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Effect of Bending Unit Cell of Circular Split Ring Resonator on Optical properties

Widad Hamza Tarkhan Sundus .Y. Hasan
University of Kufa / Education College for Girls/ Physics Department

Widadh.alamiry @uokufa.edu.iq
sundus.alasadi @uokufa.edu.iq

Abstract:

In this work, bending one unit cell of a circular Split Ring Resonator (SRR) was demonstrated with different curvature angles (0°, 10° .. 90°), within a frequency range about (11-16) GHz. The optical properties of the metamaterial, such as electric permittivity (ε), magnetic permeability (μ), refractive index (n), and impedance (Z) were studied. The results showed that all the resonant frequencies were slightly shifted to higher values as the bending of the unit cell increased. It can be concluded that controlled bending or deformation can serve as a tuning mechanism for SRRs, enabling dynamic control of their electromagnetic properties.

keywords: Metamaterial, unit cell bending, S-parameters. Optical properties

1. Introduction:

A metamaterial is an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties. The structural units of a metamaterial, known as meta-atoms or meta-molecules, must be substantially smaller than the wavelength being considered, and the average distance between neighboring meta-atoms is also subwavelength in scale[1]. The term metamaterial originates from the Greek word "meta" (which means beyond) and refers to artificially made materials with constitutive parameters (CP) that are not available in the conventional materials, i.e. materials that cannot be found in the nature[2]

During recent years, Metamaterials have generated a tremendous amount of research interest due to their extraordinary response to electromagnetic waves. The engineered structures of metamaterials replace the atoms and molecules that determine the overall electromagnetic response of a conventional material. Because of the smallness of the structuring in comparison with the wavelength of the light electromagnetic wave, the incident electromagnetic radiation encounters a nearly homogeneous material during wave-material interaction[3].

It is well known that the response of a system to the presence of an electromagnetic field is determined to a large extent by the properties of the materials involved. We describe these properties by defining the macroscopic parameters permittivity ε and permeability μ of these materials. This allows for the classification of a medium as follows. A medium with both permittivity and permeability greater than zero ($\varepsilon>0$, $\mu>0$) will be designated a double positive (DPS) medium. Most naturally occurring media (e.g., dielectrics) fall under this designation. A medium with permittivity less than zero and permeability greater than zero ($\varepsilon<0$, $\mu>0$) will be designated an epsilon-negative (ENG) medium. In certain frequency regimes many plasmas exhibit this characteristic. For example, noble metals (e.g., silver, gold) behave in this manner in the infrared (IR) and visible frequency domains. A medium with the permittivity greater than zero and permeability less than zero ($\varepsilon>0$, $\mu<0$) will be designated a mu negative (MNG) medium. In certain frequency regimes some gyrotropic materials exhibit this characteristic[4,5].

Artificial materials have been constructed that also have DPS, ENG, and MNG properties. A medium with both the permittivity and permeability less than zero ($\varepsilon<0$, $\mu<0$) will be designated a DNG medium. To date, this class of materials has only been demonstrated with artificial constructs. This medium classification can be graphically illustrated as shown in Figure (1) [6].

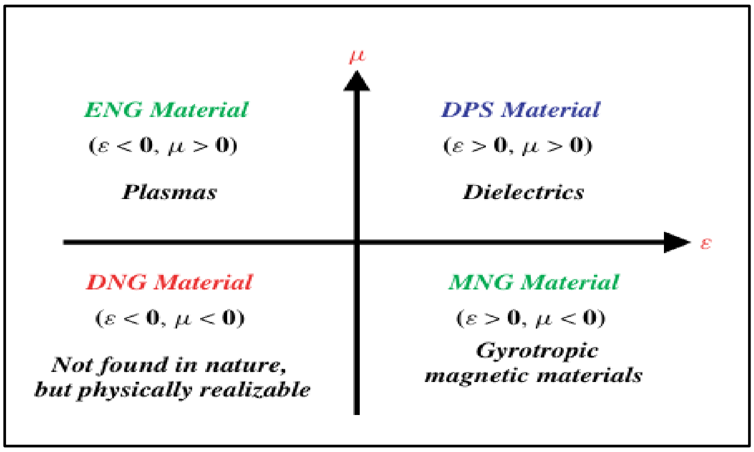


Figure (1): Material classifications.

Metamaterials, also known as left-handed metamaterial(LHM) is a material that have simultaneously negative value of permeability and permittivity. LHM is an interesting material to be investigated where this artificial material has several unique properties such as the backward wave and the focusing effect inside it slab [7]. The history of LHM was started from Veselago when he made a theoretical speculation of this artificial material that exhibit negative permittivity and negative permeability[8].

For metamaterials with negative permittivity and permeability, several names and terminologies have been suggested, such as media with “negative refractive index” (NRI), “backward-wave media” (BW media) and “double-negative (DNG)” metamaterials [9].

Bending a unit cell of a Circular Split Ring Resonator (SRR) has significant effects on its performance and electromagnetic constitutive parameters. Studies have shown that bending impacts the retrieved values of these parameters, crucial for designing flexible and conformal microwave and optical devices. The bending effects on SRRs, which are fundamental components of left-handed metamaterials, are essential to consider for future microwave and optical applications[10]. Numerical simulations have demonstrated that bending alters the constitutive parameters, emphasizing the importance of accounting for such changes when designing flexible metamaterials[11]. Understanding the impact of bending on SRRs is crucial for optimizing their performance and ensuring the effectiveness of metamaterial-based devices in various applications.

