

A Study of Dielectric Effects on Resonance Frequency of a Split Ring Shaped Inclusion

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ABSTRACT

Resonator designs are central to the development of subwavelength unit structures of metasurfaces to create exotic and unique electromagnetic properties by modifying the host structure to tune impinging electromagnetic waves. The act of intentional control of propagating electromagnetic fields are actively being explored in wireless radio environment control for sixth generation (6G) and beyond. In this paper, we study the effect of dielectric properties on electric field distribution and resonance frequency of a circular split ring resonator (SRR). The subwavelength resonator structure is modelled and simulated using High Frequency Structure Simulation (HFSS) software. Rogers R03003 and R03210 were used at different thickness to study the field distribution and its effect on resonance frequency of the SSR. The results show a decrease in resonance frequency of 38.41% from R03002 (lower relative permeability of 3) to R03210 (higher relative permeability of 10.2). With change in Rogers R03210 thickness from 1mm to 1.525mm, the resonance frequency has changed from 5.5GHz to 5.2313 GHz. This indicates that the material composition of the substrate and the physical dimension of the SRR unit cell affects the resonance frequency of the structure.

Keywords: Split Ring Resonator, Electromagnetics, Metasurfaces, Relative permeability, Resonance frequency.

INTRODUCTION

In 19678, Viktor Veselago predicted a material that possesses simultaneous negative permittivity and negative permeability and explained the potential of using materials with such unusual properties to alter the phase of propagating electromagnetic fields impinging on the material. The physics of the existence of such materials was mathematically demonstrated (Veselago ,1968). The discovery of artificially engineered materials that exhibit exotic and unique properties predicted by Veselago gave an impetus to the

development of electromagnetic metasurfaces. However, the wide application of metamaterial is limited due to challenges in fabricating the 3D structure, bulky profile, and high material dispersion (Hu et al., 2021; Ding et al., 2015; Estakhri and Alu, 2016).

The practical realization of 2D metamaterial structure was developed using a set of circular or rectangular split ring resonators to achieve the desired electrical and effective material properties that cannot be found in nature (Pendry, 1999; Pendry and Smith, 2003). Periodic arrangement of 2D subwavelength unit cells called scatterers on dielectric materials can control the phase, absorption and amplitude of electromagnetic waves in wireless assisted communications (Holloway, et al, 2019; Wu and Zhang, 2019). Ease of fabrication coupled with low dispersion loss of metasurfaces, make it possible to design and fabricate thin surfaces that can spatially vary the distribution of electromagnetic waves.

Split Ring Resonator (SRR) fabricated on FR-4 substrate has been used in frequency selective-based metasurfaces applications (Perez-Adan et al., 2021; Khana et al., 2019). SRR, at resonance frequency, has shown negative permeability and negative permittivity (Sydoruk et al., 2009; Pendry, 1999; Smith and Pendry, 2006; Wu et al., 2006). SRR can be designed to accommodate different frequencies range and applications in IRS. Arrays of SRR in matrix forms the IRS, and each element can be independently controlled in real-time using software. In this paper, we study the effect of permeability and thickness of dielectric substrate on electric fields distribution and resonance frequency of the SRR subwavelength unit cell. The paper is organised into five sections. In Section II, the theory and mathematical principles are laid out. Section III presented materials and methods of the paper, and specifications of the circular split ring resonator structure. In Section IV, the results of the simulation are discussed. Finally, Section V concludes and summarize the main results of the modelling and simulations.

THEORETICAL ANALYSIS

Split Ring Resonators (SRR) are artificially engineered structure that manipulate electromagnetic fields at certain frequencies. They have demonstrated a promising application in the development of metasurfaces and Intelligent Reflecting Surfaces (IRS). SRR are fabricated on a suitable dielectric material to provide frequency selectivity (Perez-Adan et al., 2021; Khana et al., 2019). SRR, at resonance frequency, has shown to have negative permeability and negative permittivity (Sydoruk et al., 2009; Pendry, 1999; Smith and Pendry, 2006; Wu et al., 2006). Design of Metamaterials based on dual frequency band with centre at 9.69GHz and 11.1GHz has been investigated using SRR as the primary structure, and triple frequencies have been proposed (Khanna et al., 2019). The results indicated that SRR are capable of being frequency selective element. SRR can be designed to accommodate different frequencies range and applications in IRS.

MATERIALS AND METHODS

The unit cell structure is designed and modelled using circular split ring copper inclusion on Roger's substrate. The selected substrates are Rogers RO3003 and R03210 having a relative permittivity of 3 and 10.3 respectively. Fig. 1 shows the modelling of the SRR on dielectric Roger's substrate. The outer rings have a radius of 2.4mm while the inner radius of the concentric circles is 0.4mm. The thickness of the copper inclusion on the substrate is 0.1mm.

The physical dimension (length or width) of the unit cell is such that it is less than wavelength of the propagating electromagnetic waves ($L < \lambda$).

