Analysis of resonant behaviour of Fractal Spiral Resonator based unit-cell on different substrates

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Abstract— *This paper presents an investigation on a compact cell geometry of Fractal Spiral Resonator. The design of the established cell designs may be an option to design more homogeneous left-hand materials. This paper shows comparative performance of single fractal geometry, designed with Hilbert Curve, on four different substrates. The Ansoft Electromagnetic solver "High Frequency Structure Simulator" has been used for implementation of the intended work.*

Keywords—*Spiral Resonator, Hilbert Curve, High Frequency Structure Simulator, Metamaterials, Fractal Spiral Resonator.*

I. INTRODUCTION

The promising requirements of wireless systems need development of novel design methods of wireless components for the fulfilment of various performance criteria. With the advancement of technology, miniaturization and multiple band performance of antenna have become considerable issues. The multiband operation and a certain extent of frequency independence are possible with array design. However the introduction of Defected Ground Structure [1], Metamaterials [2, 3] and Fractal [4] into antenna design is the great step towards miniaturization. Fractals, a Latin word, related to the verb fangere, means fractured or broken was originally coined by Mandelbrot to describe complex shapes possessing an inherent self-similarity or self-affinity in their geometrical structure [5]. Fractal has found extensive applications in several branches of science and technology. Disciplines such as atmospheric science, geology and forest science have been favored considerably by effective implementation of fractal modeling of naturally occurring phenomena. Mandelbrot defined the Euclidean geometries as fractal geometries which were termed as formless and rejected by many investigators [6]. After that innumerable fractal shaped antennas like Sierpinski Gasket [7, 8], Sierpinski Carpet [9], Koch Loop and Cantor Slot patch etc., shown in Figure 1, have been successfully designed and implemented in last two decades. The inclusion of the characteristics of Sierpinski and Koch fractals into microstrip patch antenna has resulted in smaller resonant frequencies with higher iteration order, more bandwidth and reduced size [10, 11]. For the multidimensional databases, Hilbert order has been proposed to be used because it gives mapping between 1D and 2D space and has better locality-preserving behaviours. They have also been used to help compress data warehouses [12, 13].

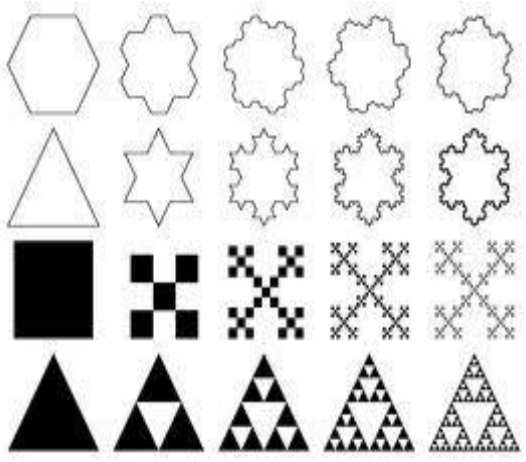

Fig. 1. Fractal antenna

The fractals own a useful property of structure self-similarity. Fractal geometries are of two types- Deterministic fractals and Random fractals. The deterministic fractals are shapes including the self-similar and rotated copies at different scales. The random fractals include those shapes which are statistically self-similar. Most of the shapes of fractals are stimulated by the naturally occurring phenomena like clouds, trees and lighting etc. [14]. The resonant frequency of fractal antenna can be moved to lower frequencies by increasing the number of iterations [15]. The performance of antennas such as radiation efficiency, radiation resistance, bandwidth, current density distribution, quality factor and resonant frequency can also be improved by changing the total length of fractal structure. The control of side-lobe levels has been achieved with the implementation of random fractals. The random fractal geometries result in better response as compared to deterministic geometry fractal antennas. The irregularity of antenna structure affects the radiation pattern of antenna [16]. Fractal antennas have also been customized to achieve high efficiency and good gain. The field of fractals still in development phase and is progressing day by day.

