A Multiband Metamaterial Absorber with Concentric Continuous Rings Resonator Structure

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Abstract. This paper presents the design, simulation and parametric analysis of a concentric continuous ring resonator structure for a multiband metamaterial (MM) absorber. The unit cell of MM structure consists of concentric annular rings of different radii as well as width arranged in four different quadrants. The three layered proposed MM absorber design has an upper layer comprising of continuous annular ring structured sub-cells separated by a bottom laminated copper layer of FR4 substrate. The highly symmetrical annular ring structures in nature make this absorber insensitive to any polarization state of incident EM waves. The scattering parameter and absorption coefficient are obtained for the present MM absorber. The electric and magnetic fields are monitored to realize the behavior of MM structure. The absorbance for this MM absorber are also obtained as 98%, 98%, 96% and 92% at 7.102 GHz, 9.104 GHz, 12.558 GHz and 13.097 GHz frequencies respectively for the normal incidence of EM waves. The high absorbance makes this MM absorber suitable for various microwave applications including airborne and radar signal absorption.

Keywords: Microwave absorber, metamaterials, multiband, periodic structure

1. Introduction

Metamaterials (MMs) are artificial media constructed from sub-wavelength dimension conducting elements embedded in a dielectric material. Light refracts in the non-conventional direction in materials where both the permittivity (ε) and the permeability (μ) are negative was pointed out in 1968 by Veselago [1]. The permittivity (ε) and the permeability (μ) enable the engineering of electric and magnetic resonant responses that do not occur in nature. The electromagnetic response of MMs is principally controlled by creating geometrical plasma-type resonances, which neglecting losses, take the form,

$$\varepsilon_{eff} = 1 - \frac{\omega_p^2}{\omega^2} \qquad (1)$$

$$\mu_{eff} = 1 - \frac{\omega_m^2}{\omega^2} \qquad (2)$$

where ω_p and ω_m are respectively the effective electrical and magnetic plasma frequencies, ε_{eff} and μ_{eff} are respectively the effective permittivity and effective permeability of the medium. For example, low frequency electrical resonances can be engineered using thin wire arrays [2] and magnetic responses can be set up using discontinuous current loops termed split ring resonators (SRRs) [3].

The ability to use MMs to create artificial electromagnetic responses has led to growing research interest and a range of potential applications such as perfect lens [4-5], cloaking at microwave frequency [6-7], compact antennas [8], microwave absorbers [9-15], etc. MM based microwave absorbers found applications in reduction of the radar signature of aircrafts, ships, tanks and other targets for stealth and camouflage purposes as well as to reduce the electromagnetic interference among microwave components or electronic circuits mounted on the same platform, in satellite and mobile phone terminals. Microwave absorbers are essential to reduce the back-radiation of the radiators for high-precision radio navigation systems and mobile communication characterized by low electromagnetic pollution. MM absorbers backing to the solar cell can facilitate the energy absorption of the desired wavelength thereby increasing the efficiency. In similar fashion MM absorbers can be used in thermo-sensing devices useful for military application in which incident electromagnetic radiation will be absorbed by MM absorber and then sensed by a thermometer [9-15].

The design of MM absorber is based on the principle of lossy surface that matches with the free space impedance at resonant frequency [16]. To fulfill this condition, the imaginary part of the refractive index, η (ω), which contributes to the energy loss, should be large. This can be achieved by proper design of the MM structure [17]. At the same time, $\mu(\omega)$ and $\varepsilon(\omega)$ should be the same in order to achieve the condition where MM absorber normalized impedance is $Z(\omega) = 1$ fulfilling the condition of impedance matching of the structure to that of free space [18].

In this paper, a MM absorber is proposed with application in the C-band, X-band, and K_U-band frequency ranges. The continuous concentric annular rings shaped MM structure is chosen to realize the polarization insensitive MM absorber. The geometrical dimensions are parametrically optimized to obtain the maximum absorption at the frequencies of operations. The MM absorber is simulated in commercially available code ñCST microwave studioò. Scattering parameter and absorption coefficient are estimated for this MM absorber. Field patterns and current densities are also monitored to realize the behavior of MM structure.