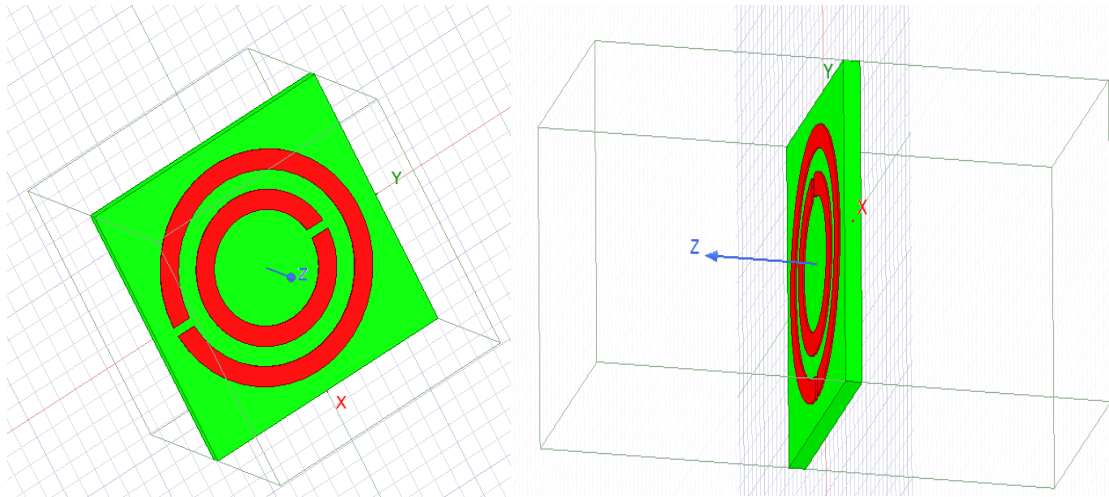


Fig.1. Double Split Ring Resonator on Rogers substrate.

To study the effect of variability of length and permittivity on field distributions and resonance frequency on the SRR structures, substrate thickness of 1 and 1.525mm were used. Thus, the total cell dimension of the structure including the floquet ports is 14mm x 14mm x 1mm and, in subsequent simulation, structure dimension of 14mm x 14mm x 1.525mm was used.

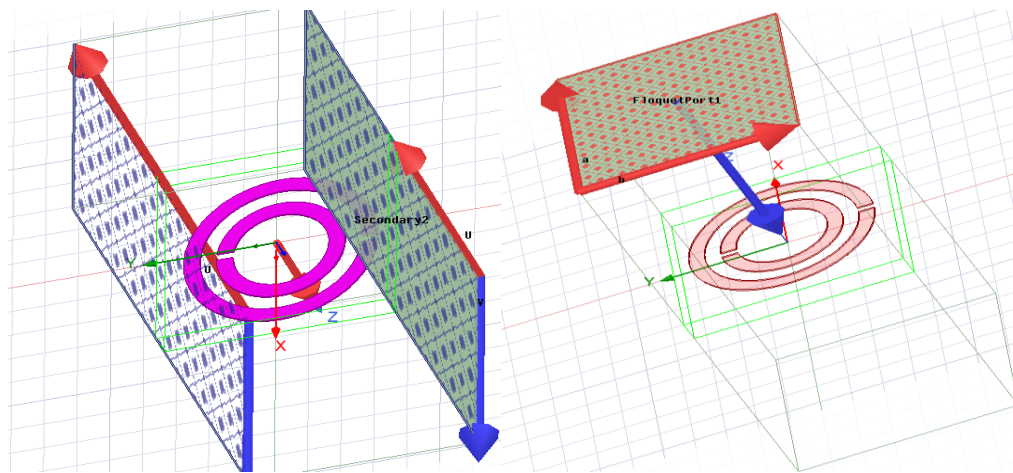


Fig.2. Master/Slave and Floquet port boundary conditions.

The modelling of the SRR cell structure using HFSS is shown in fig. 2 with the boundary and excitation ports. The wave is propagated in z-direction as indicated in Fig.2. The Floquet ports are situated directly above and below the SRR cell structure at 15mm on either side of the port. Master/Slave boundary conditions was applied to the structure to simulate the S-parameters.

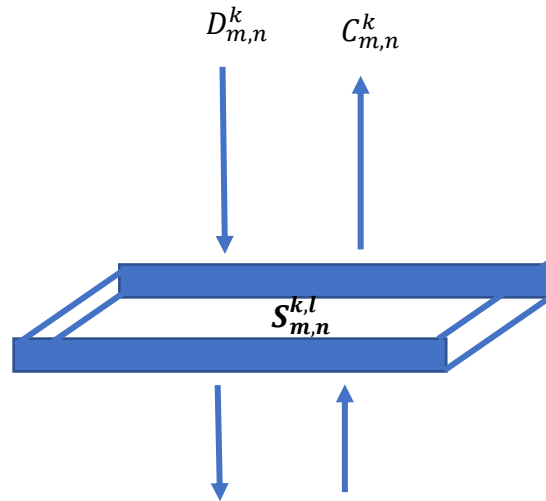


Fig.3. Structure surface showing incident, reflected and scattered waves.