2. Results and discussion

The circular SRR design made of cupper, Cu, is placed on the front face of an insulator substrate (SiO_2) with a rod (Cu) on the back face of the substrate. The geometrical structure parameters (SRR- rod), like radii of the outer ring (R_1=1.1mm) and (R_2=0.9mm), the radii of the inner ring (r_1=0.8mm) and (r_2=0.6mm), width gaps (g=0.2mm) ,the width of the rings (wt=0.2mm), thickness of rings and rod (t=0.025mm),distance between the rings (d=0.1mm), side length of insulator substrate (a=2.5mm), thickness of insulator substrate(h=0.25mm) and width rod(s=0.14) were kept constant each times. As shown in Figure (2).

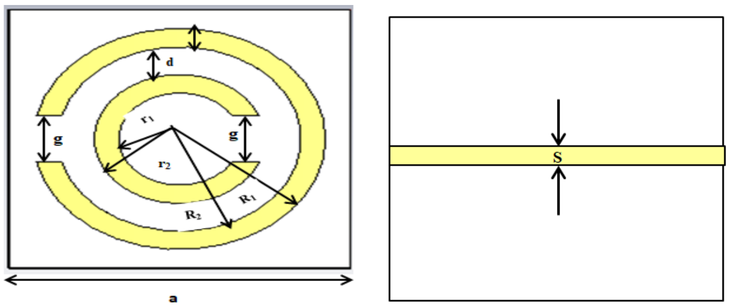


Figure (2): A typical unit cell contains (c- c) SRR with metallic rod rested on the dielectric board

The reflection (S11) and transmission (S21) coefficients, of the electromagnetic EM wave passing through the cell were calculated using CST microwave studio (Computer Simulation Technology). These coefficients were used to determine the optical properties of the designed metamaterial, such as magnetic permeability μ, electric permittivity ε, refractive index n, and impedance Z.

In this work, bending one unit cell of circular SRR design was made with different curvature angles from (0°, 10° .. 90°). The degree of curvature is defined as the central angle to the ends of an agreed length of either an arc or a chord[12]. various lengths are commonly used in different areas of practice. This angle is also the change in forward direction as that portion of the curve is traveled. In an n-degree curve, the forward bearing changes by n degrees over the standard length of arc or chord) for frequency range (11- 16) GHz, as shown in Figures (3,4):

Degree of curvature can be converted to radius of curvature by the following formulae:

$$r = \frac{180^{o}A}{\pi D_c} \qquad (1) \qquad \text{(Formula from arc length)}$$

$$r = \frac{C}{2\sin\left(\frac{D_c}{2}\right)} \qquad (2) \qquad \text{(Formula from chord length)}$$

Where (A and C) are the arc and chord lengths , (r) is radius of curvature and (D_c) is degree of curvature.

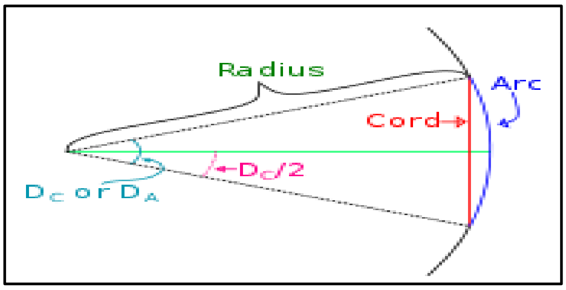
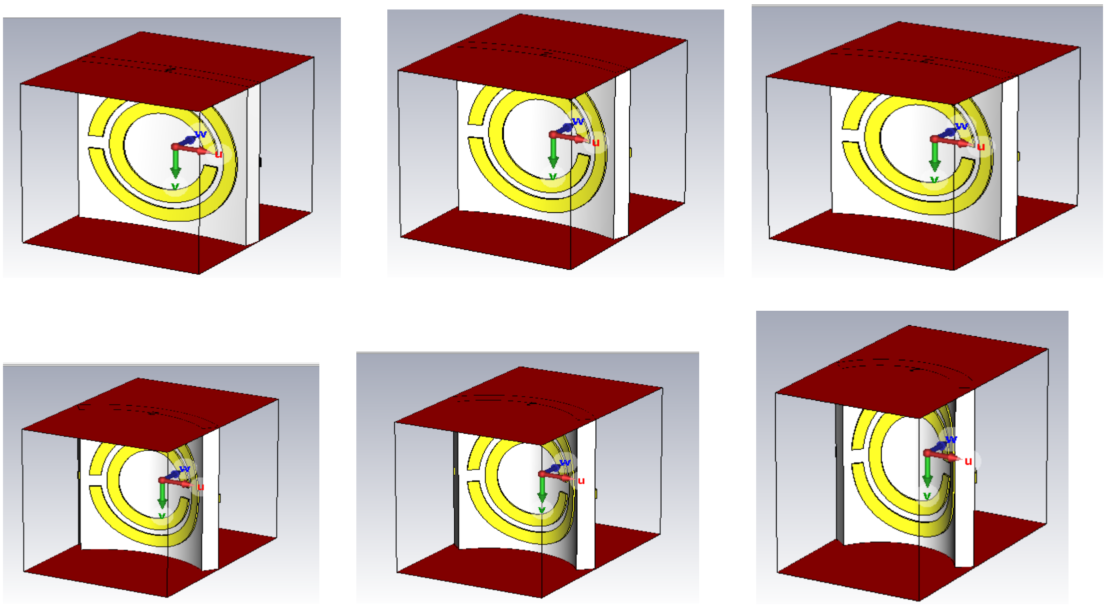


