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RESEARCH ARTICLE

A modified sierpinski carpet antenna structure for multiband wireless applications

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Abstract

Multiband patch antenna is very important in communication devices and systems. The benefits in designing and testing of Sierpinski carpet geometries for a low-profile, cost-effective multiband microstrip patch antenna for wireless standards is reviewed in this paper. The basic structure of the patch antenna is designed using the FR4 substrate with a thickness of 1.3 mm. The designed patch antenna structure is excited using the microstrip feed system. The Sierpinski carpet antenna structure is designed and simulated using High-frequency Structural Simulator (HFSS) software. The available Sierpinski carpet antenna structure in the literature is modified to make the preferred radiation patterns. The effects of the iterations of the modified Sierpinski carpet antenna structure over the generated return loss plots are discussed in this work. Based on the generated multiband behavior in the simulated results, the accomplishment of the designed antenna in the wireless domain was analyzed.

Keywords: Sierpinski carpet, multiband, microstrip feed, HFSS, FR4, Square patch.

Introduction

The communication antenna plays a significant part in designing communication devices and systems. The size of antenna and its associated systems determines the size of the communication device. The antenna size can be made thinner and conformal by inducing fractal geometries in patch or ground planes. The existing natural structures and phenomena are used to derive the fractal geometries. The physics behind the fractal structures are convened by their self-similarity and plane filling nature. The same structure is miniaturized within the antenna at different scales which accounts for the miniaturization of the antenna.

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Different types of fractals like Koch fractals, Minkowski fractals, Sierpinski carpet, etc are available for designing the antenna (Alle *et al.*, 2005). Sierpinski carpet fractal structure is modified and utilized for the wireless communication standards in this work.

The patch structure can be made in all the geometries that are available in the world. The microstrip patch structure is in demand among the available antenna types due to its cost-effectiveness nature and easy to design approach. The patch antenna is more stable and reliable due to its mechanical characteristics called ruggedness. The disadvantage in the structure of the patch antenna during excitation is its narrow band nature. Still, multiband characteristics can be inducted in the patch by altering the shape of the patch and ground plane. Square shaped patch forms the basis of the antenna design and the fractal designs are etched over it (Joe, 2021). The rectangular, circular and other forms of patch shall also be used as an initiator for the basic antenna design.

The antenna is fabricated over an FR4 epoxy substrate material to improve the cost-effectiveness of the antenna. FR4 substrate is a dielectric insulator that is a poor conductor of electricity. When the FR4 substrate is roofed with copper coating on the top and bottom layers and if excited, it radiates electromagnetic waves. All the materials exhibit a dielectric constant value which is the ratio of electric permeability of the physical material to the electric permeability of the vacuum. The preferred FR4 substrate has a dielectric constant value as 4.4 and a relative permeability

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value as 1. The dielectric loss tangent parameter measures the dissipation of the available electric energy in a dielectric material. For FR4 substrate, the dielectric loss tangent value is 0.0018, mass density is 1900 and Lande G factor is 2 (Kiris *et al.*, 2020).

The patch antenna when excited generates a single band resonant frequency that is the fundamental frequency of the antenna. The patch antenna shall be made multiband or wide band by altering the shape of the patch by introducing the slot structures. The slot structures' location and size will adjust the patch antenna's radiation pattern. The slots in the Sierpinski carpet antenna structure create additional resonant frequencies in addition to the fundamental frequency and improve the radiation characteristics of the antenna. Fractal antennas that are used in the antenna design have multimodal radiation capabilities. Machine learning algorithms can be used to create and optimize the radiation characteristics of the designed Sierpinski Carpet antenna (De Nicola *et al.*, 2018). The reconfiguration of the antenna can be done by changing the antenna properties using different diode techniques (Masroor *et al.*, 2021). The depth of the fractal structure depends on the number of iterations created in the antenna. The depth of the fractal structures can be adjusted to study the Hall conductivity principle (Iliasov *et al.*, 2020). The fractal structures can be symmetrical or non-symmetrical in nature (Han, *et al.*, 2020).