The electric field for the structure is solve at excited frequency using,

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times E \right) - k_0^2 \varepsilon_r E = 0 \quad (1)$$

And the magnetic field strength is computed using the following equation,

$$H = \frac{1}{\omega \mu} \nabla \times E \quad (2)$$

The relationship between scattering wave, S-parameters and incident waves is given in vectorial equation

$$\vec{C}_{mn}^k = S_{mn}^{k,l} D_{mn}^k \quad (3)$$

Where: $\vec{C}$ is the scattering wave vector, $\vec{S}$ is the S-parameters vector, $\vec{D}$ is the incident wave vector and the mode is given by $m, n \in \{1, 2\}$ and $k, l \in \{TE, TM\}$.

RESULTS AND DISCUSSION

This section presents the results of the cell structure simulation using HFSS at variable substrate thickness and permeabilities.

RO3003 Substrate

The SRR cell structure modelled on RO3003 substrate with relative dielectric permeability of 3 and thickness of 1mm is simulated at the frequency of 10 GHZ. The scattering parameters and resonance frequency of the structure are determined from the software simulation.

The SRR cell structure attained resonance at 9.0125 GHZ. The reflection coefficient, S_{11} , at port mode (1,1) was obtained to be -26.7802 db. Fig.4 shows the plot of resonance characteristics of the SRR cell structure. As the excitation frequency is approaching

resonance, the S11 parameter, sharply decrease in amplitude (dB) to point. At resonance frequency, S11 reached the minimum value of -26.7802 dB and appreciably rise as the excitation frequency increases beyond the resonance frequency. The decrease in amplitude is caused by unique and exotic properties of SRR at the point where permittivity and permeability of the structure's material are both negative.

Similar, the transmission coefficient of the cell structure was simulated as shown in fig.5. The plot describes the behaviour of the SRR structure using Floquet Port 1 in mode 1 and Floquet port 2 in mode 2 (S12), and Floquet Port 1 in mode 2 and Floquet port 2 in mode 2. Scattering at port 2 in mode 2 consequence of port 1 indicates that the structure achieved resonance at 5.4875 GHz with -34.5305 dB and at 10.4313 GHz with -43.2414 dB.

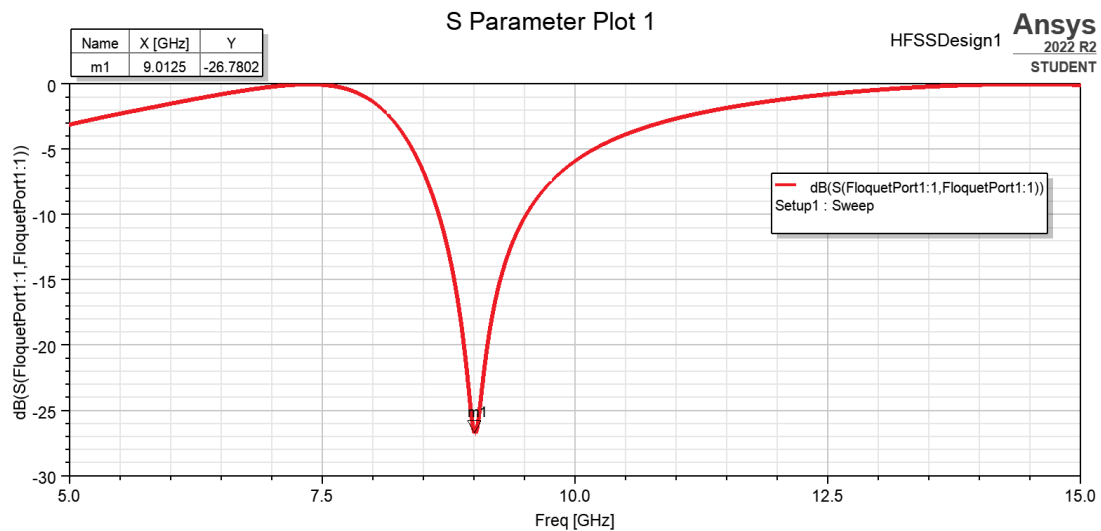


Fig.4. S-parameters, S11, at the face of the SRR with Rogers RO3003 substrate thickness of 1mm.