Figure (3): Different parts of the curve



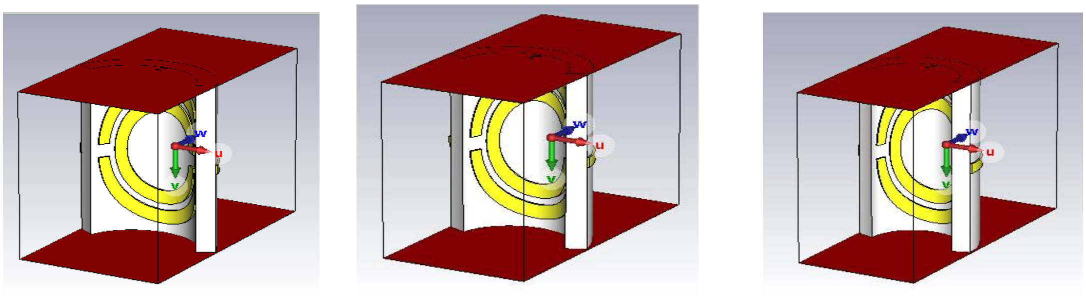
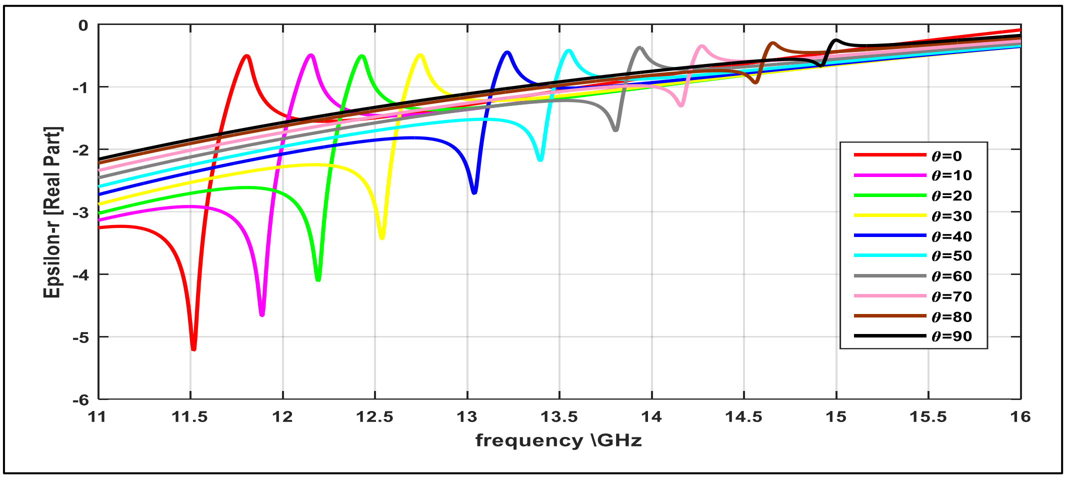


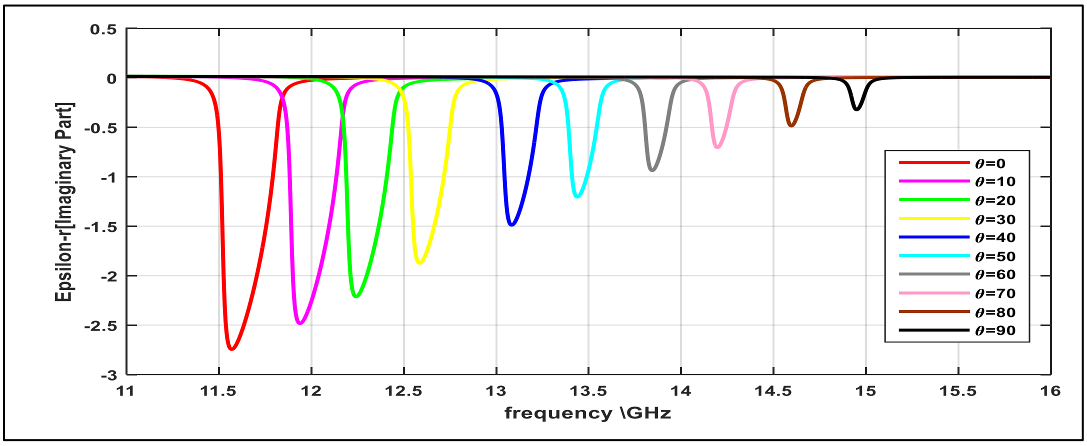
Figure (4): Bending a unit cell circular SRR design with different of curvature angles from (0°, 10° .. 90°).

2.1- Electric permittivity (ε)

Figure 5 shows the effect of bending of the unit cell on real and imaginary parts of permittivity (ε_{eff}), where the real part is related to the storage of energy in the material, while the imaginary part is about the energy dissipation. The curves of real and imaginary parts were shifted to the right as the curvature angle increased. This can be explained because the bending of the unit cell affects its effective capacitance and inductance, which in turn alters the real and imaginary parts of permittivity. The resonance frequency for minimum value of ε is increased from (11.7 Hz) for 0° to (15Hz) for 90°, this because the resonance frequency is determined by the orientation and geometry of the SRR, its effective dimensions change as the bending change. This geometry alteration affects the resonance frequency, and by bending the net capacitance and inductance were decreased so the resonance frequency will increased. The figure also shows the area of negative region is decreased, this means that the unit cell bending can lead to reduce the negative region area due to changes in the resonant behavior and electromagnetic response of the SRR, and the metamaterial behavior is decreased.