The link between the thermal conductivity and the fractal number underlines the stability of the system. The thermal conductivity decreases and then becomes stable as the fractal number increases. The fractal structures can be used in ultra-wideband communication systems with high-capacity transmission and more immune to environmental noise. The space filling property of fractal structures is used to miniaturize antenna and induce multiband and broadband features in a narrow band antenna structure (Chaouche *et al.*, 2018). Future wireless communication devices need to support higher data rates and huge user densities. To satisfy this purpose, mobile communication needs to provide a methodology for sharing its available limited spectrum and avoid co channel interference. The planar microstrip antennas can accommodate this mobile communication feature (Soren *et al.*, 2018).

The filters are used in the communication devices to select the desired information and reject the unwanted noise in the spectrum. Numerous filter types can be made in the microwave high-frequency domain. The compact sized communication filters with high sensitivity can be designed using fractal structures (Krishnan *et al.*, 2019). Sierpinski fractal antenna is best suitable for the high-speed switching networks used in modern communication systems that provide lightweight and integrate easily with other radio frequency circuits (Kumar & Jayappa, 2022). The microstrip feed mechanism provides a very good impedance matching that does not require any additional matching elements, reducing the space necessary and improving the device's compactness. This feed is very useful in wireless communication systems that have higher data rates (Kumar & Pharwaha, 2020).

The complex designs of the fractal geometries require optimization to make it radiate for the desired applications. Optimization algorithms can be used to get better antenna parameters and improve the performance of the antenna. The desired frequency band of operation can be found either by using the optimization algorithms or the length and width of the patch structure of the antenna as well as the matching line in the antenna can be adjusted for better performance. Sierpinski fractal antennas are effective for wireless standards since they are small and have a multiband operation. The bandwidth enhancement capability of the antenna structure can also be increased by using fractal structures (Anuradha & Viswasom, 2020). Sierpinski carpet antenna structure improves the transmission capacity of the antenna by getting better effectiveness of the length of patch antenna (Bharathi *et al.*, 2020).

The fractal structures, i.e., defections or deformations created in the antenna patch, are grouped as Defected Microstrip Structure (DMS). The defections and irregularities created in the patch antenna's ground plane are characterized as Defected Ground plane Structure (DGS) (Joe *et al.*, 2020). The DMS and DGS techniques shall be used for size reduction as well as inducing multiband and wide band behavior in the patch antenna if used appropriately. The DGS and DMS structures' different dimensions, size and locations will provide different radiation patterns. The wide range of DMS and DGS structures can be used to alter the wireless behavior of the designed patch antenna.

The paper is ordered as follows: The subsequent section explains the various components involved in the basic antenna design. The prefinal section discusses the results and the optimization of results using the partial ground plane structures. The main conclusions involved in the work discussed in this paper are discussed in the final section.

Antenna Design

The planned antenna design involves using modified Sierpinski carpet fractal structures to design a cost-effective multiband antenna in wireless domain applications. The general antenna design flow is shown in Figure 1. Based on the design specifications, the square-shaped patch is created over an FR4 epoxy substrate. Then based on the available Sierpinski carpet structure in the literature is modified and is introduced in the patch. The iterations are created in the modified Sierpinski carpet structure. The modified Sierpinski carpet antenna is designed and simulated in the HFSS software domain and optimized by varying the size of the ground plane. The optimized design that suits well for wireless applications is chosen. The chosen antenna design will be fabricated in the substrate with copper coating for

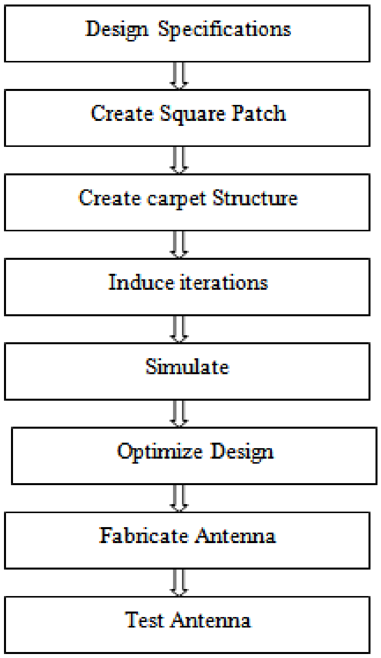

Figure 1: Antenna design flow

patch and ground plane and tested for the validation of the results.