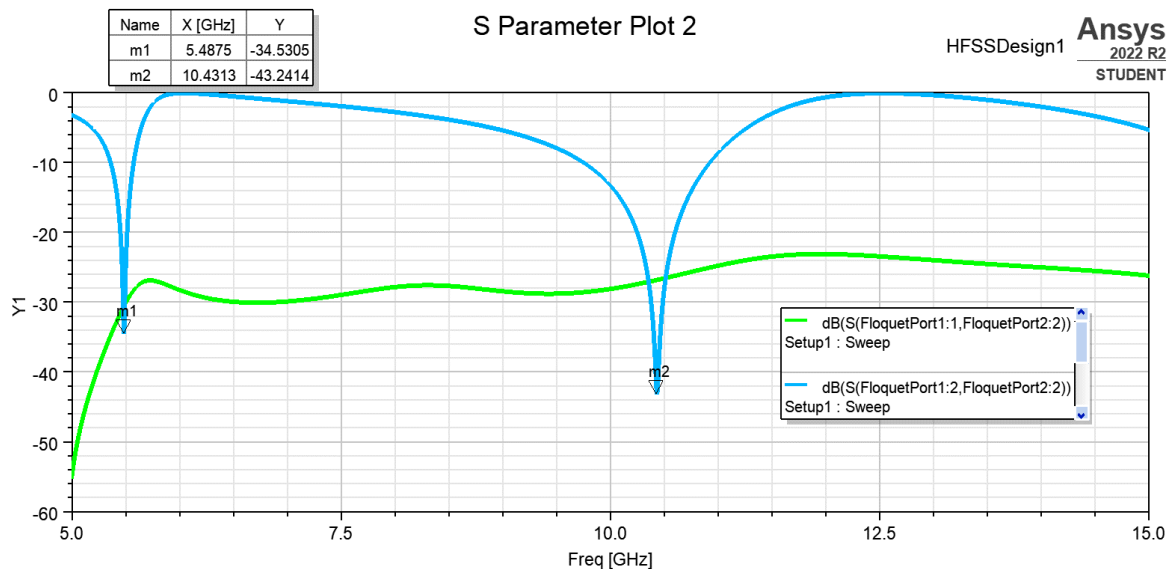


Fig.5. S-parameter S12 at mode (1,2) and S12 at mode (2,2) with Rogers RO3003 substrate thickness of 1mm.

Field distribution over the SRR surface is studied. The electric field vector is moving in y-direction and perpendicular to the z-axis while the magnetic field vector is pointing in x-direction perpendicular to both x-axis and y-axis. Fig.6 and 7 show intensity of field strengths and field directions over the SRR structure.

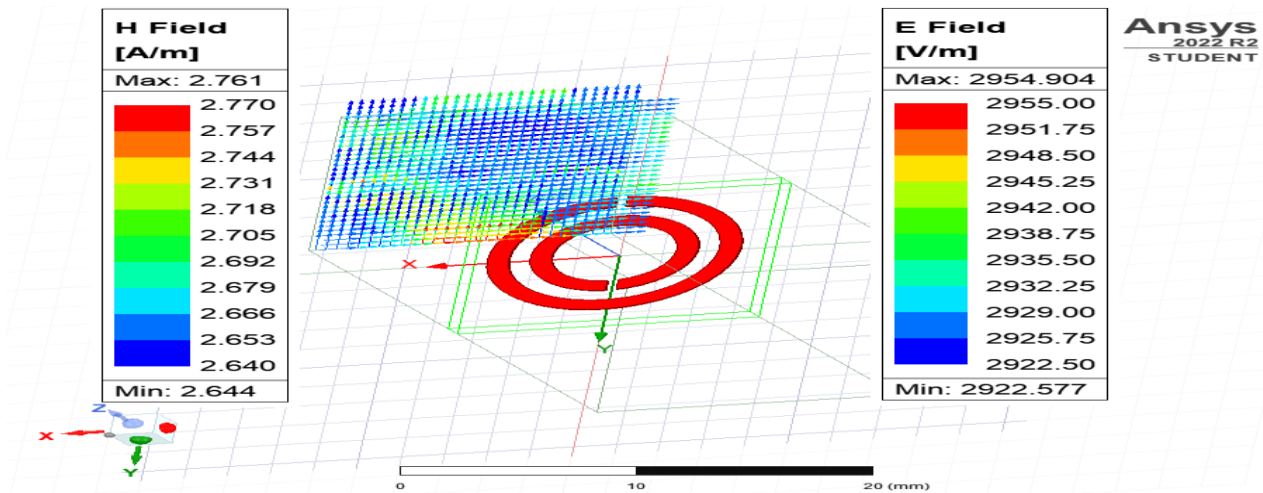


Fig.6. Electric and Magnetic field vectors over SRR.