Metamaterials, the artificial structures proposed by Victor Veselago [17, 18] are realized with a composed structure of Split Ring Resonators (SRR) and metallic thin wires (TW) [19, 20]. The structures are employed as inclusions to a natural dielectric when a metamaterials substrate is to be used. A number of geometries of SRRs have been suggested by researchers such as square, circular, U-shaped, S-shaped and spiral etc. [21-25]

The present work describes the printing of the spiral shaped fractal resonator on Rogers (RT/Duriod 5880) substrate to induce the metamaterial characteristics in the host material. Further this fractal spiral resonator on different substrates is analyzed for the metamaterial behaviour with electromagnetic solver. The paper is planned into six sections. After describing introduction in Section I, Section II gives the use of fractal Hilbert curve as space filling curve. Section III provides the design of fractal spiral resonator. Simulation methodology is explained in Section IV. Simulation results are reported in Section V. The presented work is concluded in the Section VI.

II. FRACTAL AS SPACE FILLING CURVE

Fractals are infinite geometries having endless complexity. The generation of fractals should be done such that the total length of wire remains unchanged and the dimension is reduced successively by the application of a chain of iterations as depicted in Figure 2. The region enclosed by the structure decrease with the increase in the number of iterations. The increase in the number of iterations leads to decrease in resonant frequency [15, 26]. It is proved cost effective as compared to other antennas. This concept is one of the successful approaches for antenna size reduction.

A fractal is mathematically defined to be infinite in complexity and it can be truncated into a number of similar parts so as to reduce the complexity. The resulting geometry after reducing the complexity is called pre-fractal. A pre-fractal drop the details that are not further distinguishable.

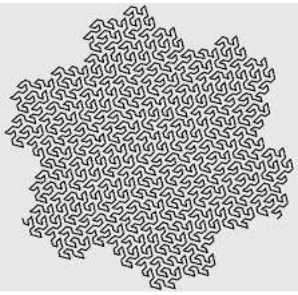

Fig. 2. Fractal as space filling curve

Hilbert curve- The space-filling curves were discovered by Giuseppe Peano in 1890 [27]. A variant of same was first described as Hilbert Curve by the German mathematician David Hilbert in 1891. Hilbert discovered and developed a broad range of fundamental space-filling ideas using continuous fractal in many areas shown in Figure 3.

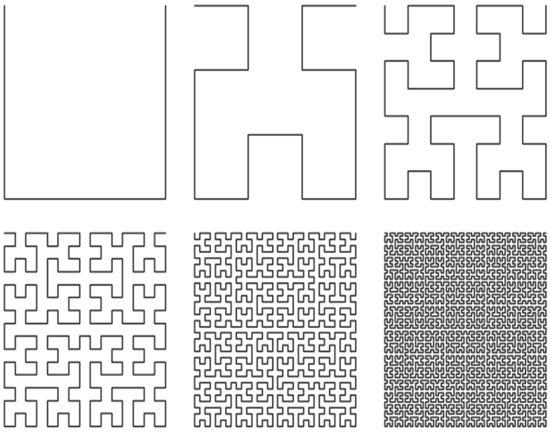

Fig. 3. Hilbert Curves with increasing density

III. DESIGN OF FRACTAL SPIRAL RESONATOR

The topology of the artificial magnetic unit cell based on fractal spiral geometry is presented in Figure 4. The resonator is basically designed by connecting two fractal ring resonators in a spiral form. Both outer and inner rings are the mirrored image of the first order Hilbert fractal to form the ring shape. Upper half of the inner and outer rings is the replica of the lower half. These two concentric rings are then joined at one end to achieve the spiral form. The marked inner section is the extension of the inner curve. It is imperative in order to decrease the resonance frequency through inductive and capacitive coupling amid the different sections.