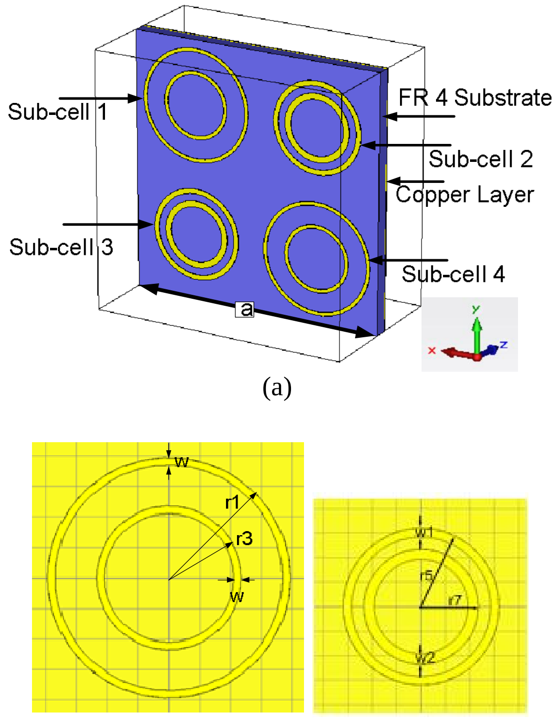
2. Design of multiband metamaterial absorber

The 3-D view of the basic unit cell of the proposed structures is shown in Fig. 1(a). MM structure consists of four sub-cells in which sub-cells 1 and 4 and sub-cells 2 and 3 are identical. The symmetrical concentric annular rings are arranged diagonally. Each sub-cell has two concentric annular loops of different radii and widths. The directions of the electric field, magnetic field, and wave propagation in the structure are in *x*, *y*, and *z*-directions respectively. The wave incidents normally on the front surface of the structure. The proposed structure is fabricated on FR4 substrate (relative permittivity of 4.4 and dielectric loss tangent of 0.02) of 1mm thickness. For the structure in Fig. 1(a), the dimensions of unit cell are a=18 mm, r_1=3.935 mm, $r_2=(r_1 - w)$=3.685 mm, r_3=2.35 mm, $r_4=(r_3 - w)$=2.10 mm, r_5=3.2 mm, $r_6=(r_5 - w_1)$ =2.85 mm, r_7=2.35 mm, $r_8=(r_7 - w_2)$=1.93 mm. The closed rings are made up of copper film of 0.035 mm thickness.

The absorptivity can be found from Eq. (3), where $A(\omega)$, $|S_{11}(\omega)|^2$, and $|S_{21}(\omega)|^2$ are the absorptivity, reflected power, and transmitted power, respectively, of the incident electromagnetic radiation of angular frequency ω,

$$A(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2 \qquad (3)$$

Since, the MM structure is entirely copper laminated on the back side, $S_{21}(\omega) = 0$ and thus Eq. (3) reduces to $A(\omega) = 1 - |S_{11}(\omega)|^2$. Therefore, absorptivity can be maximized by minimization of reflection from the top surface of the proposed structure.



(a)

(b) (C)

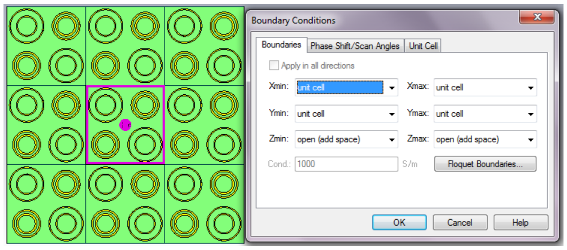
Fig.1. (a) The geometry of a unit cell of MM absorber (a) Perspective view (b) Dimensions of the sub-cells 1 and 3: *a*=18 mm, r_1=3.935 mm, r_3=2.35 mm, *w*=0.25 mm (c) Dimensions of the sub-cells 2 and 4: r_5=3.2 mm, r_7=2.35 mm, w_1= 0.35 mm, w_2= 0.42 mm.

In the proposed structure, the sub cells 1 and 4 are identical with two annular loops, each of width *w* = 0.25 mm. Also, the sub cells 2 and 3 are identical with two annular loops with widths w_1 = 0.35 mm and w_2 = 0.42 mm, respectively. The radii of inner annular loops of sub cells 1 and 3 are same, but their strip widths are different (*w* and w_2) resulting in broader bandwidth response.