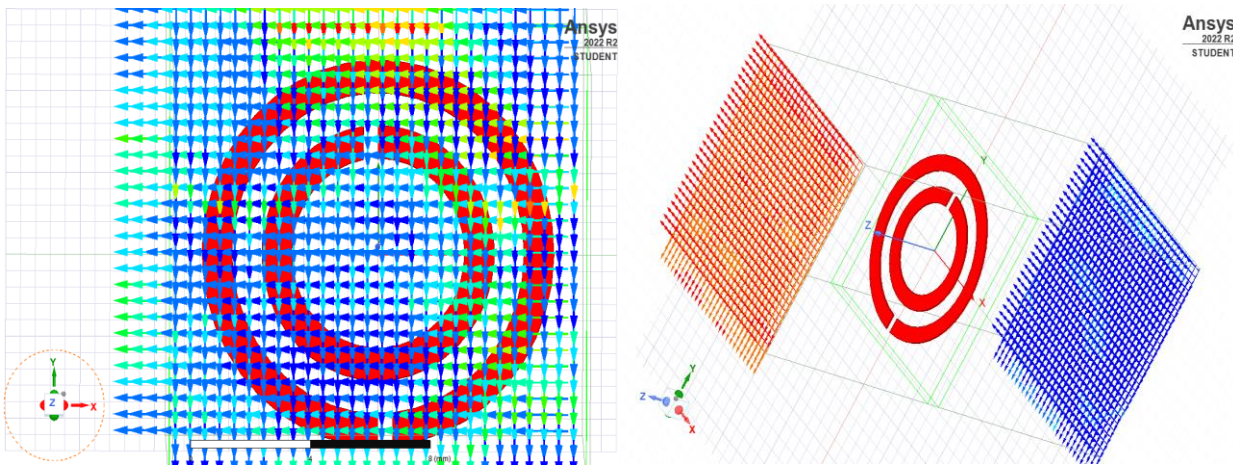


Fig.7. Direction of electromagnetic field at the top and bottom of the SRR structure.

RO3210 Substrate

To study the effect of permeability on resonance frequency and field distribution of SRR, we considered Rogers RO3210 substrate with thickness of 1mm and relative dielectric permeability of 10. The structure was excited at frequency of 10 GHz and the behavior of the circular SRR based on RO3210 is studied relative to RO3003 substrate as shown in fig.8.

When the structure was excited, the signal reflection decreases with increase in frequency until the resonance frequency is attained at 5.55 GHz. At resonant frequency, a minimum signal reflection of -20.9046 dB was recorded in the simulation. Also, a valley was observed at the frequency of 12.2500 GHz during fast frequency sweep with -8.7067 dB before steadily rising to a peak value of -0.6511 dB at frequency of 12.75 dB. Fig.9 shows the plot of scattering parameter, S₁₂, at different modes. Scattering at port 2 in mode 2 consequence of incident

wave at port 1 in mode 2 shows that S12 has a minimum value of -41.1786 dB at frequency of 6.6937 GHz.

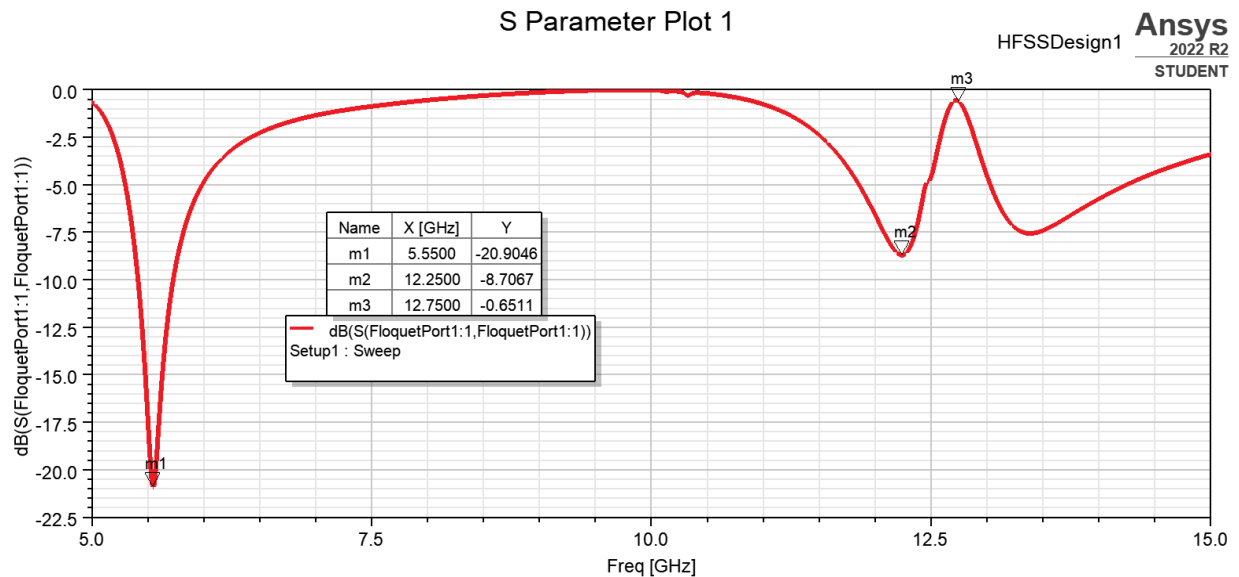


Fig.8. S-parameters S11 at face of the SRR (Port 1) with Rogers R03210 substrate thickness of 1mm.

