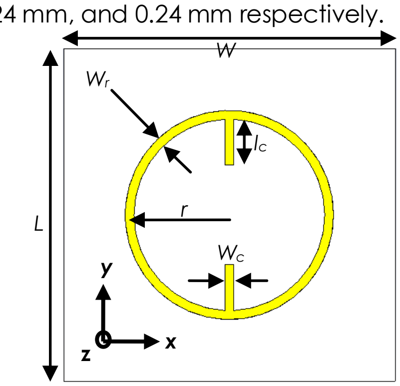


Figure 11 A unit cell view of CRMMAbs with copper lines.

The simulated result for different l_c is presented in Figure 12. It shows that the copper lines reduce the operating frequency of the CRMMAbs. To achieve resonant frequency of 10.00, 9.50, 9.00, 8.50, and 8.00 GHz, l_c are 0 mm, 0.715 mm, 1.240 mm, 1.790 mm, and 2.265 mm respectively. It is verified that by increase l_c, the operating frequency of the CRMMAbs is reduced. This is because, adding the copper lines on the original circular ring structure gives an additional electrical length on the structure so that lower resonant frequency can be achieved. Another interesting finding by adding the copper lines is that the absorbance magnitude can be increased compared to the original CRMMAbs without copper lines. The absorbance of the CRMMAbs with the additional of copper lines are 96.49%, 99.33%, 99.49%, and 94.16% at the frequency of 9.50, 9.00, 8.50, and 8.00 GHz respectively. All absorbance magnitudes are higher than 93.10%, which is the absorbance for circular ring without copper lines.

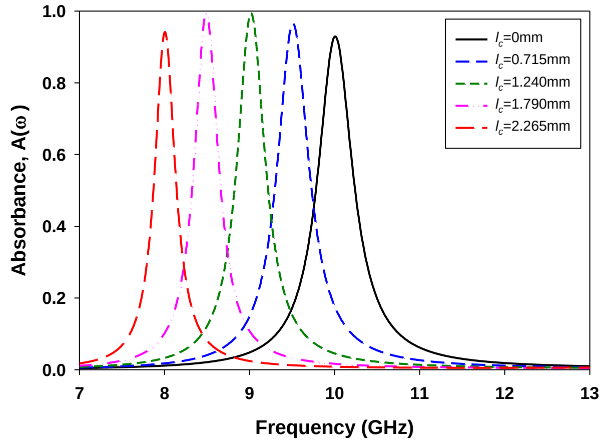


Figure 12 Absorbance for different length of copper lines.

3.2 Dual Band Modified CRMMAbs

It is proved that the additional of copper lines can reduce the operating frequency of CRMMAbs and in the same time increase the absorbance magnitude at resonant. To observe the polarization behavior of the structure, l_c is set to 1.24 mm to achieve resonant frequency of 9 GHz. However, due to the non-symmetrical geometry of the structure, the resonant frequency and absorbance magnitude vary with polarization angle, as shown in Figure 13.

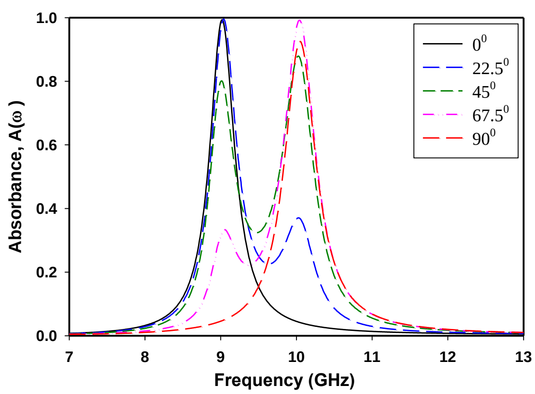


Figure 13 Absorbance for different polarization angle.

Interestingly, when polarization angle is altered to 45°, it is observed that the structure can resonate at two different frequencies, 9 GHz and 10 GHz respectively with absorbance more than 80%. From this findings, the MMAbs in Figure 13 is proposed. It consists of four resonating elements in each unit cell which has angle different of 90° with their adjacent resonating elements. It is designed to maintain the absorbance characteristic in any polarization angle. The corresponding parameters labeled in Figure 14 are tabulated in Table 4.

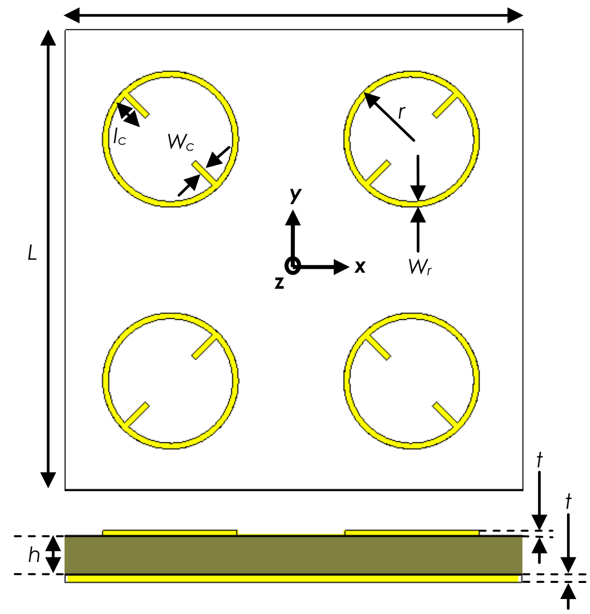


Figure 14 Unit Cell view of dual band modified CRMMAbs.

Table 4 The reference parameter of the proposed dual band modified CRMMAbs.

Parameters	Dimension (mm)	Dimension in λ_g at resonant
W	18.000	$1.059\lambda_g$
L	18.000	$1.059\lambda_g$
r	2.700	$0.159\lambda_g$
W_r	0.240	$0.014\lambda_g$
W_c	0.240	$0.014\lambda_g$
l_c	1.230	$0.072\lambda_g$
h	0.800	$0.047\lambda_g$
t	0.035	$0.002\lambda_g$
W	18.000	$1.059\lambda_g$

The simulated absorbance for different polarization angle is presented in Figure 15. It shows that the pattern of graph is almost unchanged for different polarization angle of incident EM wave proving that the proposed structure is polarization-insensitive.

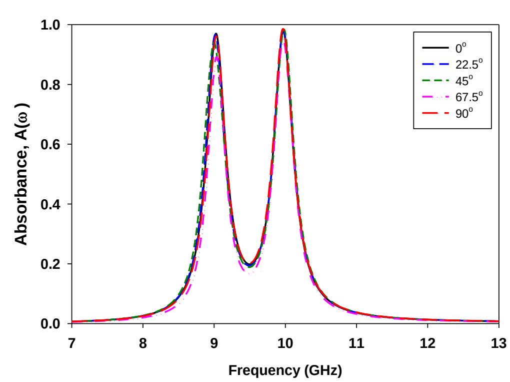


Figure 15 Absorbance of dual band modified CRMMAbs for different polarization angle.

4.0 CONCLUSION

In summary, circular ring metamaterial absorbers (CRMMAbs) have been designed and simulated to operate at single band and multi band frequency. A parametric study is done to observe the effect of each parameter of metamaterial absorber on resonant frequency and absorbance. A modified circular ring metamaterial absorber (Modified CRMMAbs) is also designed and simulated to overcome the limitation of the original circular ring design. It is observed that modified CRMMAbs can achieves higher absorbance with small separation distant between two resonant frequency. However, the modified CRMMAbs can only works at two resonant frequencies compared to the multiple circular ring structure which can obtain more than two resonant frequencies.

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