3. Results and discussion

The proposed MM structure is simulated using frequency domain solver of the code for normal incidence of the electromagnetic wave. Hexahedral meshing has been used. For the mesh refinement, AR filter module has been adopted. The boundary conditions are shown in Fig. 2. Open boundary conditions are taken along the wave propagation direction i.e. *z*-direction and unit cell periodic boundary conditions are taken along x-direction and y-direction.

The reflection coefficient and absorptivity for this MM absorber are shown in Fig. 3. The absorption peaks appear at four different frequencies 7.102 GHz, 9.104 GHz, 12.558 GHz, and 13.097 GHz with absorptivities of 98%, 98%, 96% and 92%, respectively. The last two frequencies of absorptions are very close, and they provide a broader bandwidth response.


Boundary Conditions

Boundaries | Phase Shift/Scan Angles | Unit Cell

☐ Apply in all directions

Xmin: unit cell Xmax: unit cell

Ymin: unit cell Ymax: unit cell

Zmin: open (add space) Zmax: open (add space)

Cond.: 1000 S/m

Fig.2. Boundary conditions along the MM structure.

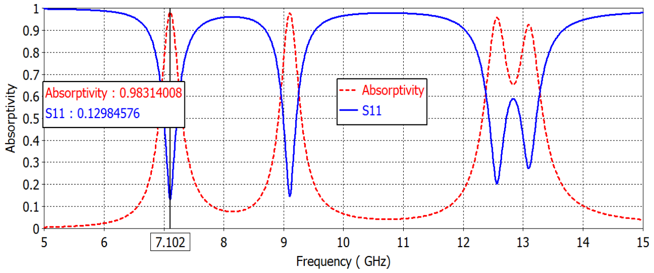
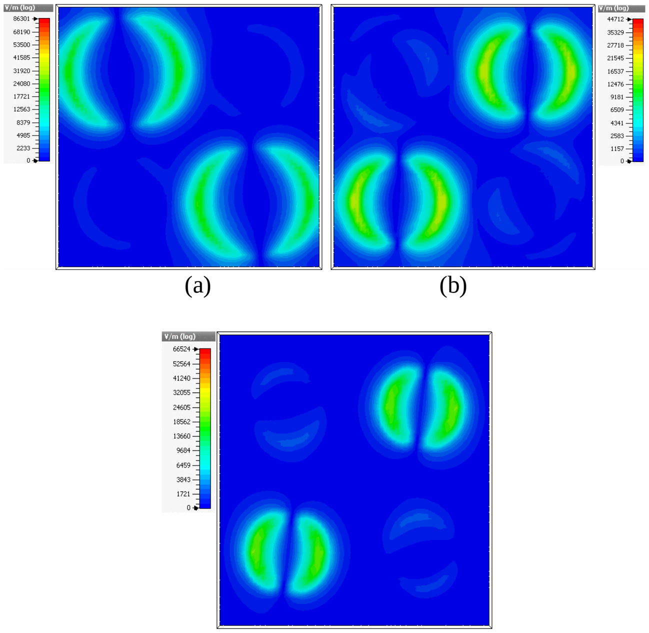


Fig.3. Reflection coefficient and absorptivity of the proposed MM structure.

In order to understand the behavior of MM absorbers, electric and magnetic field distributions are monitored at all resonance frequencies as shown in Figs. 4 and 5. In the Fig. 4, the electric field is concentrated along +*x* and −*x* axes of the ring structures which is parallel to the electric field component of the incident EM waves. At the first resonance frequency 7.102 GHz, the *E*-field is concentrated at the outer ring of sub-cells 1 and 4 (Fig. 4(a)). It reveals that these larger annular rings are responsible for the occurrence of the first absorption peak. The distribution of *E*-field is more concentrated at the outer ring of sub-cells 2 and 3 thereby generating second absorption peak at 9.104 GHz. Similarly, the inner ring of sub-cells 2 and 3 contribute for the occurrence of third absorption peak at 12.558 GHz. Hence, the different annular rings of the unit cell are responsible for the multiband operation of the present MM absorber.