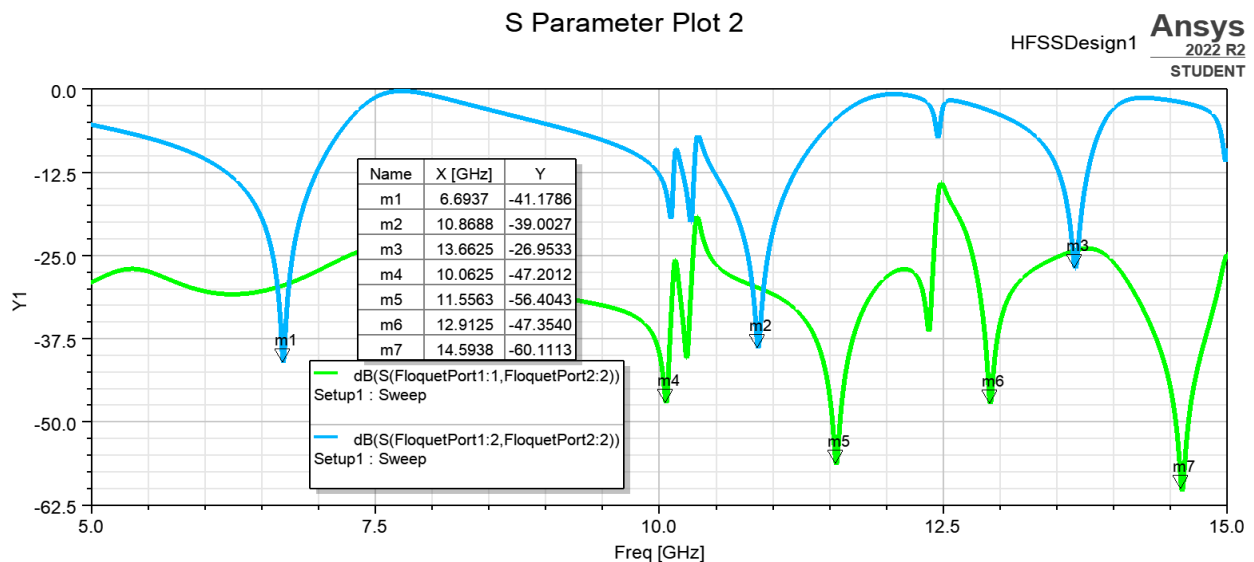


Fig.9. S-parameter S12 at mode (1,2) and S12 at mode (2,2) with Rogers R03210 substrate thickness of 1mm.

The field distribution above the circular SRR indicated areas of maximum and minimum electric fields. In this case, the electric fields are moving in z-direction and perpendicular to x and y- axes. The magnetic field is showing to be moving in x- direction and perpendicular to z and y axis as indicated in fig. 10. The fields at both ends of the SRR are shown in fig. 11. The result indicated that the electric field is travelling parallel to the z-axis.

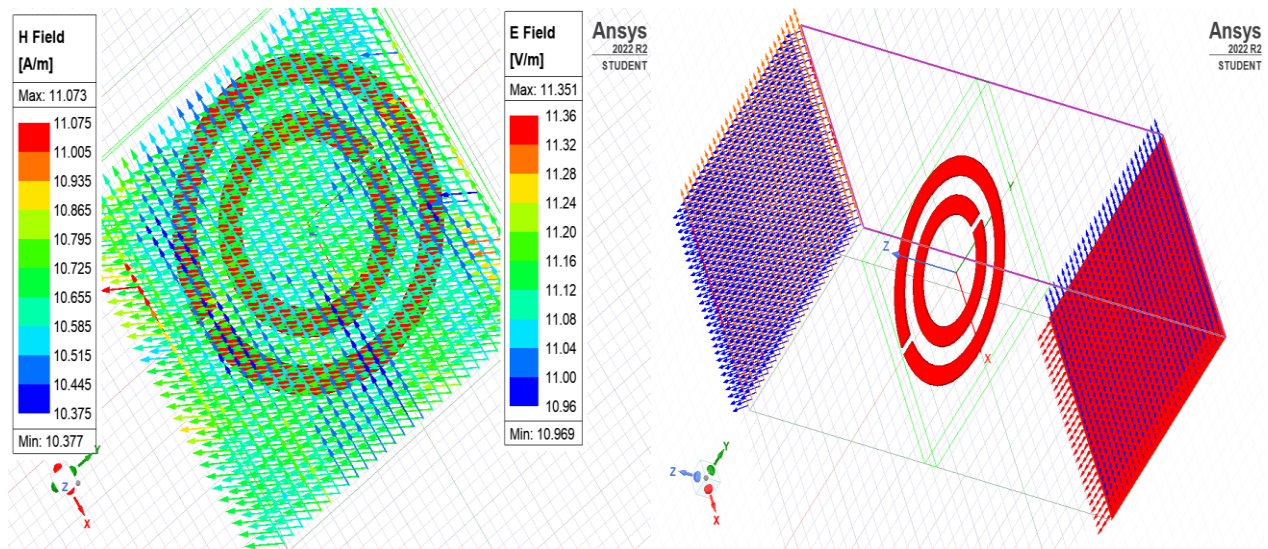


Fig.10. Electromagnetic field vectors and their direction over the Circular SRR.