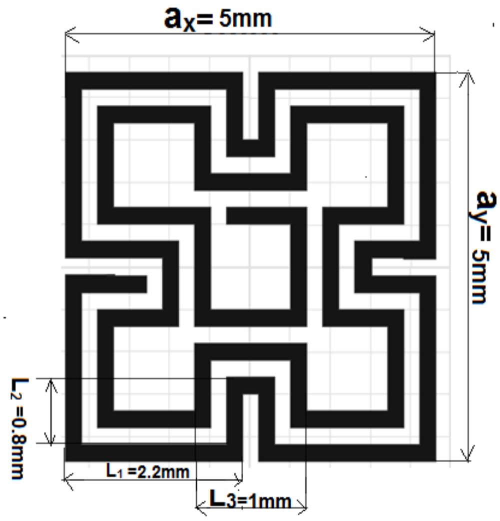

Fig 4. Geometry of a fractal spiral resonator

The substrate sheet is 0.5 mm thick and loss tangent is 0.02. The metal line width and minimum distance between any two lines are 0.2 mm. The other geometrical parameters are L1= 2.2 mm, L2= 0.8 mm and L3= 1 mm. The unit cell size is ax = 5 mm, ay = 5 mm and az = 2 mm. On one side of the substrate, the prescribed fractal geometry is printed.

IV. SIMULATION METHODOLOGY

Figure 5 depicts the geometry of 3D unit-cell structure modeled with electromagnetic solver “High Frequency Structure Simulator (HFSS)”. This is the Finite Element Method (FEM) based Simulator employed for determining the electromagnetic behaviour of a structure and provides the details about the various aspects of modeling and running simulations.

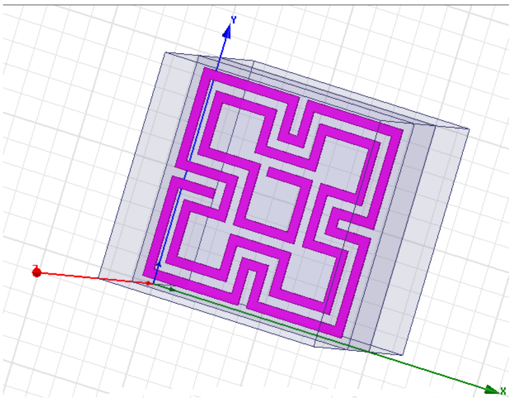

Fig 5. Geometry of fractal spiral resonator in radiation box

In HFSS, the solutions can be envisaged in terms of the electric and magnetic fields, currents or S-parameters in 1D, 2D and 3D. For the simulation of this structure, the ports and sources are identified, the necessary field solutions for the system is generated. Perfect H boundary condition is assigned on the z-faces of the radiation box while Perfect E boundary condition is assigned to the x-faces of the radiation box [25, 28]. Two wave port excitations are assigned on the y-faces of the radiation box.

V. RESULTS AND DISSCUSION

After modeling and simulating the fractal structure, Scattering parameters are evaluated. Initially the results have been taken with Rogers Duroid substrate of dielectric constant 2.2. Further fractal spiral unit cell with same geometrical parameters is numerically analysed using different substrates such as FR4 of dielectric constant 4.4, ARLON 600 of dielectric constant 6.15 and GLASS of dielectric constant 5.5. Figure 6 and Figure 7 show transmission coefficient (S_{21}) and reflection coefficient (S_{11}) of unit cell vs. frequency respectively. The magnitude and phase of S_{21} and S_{11} are shown in Figure 8 and Figure 9 respectively. For a metamaterial medium with negative permeability (μ), the phase velocity will be in reverse direction to the energy flow signified by group velocity. The reversal of phase of S_{11} and S_{21} at resonant frequency validates the metamaterial behaviour of fractal spiral resonator.