Basic Square Patch

A square shaped FR4 epoxy substrate with dimensions 100 mm X 100 mm is chosen. Designing a square patch structure based on the design specifications, which resembles a truncated microstrip transmission line simulated using HFSS Software is the preliminary procedure for this antenna design. The Width (90 mm) and Length (90 mm) of the patch are determined by the design equations 1 – 8 (TMilligan, 2005). The value of ε_{reff} is calculated by,

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (1)$$

The parameters used in equation 1 are ε_{reff}, ε_r, h and W where ε_{reff} denotes the Effective dielectric constant structure, ε_r represents the Dielectric constant of the substrate structure, h points out the Height of the dielectric substrate structure and W determines the Width of the patch structure

$$\Delta L = 0.412\frac{(\varepsilon_{reff} \pm 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.3)\left(\frac{W}{h} + 0.8\right)} \quad (2)$$

The effective length of the patch structure is denoted by L_{eff},

$$L_{eff} = L + 2\Delta L \quad (3)$$

For a resonance frequency f_1, the L_{eff} value is denoted by

$$L_{eff} = \frac{c}{2f_1\sqrt{\varepsilon_{reff}}} \quad (4)$$

The resonance frequency in the TM_{mn} mode of the square patch antenna is found by,

$$f_0 = \frac{c}{2\sqrt{\varepsilon_{reff}}}\left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2\right]^{\frac{1}{2}} \quad (5)$$

The m and n in equation 5 denotes the modes by the side of the length L of the patch and width W of the patch. For effective radiation W is calculated using,

$$W = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \quad (6)$$

Length of the ground plane (L_g) of the patch antenna is determined by,

$$Lg = 6h + L \quad (7)$$

The Width of the ground plane (W_g) in the patch antenna is,

$$Wg = 6h + W \quad (8)$$

Microstrip feed is used in this antenna design. A short microstrip stub with dimensions 10 mm X 6 mm is used. The microstrip stub is used for matching the impedance. The radiation exerted from the antenna will be deprived if the impedance is not matched properly. The usage of short microstrip stub will create undesired radiations. Fractal structures are created over the patch to create the desired wireless radiation.

Modified Sierpinski Carpet Structure

The Sierpinski Carpet is a plane fractal curve that belongs to the fractal antenna family. A Sierpinski carpet structure is usually used to utilize the patch structure for accommodating the higher as well as the lower frequencies. The basic square shaped patch is divided into a smaller copy of itself with certain dimensions. Then some of the new copies of the divided patch structure are removed and the remaining copies are left out in a particular order to create new shapes of fractal structures.

The fundamental Sierpinski carpet structure is created in the patch antenna. The fractal antenna has miniaturization and self-similarity property that generates the multiband behavior in the antenna. The miniaturization of the antenna is achieved by removing certain sections of the patch antenna. The self-similarity of the antenna is due to the splitting of the patch antenna with different dimensions within the same structure. The antenna division based on the self-similarity principle is done only on the upper portion of the patch antenna design as increasing iterations will influence the antenna's efficiency.

Figure 2 shows the generation of the modified Sierpinski Carpet structure from the basic square shaped patch initiator. The fundamental Sierpinski Carpet structure is produced from a basic square patch. The basic square patch is created per the design parameters shown in 2 (a). A slot is created in the basic square patch and modified to form iteration 1 as shown in 2 (b). The basic big square patch is divided into smaller nine equal divisions. The smaller divided square division at the centre of the square patch is detached from the original large square patch to form iteration 2 as shown in 2 (c). The remaining smaller squares created in the patch are then splitted into nine equal parts and the centermost square from each square is removed as shown in 2 (d) to form iteration 3. By repeating this process, a pattern of Sierpinski Carpet is obtained. The Sierpinski carpet shall be modified to review its radiation characteristics and parameters.