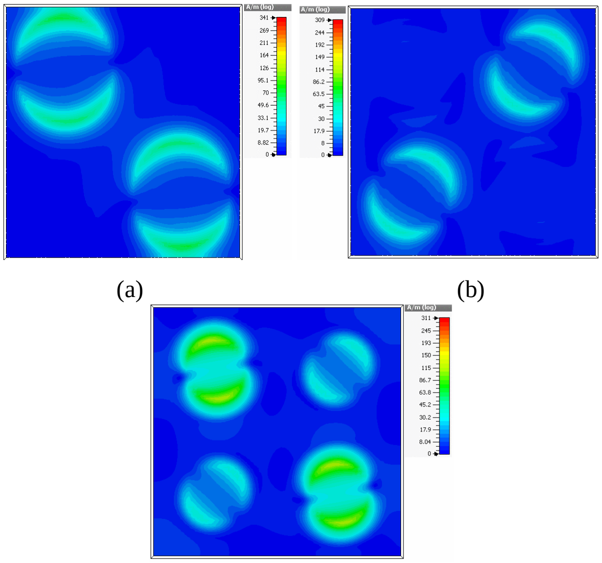
Similar to an electric field, magnetic fields are also monitored which shows that different rings are responsible for the multiband operation. The *H*-field distribution is oriented along +*y* and ï *y*-axes at all the absorption peaks. The surface current distributions on the top surface of the proposed MM structure are shown in Fig. 6, at four different frequencies of 7.102 GHz, 9.104 GHz, 12.558 GHz, and 13.097 GHz. These current distributions also reveal that the individual annular loops are responsible for the absorptions at the distinct frequencies.



(a) (b)

(c)

Fig.4. Electric field distribution in a multiband MM absorber at (a) 7.102 GHz, (b) 9.104 GHz, and (c) 12.558 GHz.



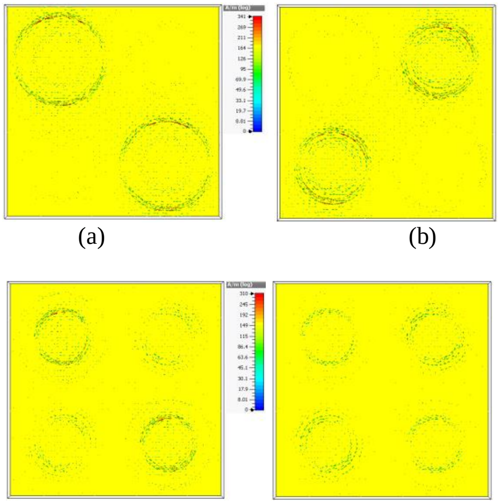
(a) (b)

(c)

Fig.5. Magnetic field distribution in a MM absorber at (a) 7.102 GHz, (b) 9.104 GHz, and (c) 12.558 GHz.

In Fig. 6 (c), the current density contributed by annular rings of sub-cell 1 and 4 for frequency 12.558 GHz is dominant over the inner annular ring of sub-cell 2 and 3. Further, the current density contributed by inner annular ring of sub-cells 2 and 3 for frequency 13.097 GHz is dominant over the inner annular ring of sub-cells 1 and 4 (Fig. 6 (d)).

The proposed MM absorber structure is analyzed for its parametric variation to observe the absorption properties. The variation of an important parameter i.e. angle of incidence (theta) is shown in Fig.7, which depicts the decrement in absorption peaks at frequencies 7.102 GHz, 9.104 GHz, 12.558 GHz, and 13.097 GHz for the different angle of incidence (theta). Fig. 8 shows the numerical variation in absorptivity for various frequencies with variation in the angle of incidence (theta) of radiation. Fig. 8 verifies a regular pattern for the decrement in absorption peaks as shown in Fig.7 where absorption of radiation normal incidence up to 40^{o} is almost constant as the EM energy coupling with the MM absorber structure is matched and beyond an angle of incidence of 40^{o} there is a decrement in the absorption peaks at different frequencies due to mismatching of the field components of the EM energy with the MM absorber structure.



(a) (b)

(c) (d)

Fig.6. Surface current distribution in a MM absorber at the top layer at frequency (a) 7.102 GHz, (b) 9.104 GHz, (c) 12.558 GHz, and (d) 13.097 GHz.