The thickness of the R03210 substrate increased from 1mm to 1.525mm, and the structure was excited with the frequency of 10 GHz. In this case, the S11 steeply decreased with an increase in the excitation frequency and reached a minimum value of -15.6245 dB at the frequency of 5.2313 GHz. Fig.12 shows the behavior of the substrate at S11 where the incident and the reflected ports were both at mode 1. Similarly, fig. 13 demonstrated scattering, S12 parameter at different fundamental modes. The electric field vector is moving in y- direction, perpendicular to the x and z axis as shown in fig.14. The distribution of field intensity indicated that the maximum electric and magnetic fields are 481.666 V/m and 9.837 A/m.

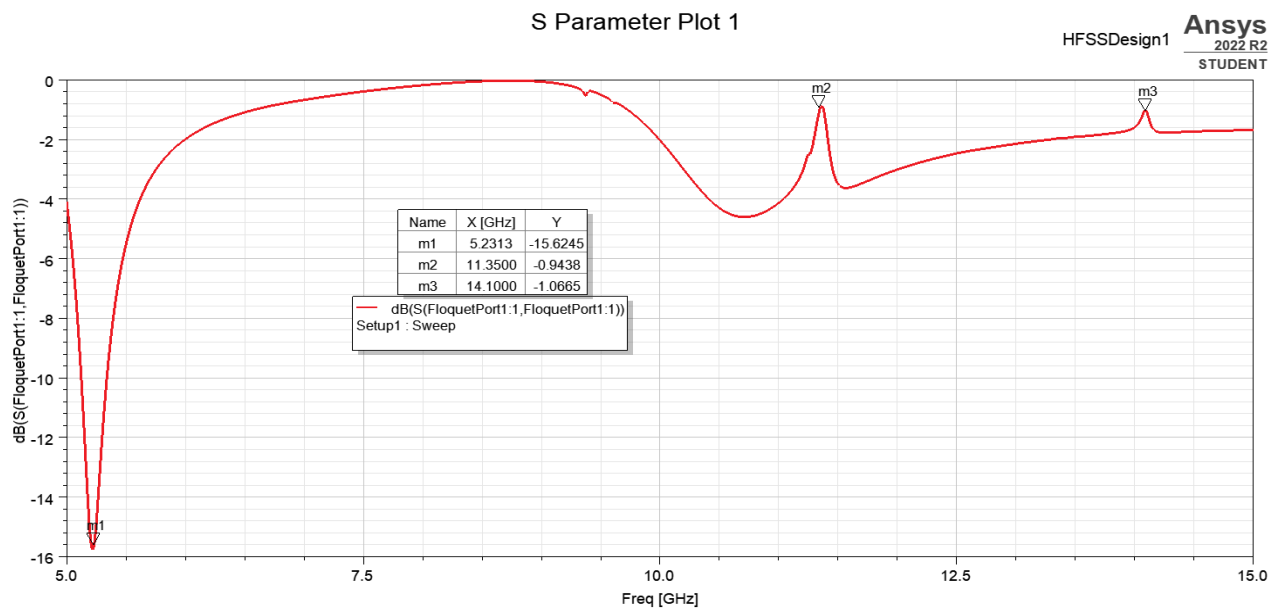


Fig.12. S-parameters S11 at face of the SRR (Port 1) with Rogers R03210 substrate thickness of 1.525mm.

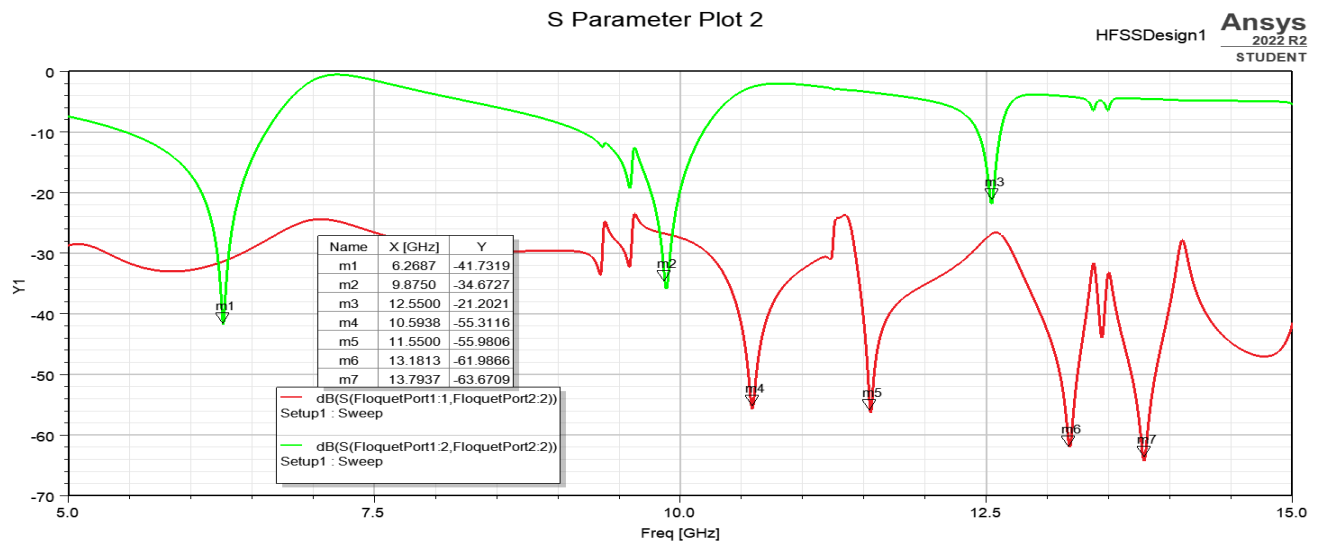


Fig.13. S-parameter S_{12} at mode (1,2) and S_{12} at mode (2,2) with Rogers R03210 substrate thickness of 1.525mm