(a)

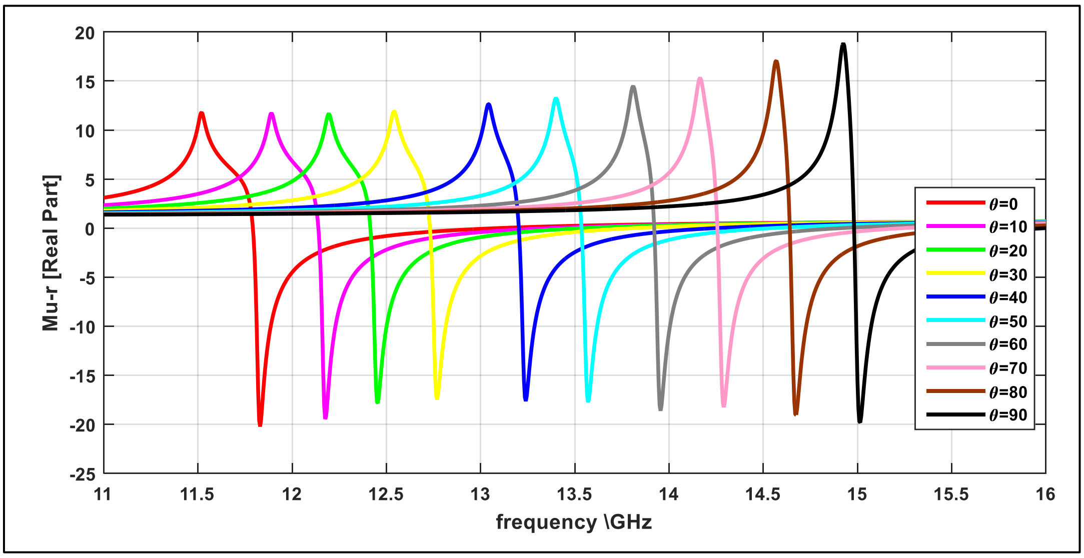


(b)

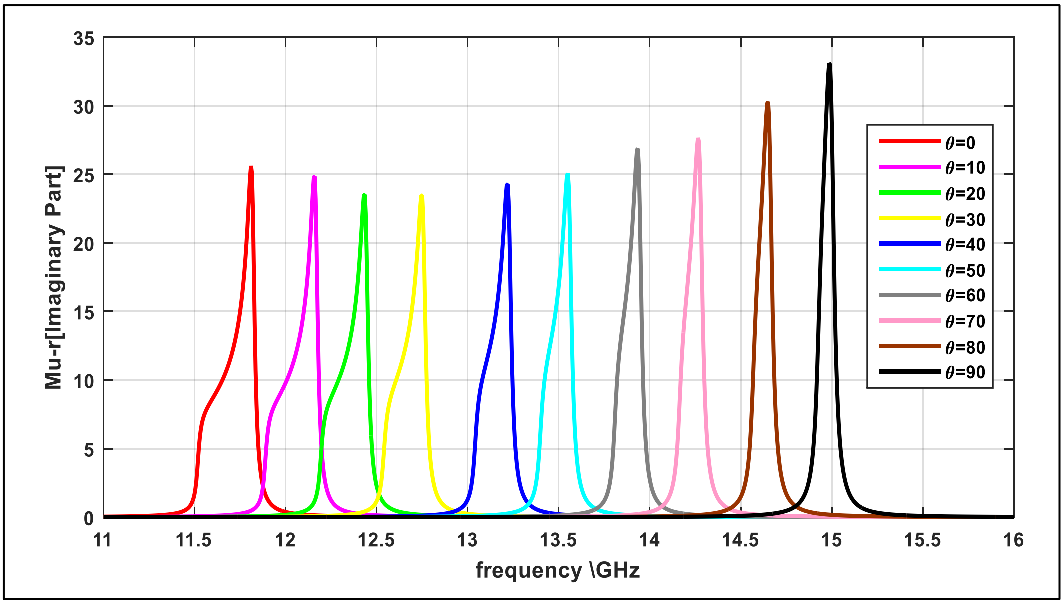
Figure (5): electric permittivity (ε_{eff}) of bending a unit cell circular a) Real part b) Imaginary part

2.2- Magnetic permeability (μ)

Figure 6 shows the effect of unit cell bending on permeability (μ_{eff}). The curves of real and imaginary parts were shifted also to the right. The resonant frequency for minimum negative μ value is increased as the bending of unit cell increased, (11.8Hz) for 0° to (15Hz) for 90°. While the area of negative region remain nearly constant. This means bending the unit cell may not significantly impact the effective magnetic properties responsible for the negative region.



(a)

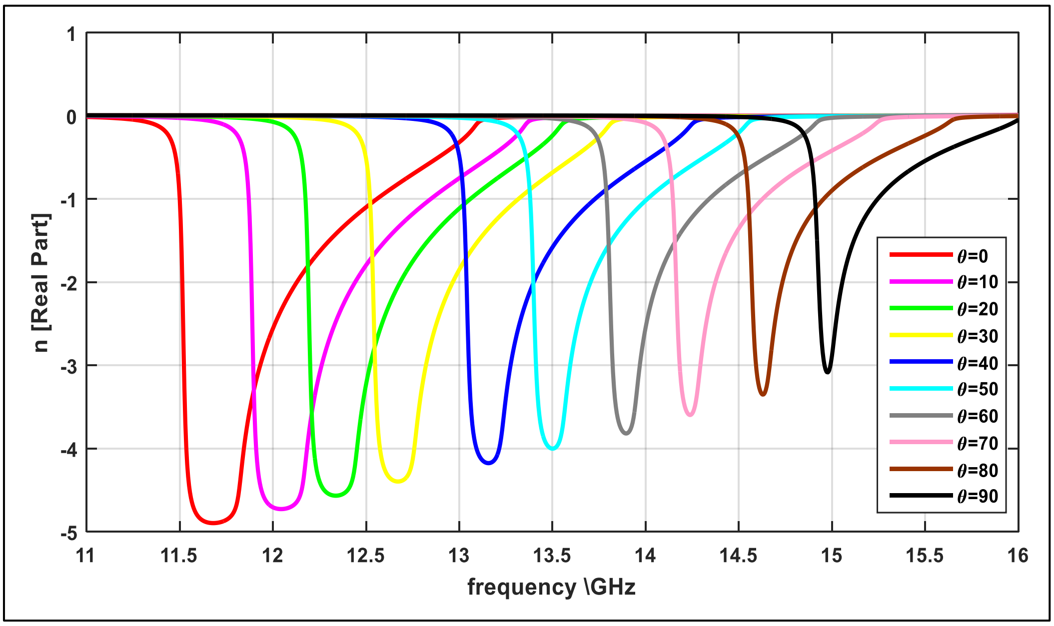


(b)