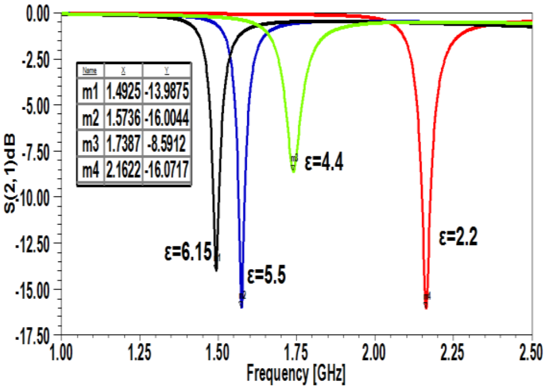

Fig. 6. Transmission coefficient (S_{21}) of fractal spiral resonator on different substrates

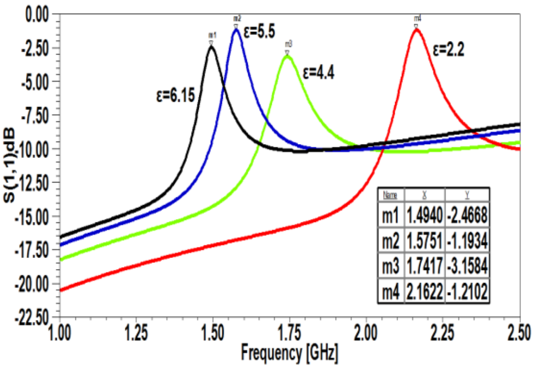

Fig. 7. Reflection coefficient **(S_{11})** of fractal spiral resonator on different substrates

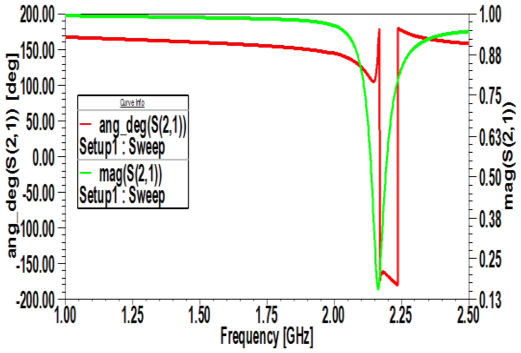

Fig.8. Magnitude and phase of transmission coefficient (S_{21}) of fractal spiral resonator

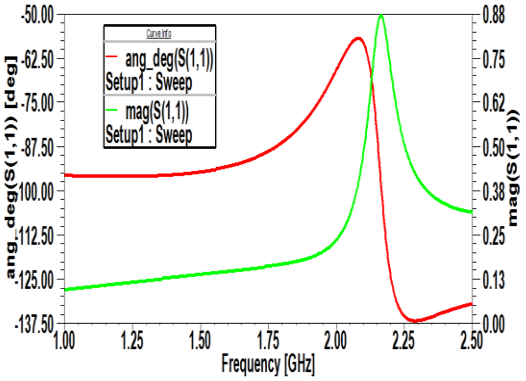

Fig 9. Magnitude and phase of reflection coefficient (S_{11}) of fractal spiral resonator

The fractal spiral unit cells using different substrates are modeled with HFSS and their results are compared with each other. The transmission minimum for the proposed structure with ROGERS RT/ DURIOD 5880 (tm) is -16.0717 dB at 2.1622 GHz., with FR4 substrate is -8.59 dB at 1.7387 GHz, with GLASS substrate is -16.01 dB at 1.5736 GHz and with ARLON 600 is -13.99 dB at 1.4925 GHz.

VI. CONCLUSION

In this presented work, we analysed S parameter characteristics for spiral fractal resonator based metamaterial unit cell on four different substrates. Fractal spiral using Rogers Duroid 5880 exhibits negative permeability at 2.1622 GHz as indicated by phase reversal at this resonating frequency. It is concluded that with increase in the dielectric permittivity from 2.2 to 6.15, the resonant frequency shifts from 2.1622 GHz to 1.4925 GHz. For increase in permittivity of the dielectric material, the resonant frequency is observed on lower side of frequency. The proposed cell designs may be chosen to design and fabricate left-hand materials.

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