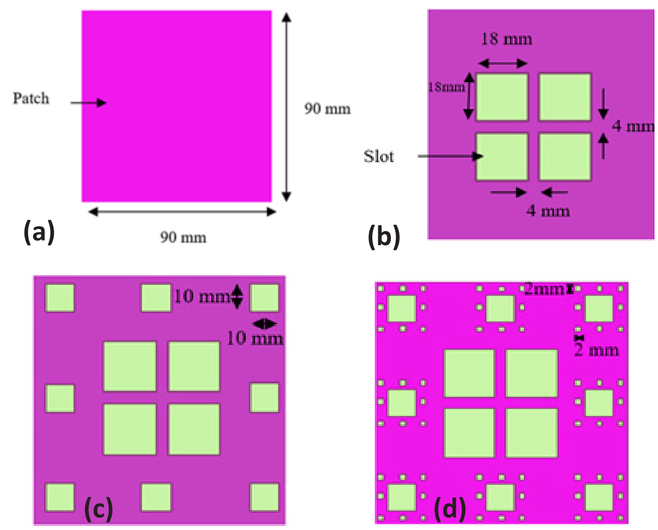

Figure 2: Modified sierpinski carpet structure (a) Initiator (b) Iteration 1 (c) Iteration 2 (d) Iteration 3

Partial Ground Plane Structures

The number of resonant frequencies is on rise as the number of iterations in modified Sierpinski carpet antenna increases, creating unnecessary and closely spaced resonant frequencies that reduce the antenna's performance. To reduce the unnecessary bands, Partial ground plane structures in the length of ground plane (L_g) shall be created. Figure 3. shows the partial ground plane structures created in the antenna. The possible ground plane structures of the antenna are L/4, L/2, and 3L/4. The L/2 and 3L/4 partial ground plane structures are chosen, and the L/4 partial ground plane is neglected since it is very close to the feed. The closeness of the feed to the partial ground plane will depreciate the radiations that are generated from the antenna.

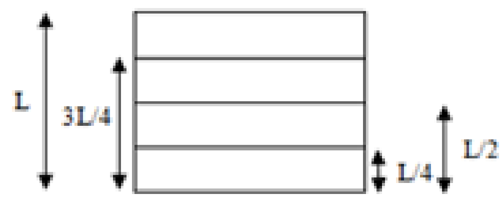

Figure 3: Partial ground plane structures

Results and Discussion

Modified Sierpinski Carpet Antenna

The modified Sierpinski carpet structure is inducted in the patch of the antenna as iterations 1, 2 and 3. The excitation for the patch antenna is given through the microstrip feed.

Figure 4 shows iteration 1 of the Modified Sierpinski carpet antenna simulated using HFSS software. Figure 5 depicts the modified Sierpinski carpet antenna's iteration 1 return loss plot using HFSS. In iteration 1, the modified Sierpinski carpet antenna generates two resonant frequencies. The modified structure has four equally spaced slots in the middle of the patch with same dimensions. The edges of the slots will generate additional resonant frequencies in addition with the fundamental resonant frequency. The antenna structure in iteration 1 generates two resonant frequencies. The basic resonant frequency is generated at 3.7 GHz with 11.02 dB as the return loss and the next resonant frequency is generated at 4.9 GHz with 31.99 dB as return loss.