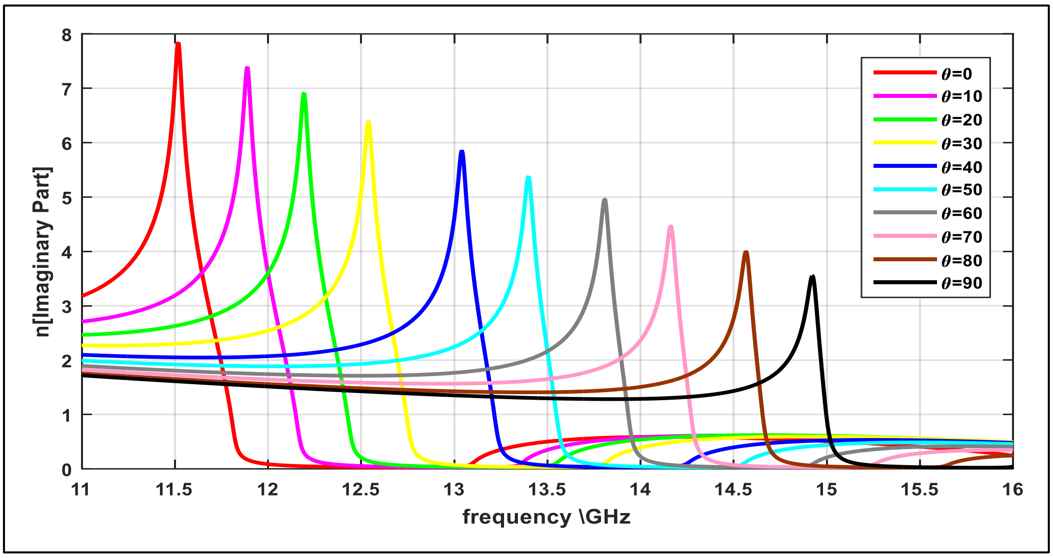
Figure (6): magnetic permeability (μ_{eff}) of bending a unit cell circular a) Real part b) Imaginary part

2.3- Refractive index (n)

Figure 7 represents the real and imaginary parts of (n_{eff}) for different bending of the unit cell. Also the figures showed a slight shift to the right, and the resonant frequency for minimum negative value of the real part is increased from (11.7 Hz) for 0o to (15Hz) for 90o, while the negative region area is decreased with the increasing the value of bending.



(a)

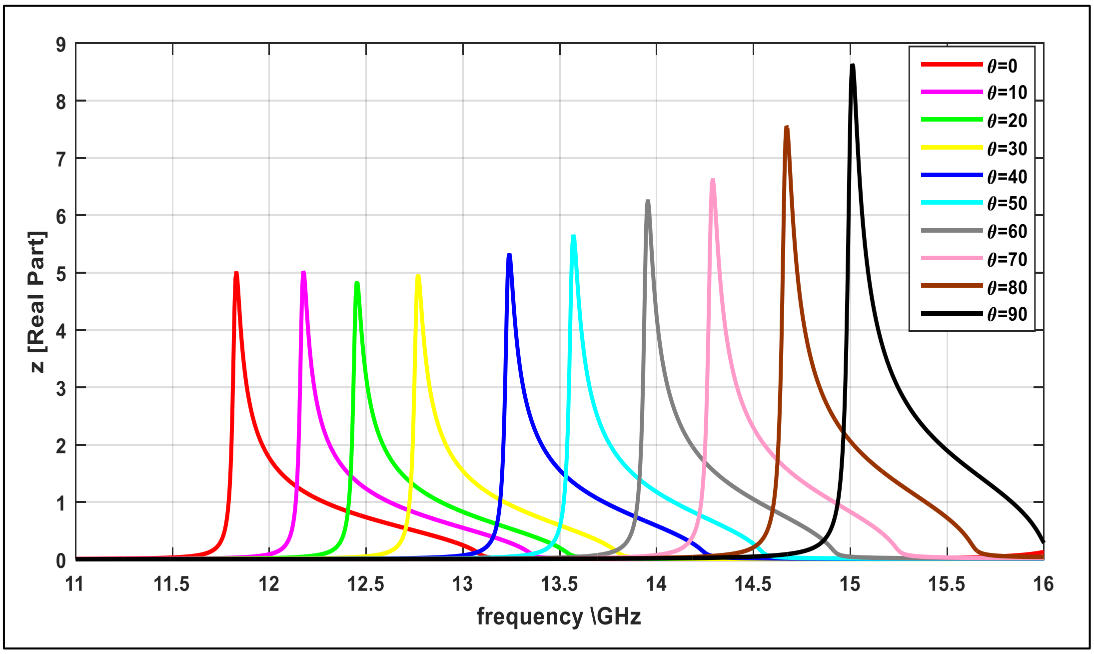


(b)