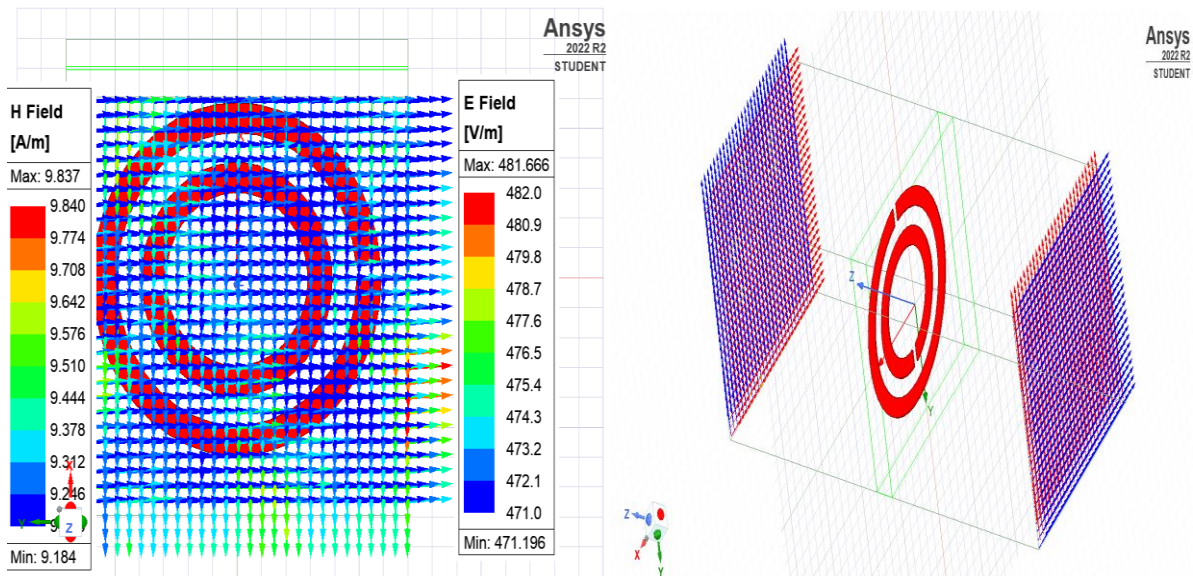


Fig.14. Electromagnetic field vectors over the Circular SRR.

The electric field vector is moving in y- direction, perpendicular to the x and z axis as shown in fig.14. The distribution of field intensity indicated that the maximum electric and magnetic fields are 481.666 V/m and 9.837 A/m.

From simulation results, the R03003 substrate whose permeability is lower than that of R03210 substrate resonated at higher frequency at S_{11} while the reflection coefficient of R03003 at resonance is lower. For transmission coefficient port, S_{12} , R03003 resonated at lower frequency than R03210 substrate. In both ports, R03003 has lower values of S_{11} and S_{12} than R03210 for the same substrate thickness. Table 1 provides the summary of the results at different thickness and substrates.

Table 1. Scattering parameters at different thickness and substrate

Thickness (mm)	Substrate	S11 (dB)	S12 (dB)	Max E(V/m)	Max. H(A/m)
1	RO3003	-26.7802 @ 9.0125 GHz	-34.5305 @ 5.4800 GHz	2954.904	2.761
1	RO3210	-20.9046 @ 5.5500 GHz	-41.1786 @ 6.6900 GHz	11.351	11.073
1.525	RO3210	-15.6245 @ 5.2313 GHz	-14.7319 @ 6.2687 GHz	481.666	9.837

When the thickness of RO3210 was increased from 1mm to 1.525mm, the resonance frequency changed from 5.55 GHz to 5.2313 GHz at S_{11} .

The reflection coefficient in dB increased at the same port. Similarly, at S_{12} , the increase in substrate thickness led to the change in resonance frequency from 6.69 GHz to 6.2687 GHz of the structure. The transmission coefficient in dB increases with increase in substrate thickness at S_{12} .

CONCLUSION

The effect of thickness and permeability variability on resonance and field strength distribution is presented in this work. The modelling and simulation of the SRR cell structure to study these effects indicated that increase in decrease the resonance frequency at S_{11} (dB). The resonance frequency is shown to decrease when the permeability of the material is increase from 3 to 10.1. Thus, effective permeability and thickness of substrates affects the resonance frequency and scattering parameters of a cell structure in metasurface design.

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