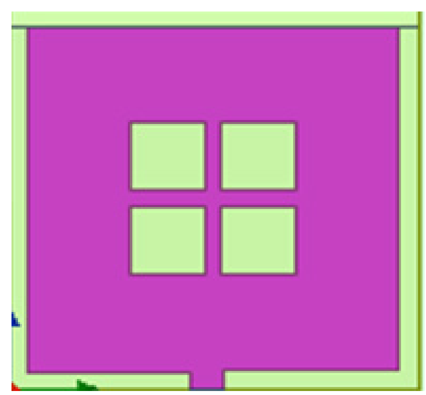

Figure 4: Iteration 1 of modified sierpinski carpet antenna

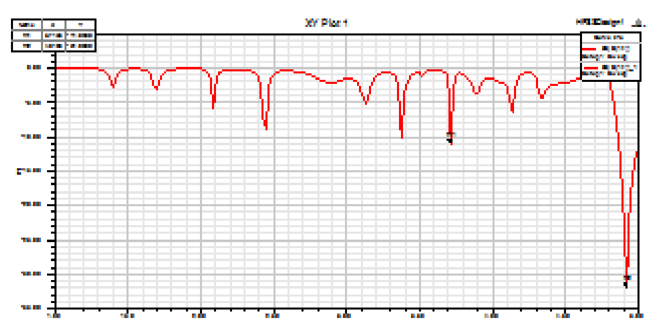

Figure 5: Return loss of Iteration 1 of modified sierpinski carpet antenna

Figure 6 shows iteration 2 of the antenna using HFSS software. Figure 7 depicts the return loss plot of the iteration 2 of the carpet antenna using HFSS software. As the number of slots in iteration 2 is much higher than in iteration 1, it tends to generate resonances at more frequencies. In iteration 2, the modified Sierpinski carpet antenna resonates with a reduced fundamental frequency while compared with the fundamental resonant frequency of iteration 1. The antenna structure in iteration 2 generates three resonant frequencies with better return loss characteristics. The basic resonant frequency radiates at 2.7 GHz with 11.09 dB as a return loss value. At 3.8 GHz the second resonant frequency is available with 38.33 dB as return loss value. The next resonant frequency is at 4.19 GHz with 16.37 dB as return loss value.

Figure 8 shows iteration 3 of the carpet antenna using HFSS software. Figure 9 shows the return loss plot of iteration 3 of the carpet antenna using HFSS. Iteration 3 has more small slots compared with iteration 1 and iteration 2. Iteration 3 of the carpet antenna resonates at six resonant frequencies. The first resonant frequency is at 1.4 GHz with a return loss value of 22.65 dB and the subsequent resonant frequency is at 1.7 GHz with 16.7 dB as a return loss value. The third resonant frequency is at 2.7 GHz with 14.29 dB as return loss value and the fourth resonant frequency at 3.2 GHz with 19.7 dB as return loss value. At 3.9 GHz the fifth resonant frequency occurs with the value of return loss as