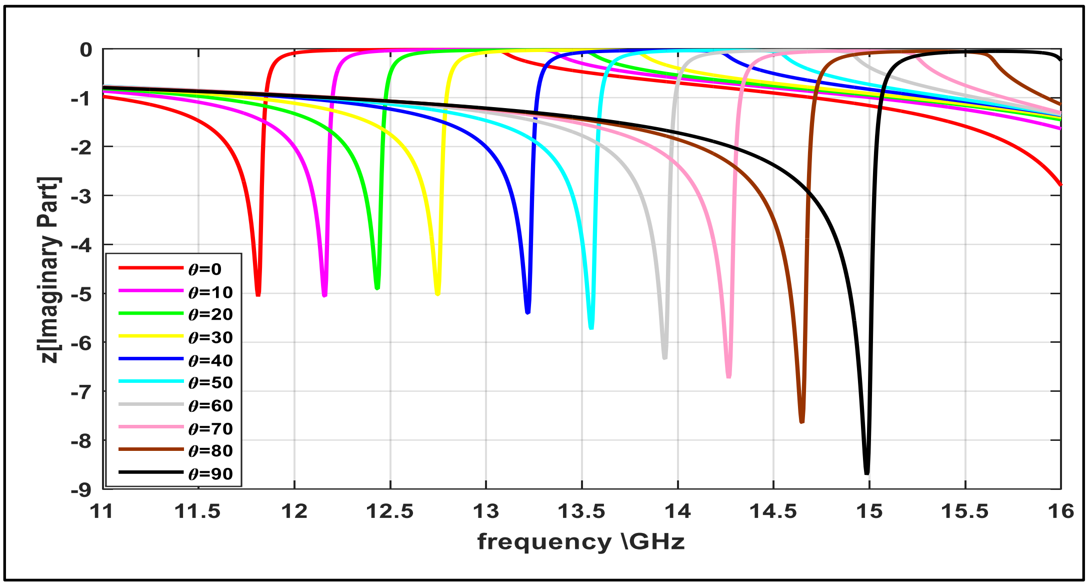
Figure (7): refractive index (n_{eff}) of bending a unit cell circular a) Real part b) Imaginary part

2.4- Impedance (Z)

Figure 8 represent the real and imaginary parts of (Z_{eff}) when a unit cell is bended. Also the figures showed a slight shift to the right, and the resonant frequency increases as the bending of unit cell increases. The curves of impedance (imaginary part) for region of negative values increased as the bending of cells increased.



(a)

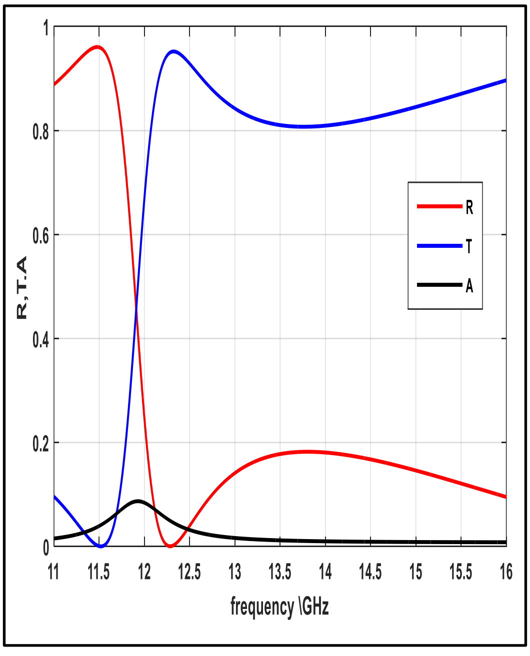


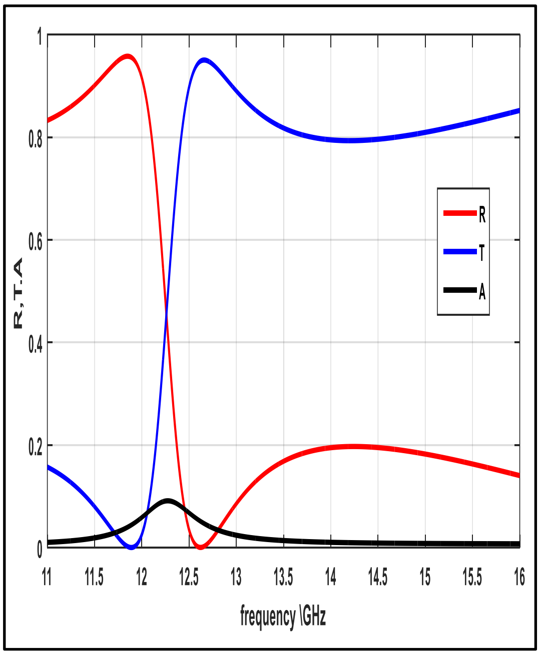
(b)

Figure (8): Impedance (z_{eff}) of bending a unit cell circular a) Real part b) Imaginary part

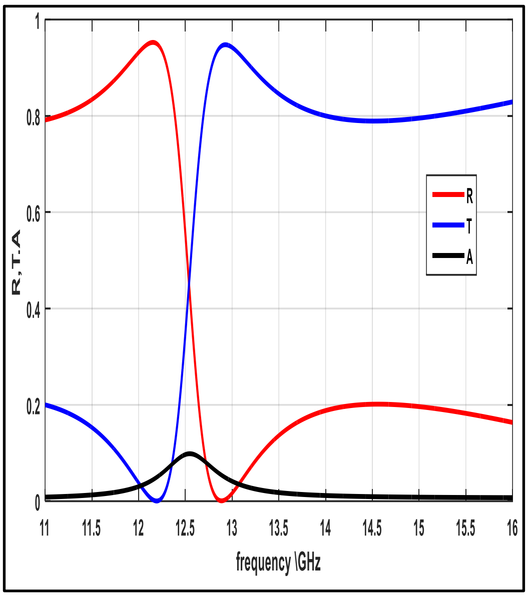
2.3- (Reflectivity (R), Transmissivity (T), and Absorptivity (A))