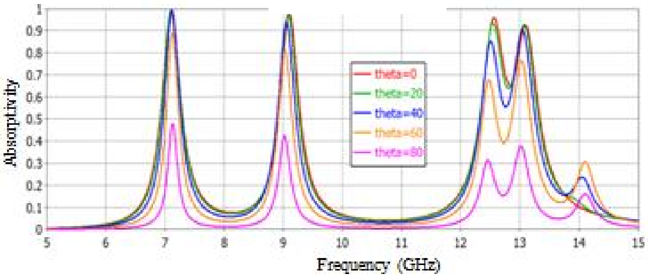


Fig.7. Absorption peaks with variation in angle of incidence (theta).

The proposed MM absorber structure is also parametrically analyzed for the variation in absorption peaks with the variation of E-Field and H-Field orientation (phi). It is shown in Fig. 9. that the absorption peaks are almost same as desired for frequencies 7.102 GHz, 9.104 GHz, 12.558 GHz, and 13.097 GHz for various E-Field and H-Field orientation (phi) values. It shows that the proposed MM absorber structure is polarization insensitive.

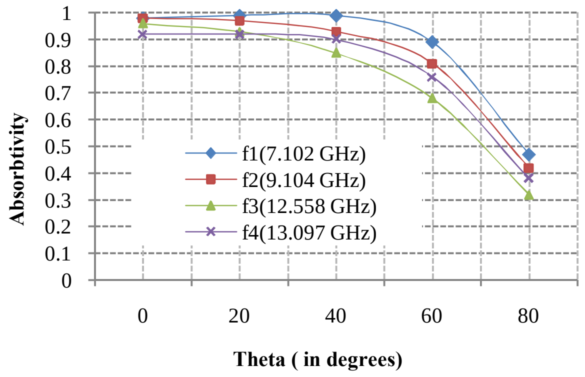


Fig.8. Variation of Absorptivity with angle of incidence (theta) of the radiation.

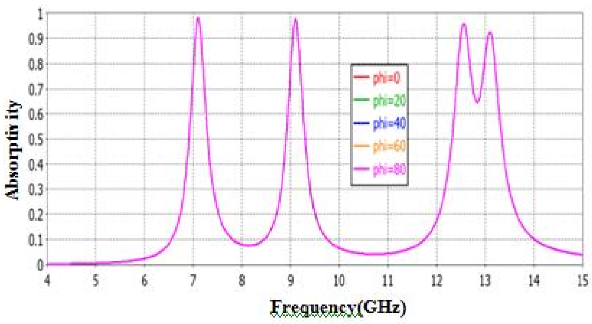


Fig. 9. Absorption peaks with variation of E-Field and H-Field orientation (phi).

4. Conclusion

A concentric continuous rings resonator structure has been proposed for the MM absorber in the microwave frequency range. A new arrangement of concentric annular rings in the unit cell has been presented which provides the multiband operation along with high absorbance of this MM absorber. The radii of annular loops and the widths of theproposed structure have been optimized in such a way that it provides maximum absorption of the received signal at different frequencies of operations. The absorptivity of the present MM absorber has been obtained as 98%, 98%, 96% and 92% absorbance at four different frequencies 7.102 GHz, 9.104 GHz, 12.558 GHz, and 13.097 GHz, respectively along with large bandwidth. The electric and magnetic field patterns and current density profiles in the MM structures have been observed at these frequencies which provide the resonating behavior of different rings. Obviously, the different annular rings are responsible for the occurrence of several absorption peaks. The proposed MM absorber structure found to be polarization insensitive and partial sensitive to angle of incidence beyond the angle of incidence (theta) of 40°. These values of absorptivity and bandwidth can be further improved by introducing the concept of the non-linear arrangement of unit cells.

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Ashutosh Singh received B.Sc. and M.Sc. degrees in Physics from Dept. of Physics, Faculty of Science, BHU, Varanasi, and Ph.D. degree in Electronics Engineering, Indian Institute of Technology (BHU) Varanasi, India, in 2004, 2006 and 2012, respectively. In 2012, he joined Shri Ramswaroop Memorial University, Lucknow-Deva road, U.P., India as an Assistant Professor in Physics. The areas of his current research and publication include modeling and simulation of microwave vacuum electronic devices and their subassemblies, cyclotron resonance measure devices including gyrotrons and gyro-TWTs and their performance improvement, Terahertz Gyrotrons, Photonic Crystal and Metamaterial based Microwave Devices, Numerical Methods.

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