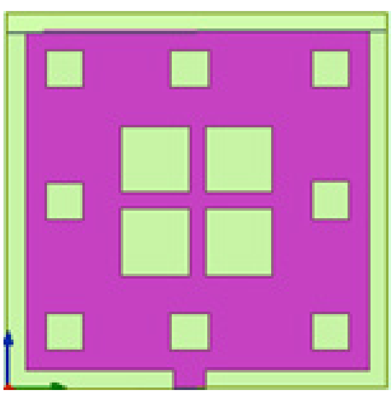

Figure 6: Iteration 2 of modified sierpinski carpet antenna

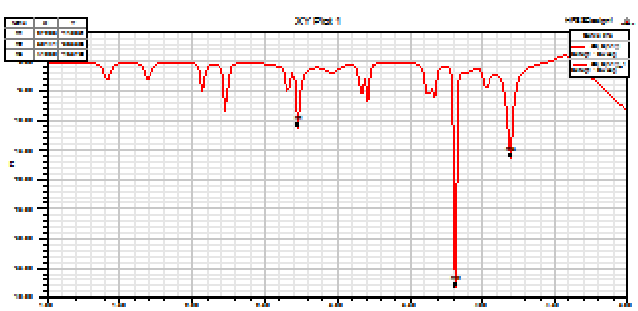

Figure 7: Return loss of iteration 2 of modified sierpinski carpet antenna

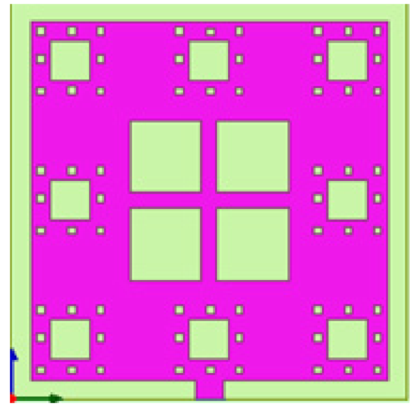

Figure 8: Iteration 3 of modified sierpinski carpet antenna

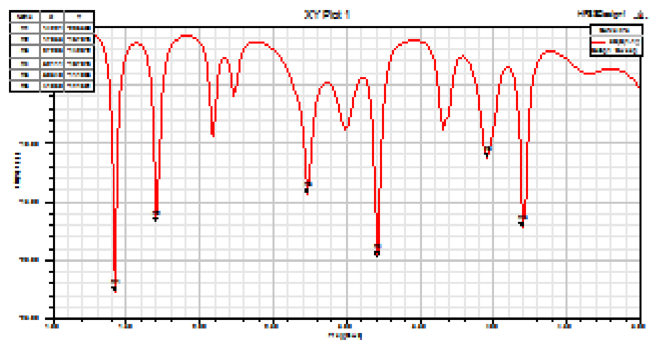

Figure 9: Return loss plot of iteration 3 of modified sierpinski carpet antenna

11.18 dB and the 4.1 GHz being the final resonant frequency with return loss value as 17.16 dB.

In iteration 1 of the modified Sierpinski carpet antenna, the number of resonant frequencies is two and three in iteration 2 and six in iteration 3. As the order of iteration in the antenna increases, the number of resonant frequencies generated also increases. As the number of resonant frequencies is on rise, the resonant frequencies are closely spaced between each other in the spectrum which requires further optimization.

Optimization using Partial Ground Plane Structures

The comparison of return loss values of iteration 1 of the modified Sierpinski carpet antenna using modified ground plane structures is shown in Figure 10. The resonant frequencies are generated by the introduction of iteration 1 of the modified Sierpinski carpet, and their return loss values are tabulated in Table 1. In tables, the return loss is mentioned as RL and the resonant frequencies 1,2,3,4,5,6 are represented by $f_1, f_2, f_3, f_4, f_5, f_6$.

In a full ground plane structure, two resonant frequencies are radiated. When the ground plane is reduced to 3L/4 only one resonant frequency is radiated with a small return loss value due to the dissimilarities introduced in the radiation. When the ground plane is reduced to half two resonant frequencies are radiated but with very less return loss values. The partial ground plane structures provide resonant

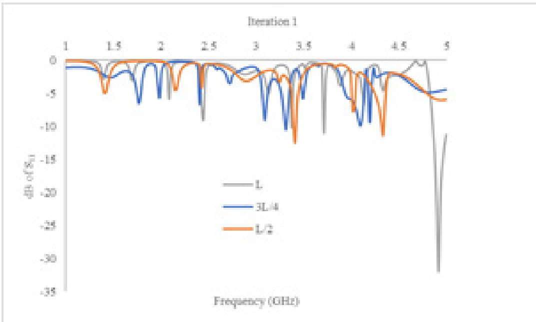

Figure 10: Comparison of return loss plot values of iteration 1 using modified ground plane structures

Table 1: Resonant Frequency Values of Iteration 1

Length of Ground Plane (L)	f_1 (GHz), RL(dB)	f_2 (GHz), RL(dB)
L/2	3.4, 12.45	4.3, 11.3
3L/4	3.3, 10.49	-
L	3.7, 11.02	4.9, 31.99

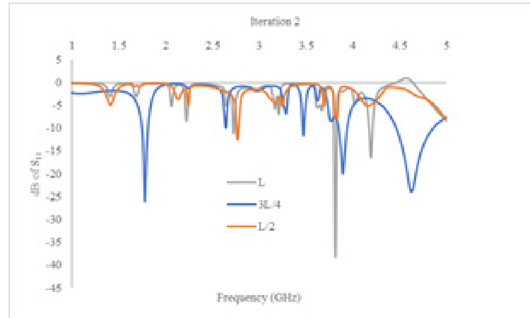

Figure 11: Comparison of return loss plot values of iteration 2 using modified ground plane structures