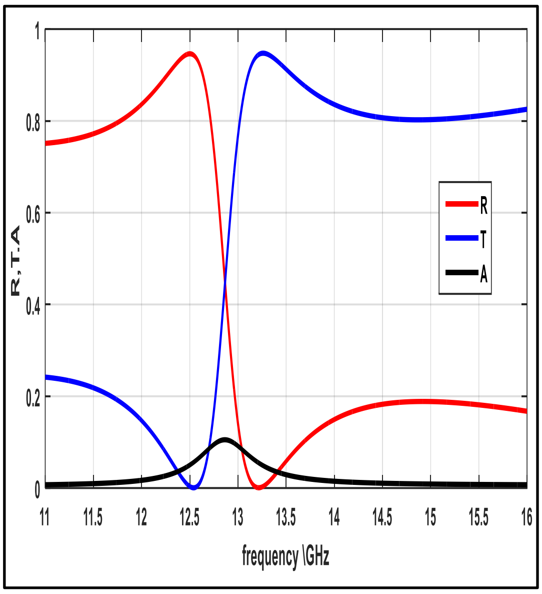
Figure (9) explains the reflectivity (R), transmissivity (T) and absorptivity (A) for bending curvature (0º , 10º .. 90º). It can be observed that at frequencies bellow (11.9, 12.3, 12.6, 12.8, 13.3, 13.7, 14.2, 14.4, 14.9, and 15.2 GHz), the unit cell reflect more power than it transmits or absorbs, while at frequencies above those values, the unit cell transmits more power than it reflects or absorbs. Additionally, it is evident that maximum absorption occurs when the reflection and transmission powers are equal.



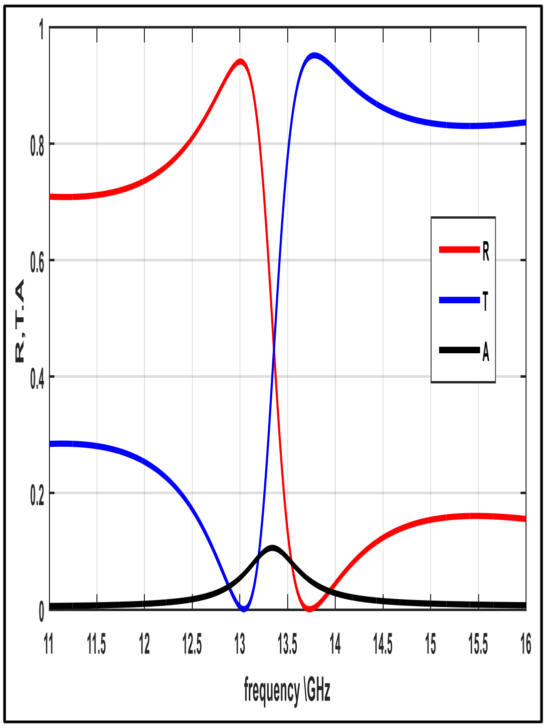


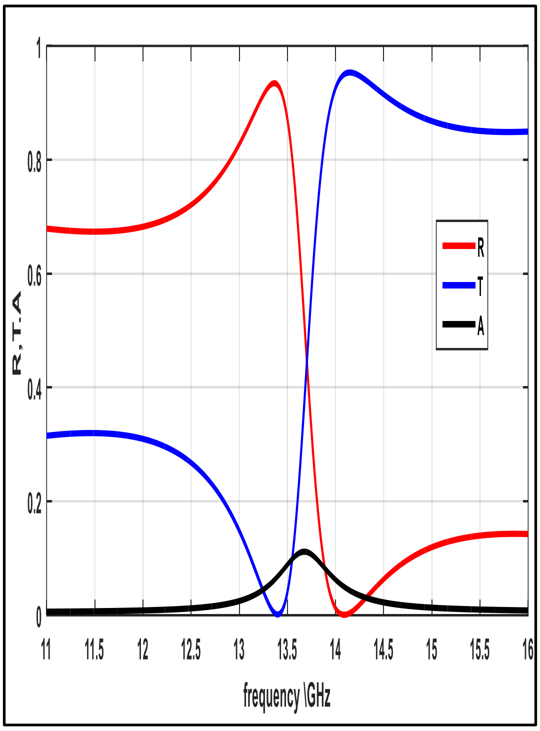
(a) (0º) (b) (10º)



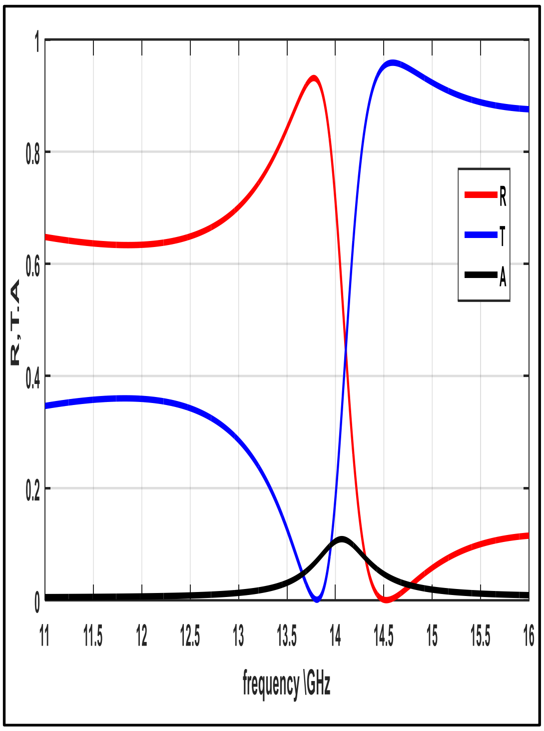


(c)(20º) (d)(30º)

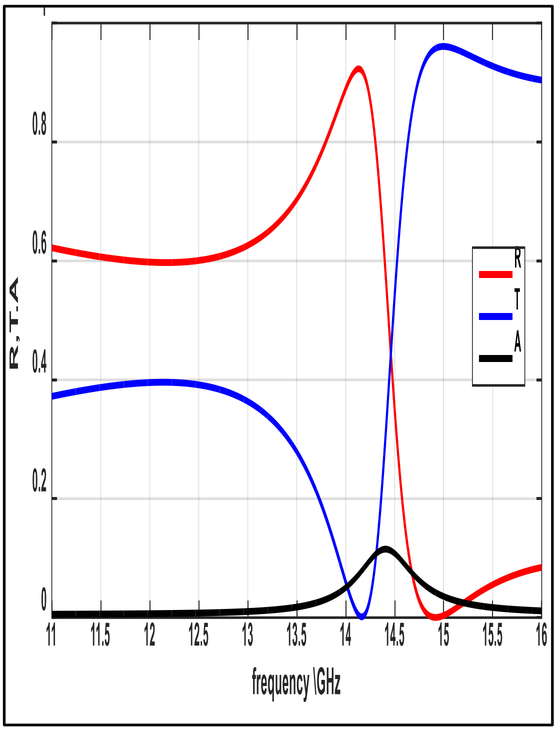




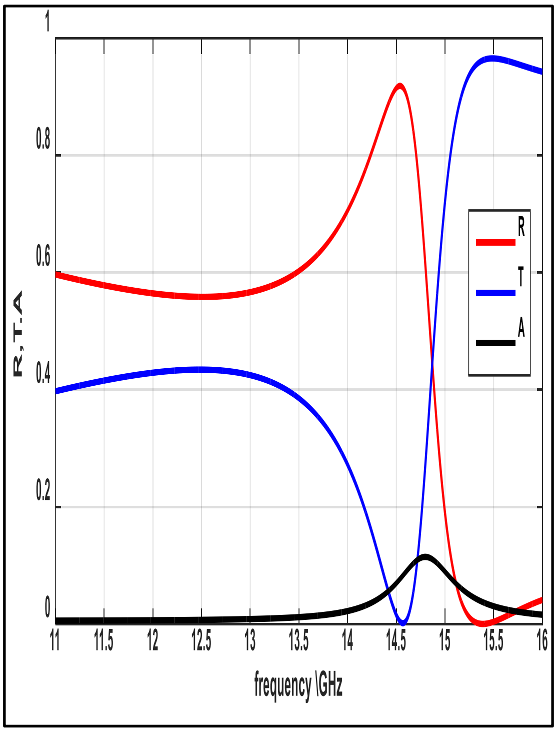
(e) (40º) (f)(50º)



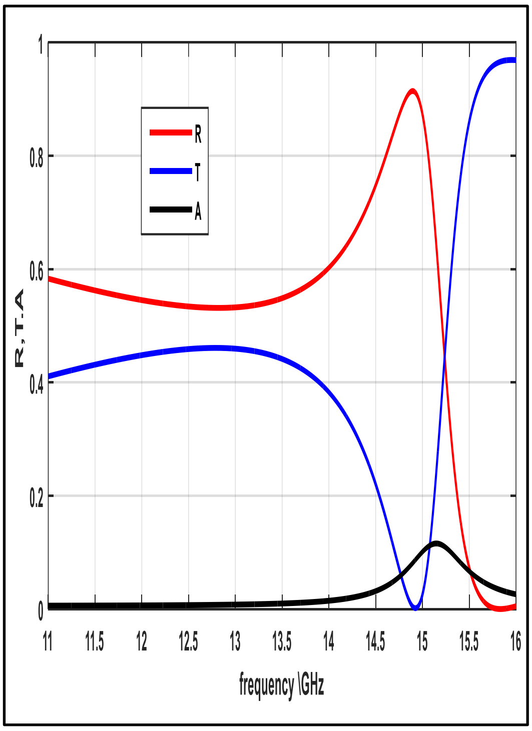
g(60º)



h(70º)



(i) (80º)



(j) (90º)

Figure (9): Reflectivity (R), Transmissivity (T), Absorptivity (A),
Bending a unit cell circular design with different of curvature angles.

3.Conclusions

The bending of split-ring resonators (SRRs) can have several effects depending on the curvature angle of the bending and the material properties involved, as follows:

1. **Shift in Resonant Frequency:** Bending can cause a shift in the resonant frequency of the SRRs. This shift can be due to changes in the effective capacitance and inductance in the L-C cuircuit corresponding to SRR due to bending.
2. **Change in Electromagnetic Response:** The bending can alter the electromagnetic response of the SRRs, affecting parameters such as the reflection and transmission coefficients, as well as the resonator's magnetic permeability and electric permittivity.
3. **Mechanical Stress Effects:** Bending introduces mechanical stress in the SRRs, which can affect their structural stability, durability, and overall performance.
4. **Tuning and Control:** Controlled bending or deformation can also be used as a tuning mechanism for SRRs, allowing for dynamic control of their electromagnetic properties.

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