Table 2: resonant frequency values of iteration 2

Length of ground plane (L)	*f_1 (GHz), RL(dB)*	*f_2 (GHz), RL(dB)*	*f_3 (GHz), RL(dB)*
L/2	2.7, 12.51	-	-
3L/4	1.78, 26.04	3.8, 19.99	4.6, 23.87
L	2.7, 11.09	3.8, 38.33	4.19, 16.37

frequencies with reduced return loss values. Hence by performing iteration 1 in the modified Sierpinski carpet the full ground plane structure provides better radiation characteristics than the partial ground plane structures. The resonant frequencies of the partial ground plane structures are slightly shifted to the left side when compared with the full ground plane structure.

The comparison of return loss values of iteration 2 of the Modified Sierpinski carpet antenna using modified ground plane structures is shown in Figure 11. The resonant frequencies generated by the introduction of iteration 2 of the modified Sierpinski carpet along with their return loss values are tabulated in Table 2. The full ground plane structure creates three resonant frequencies while the 3L/4 sized ground plane also creates three resonant frequencies. When the ground plane is reduced to half, only one resonant frequency is created with very low return loss value. In iteration 2, the antenna with 3L/4 partial ground planes provides better multiband characteristics than the complete ground plane structure.

The comparison of return loss values of iteration 3 of the Modified Sierpinski carpet antenna using modified ground plane structures is shown in Figure 12. The resonant frequencies generated by the introduction of iteration 3 of the modified Sierpinski carpet along with their return loss values are tabulated in Table 3. Six resonant frequencies are generated in the complete ground plane structure as well as the partial ground plane structures in iteration 3. The generation of resonant and radiation frequencies cannot be controlled in iteration 3 by using the partial ground plane optimization. Additional optimization techniques are needed for this higher order of iterations. The concept of partial ground plane structures works well in iteration 1 and 2 of the modified Sierpinski carpet structure.

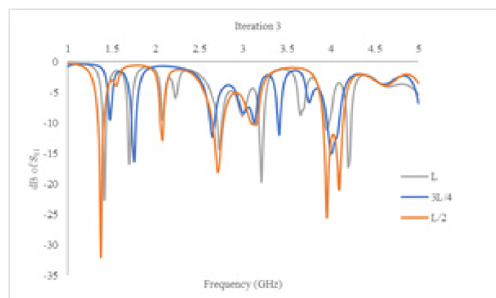

Figure 12: Comparison of return loss plot values of iteration 3 using modified ground plane structures

Table 3: resonant frequency values of iteration 3

Length of Ground Plane (L)	*f_1 (GHz), RL(dB)*	*f_2 (GHz), RL(dB)*	*f_3 (GHz), RL(dB)*
L/2	1.3, 32.06	2.08, 12.76	2.7, 18
3L/4	1.7, 16.2	2.6, 12.32	3.1, 10.02
L	1.4, 22.65	1.7, 16.7	2.7, 14.29
Length of Ground Plane (L)	f_4 (GHz), RL(dB)	f_5 (GHz), RL(dB)	f_6 (GHz), RL(dB)
L/2	3.1, 10.3	3.9, 25.51	4.09, 20.99
3L/4	3.4, 12.04	3.9, 15.04	4.6, 23.87
L	3.2, 19.7	3.9, 11.18	4.1, 17.16

Conclusion

The modified Sierpinski carpet antenna is designed over the FR4 substrate and simulated using HFSS simulation software. The return loss values of the iteration 1, 2 and 3 are optimized using the partial ground plane structures. The partial ground plane structures improve the performance of the designed antenna in iteration 1 and 2 but it does not suit well for iteration 3. The designed antenna has multiband capabilities and suits the wireless communication standards well. The different shapes of DGS can be introduced in the ground plane of the patch antenna to optimize the antenna parameters at higher order of fractal iterations.

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