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Efficient Ku Band Antenna Using Optically Transparent Materials

1st Shreedhara
Dept. of ETE
Ramaiah Institute of Technology
Bengaluru, Karnataka, India

2nd Yashas V
Dept. of ETE
Ramaiah Institute of Technology
Bengaluru, Karnataka, India

3rd Dr Parimala P
Asst.Professor Dept.of ETE
Ramaiah Institute of Technology
Bengaluru, Karnataka, India

Abstract— **This study focuses on the design and simulation of a Koch Snowflake fractal antenna for Ku band frequency applications (8 GHz to 12 GHz), utilizing optically transparent materials to enhance antenna efficiency. The objective is to evaluate the impact of various substrate and patch materials on critical antenna performance metrics, including the S11 parameter, gain, and Voltage Standing Wave Ratio (VSWR). Using ANSYS HFSS software, substrates such as FR4 Epoxy, Rogers RT, Jeans, and PVC Plastic were investigated, while Copper and Indium Tin Oxide (ITO) were used as patch materials. The simulation results demonstrate that the combination of PVC Plastic and ITO provides superior performance, achieving the lowest S11 value of -32.5038 dB and the best VSWR of 1.0621 at 11.28 GHz. This study offers valuable insights into material selection for designing high-frequency fractal antennas, with implications for advancing telecommunication, radar, and satellite communication systems.**

Keywords—Fractal Antenna, Ku Band, Indium Tin Oxide (ITO), Transparent Antenna.

I. INTRODUCTION

There have been significant improvements in antenna design that have been brought about by the growing need for small, high-performance antennas in wireless communication systems, particularly in the Ku band (8 GHz to 12 GHz) frequency range. Complex geometries and shapes, like the Koch snowflake fractal, are used in modern antenna setups to improve the performance measures such as gain, return loss (S11), and voltage standing wave ratio (VSWR), all of which are very essential for the effective signal transmission and reception. Fractal antennas are most commonly known for their multi band and space efficient designs and have proven successful in a wide range of applications, including high gain X-band and Ku band implementation, network-enabled on-body communications, and multiband wireless systems. Fractal antennas can now handle a wider range of frequency demands and enhance signal stability thanks to ongoing research into new antenna designs, such as L and inverted L slots for X-band operations [1]. The functionality of Cognitive Radio (CR) is further enhanced by quad-band reconfigurable antennas, which enable effective use across many frequency ranges and make room for a variety of communication requirements [2]. Antenna technology has advanced significantly when transparent materials like Indium Tin Oxide (ITO) are combined with unusual substrates like PVC plastic. Without compromising functionality, these materials enable smooth incorporation into applications where aesthetics are essential, such wearable technology or automobile systems. This study meticulously evaluates various substrate and patch material combinations using ANSYS HFSS software, examining crucial compromises and performance advantages. In order to help make an informed decision regarding the material selection for high-frequency fractal antennas, the study carefully evaluates conventional substrates (FR4 Epoxy, Rogers RT) alongside to unconventional and relatively inventive materials (Jeans, PVC Plastic) and patch conductors like Copper and ITO. By developing materials that maximize both functional and aesthetic qualities, the data collected seeks to provide important insights into the development of high-frequency fractal antenna design, enhancing antenna performance across satellite, radar, and telecommunications applications.

II. RELATED WORK

The Literature Review provides several Antennae for different Applications. A network-enabled on-body wireless communications using a hexagonal fractal antenna with a switchable radiation pattern was covered [3]. The printed antenna design presented in this study supports several wireless communication bands and has a compact structure [4]. The proposed single element antenna is intended to operate in X band with the center frequency (fr) of 10.00 GHz was designed and simulated [5]. The needs of condensed, low profile, and multi-band antenna structures can be satisfied by using the fractal patch. Numerous techniques as to how the size reduction of the antenna for the multi-band activity has been discussed for micro-strip fractal antennas [6]. The hexagonal form of the antenna discussed in the study is instrumental in boosting signal reception and radiation efficiency [7]. The rectangular form of the intended antenna contains non-resonating rectangular slots along the patch's sides and edges. Also, two chevron-shaped slots and a Sierpinski fractal slot are added in addition to boost impedance matching while offering a wide bandwidth [8]. A tree-shaped fractal millimeter-wave UWB antenna is achieved. The antenna incorporates a microstrip feeder, a dielectric substrate, a tree-shaped fractal, and a limited ground [9]. A planar monopole antenna that comprises of multiple wireless communication bands is described in order to provide multiple-input-multiple-output (MIMO) for handheld mobile devices [10]. Fractal antenna systems' probable functions and significant benefits in wireless communication systems [11]. A Snowflake fractal antenna for wireless communications that is compatible with both X-band and Ku-band applications is being researched [12]. An in-depth examination of the latest advances in fractal antennas with a special focus on fractal array theory and design [13]. Using three iterations, a new hexagon-shaped fractal multi-band antenna's performance is investigated [14]. The advantages of optically transparent antennas (OTAs), mainly focusing on their ability to satisfy basic coverage and bandwidth requirements while improving environmental aesthetics [15]. The development of the Koch Snowflake pattern has been discussed [16].

III. DESIGN OF THE ANTENNA

The design of the antenna with its specifications and the effect different substrates and patch materials have on the performance of the antenna has been discussed below:

A. *Design of the Koch Snowflake Antenna*

The Koch Snowflake fractal antenna design is based on the iterative construction of the Koch Snowflake, which is a classic example of a self-similar fractal. The initial shape starts off with an equilateral triangle. The construction begins with a simple equilateral triangle, which serves as the base shape (Iteration 0). Next, we go about the construction of the First Iteration. All the sides of the equilateral triangle is divided into three equal segments. An equilateral triangle is then constructed on the middle segment of every side, pointing outward. The base of each newly added triangle is removed, resulting in a star-like shape with 12 sides. For the second Iteration, each of the 12 sides of the star-like shape is further divided into three equal segments. Each of the 12 sides of the star-like shape is further divided into three equal segments. The base of each newly added triangle is removed, leading to a more intricate shape with 48 sides. Now for the Final iteration, all the 48 sides from the second iteration is again split into three equal segments. An equilateral triangle is created on the middle segment of each side, pointing outward. The base of each newly added triangle is removed, resulting in the 3rd iteration of the Koch Snowflake with 192 sides. This iterative process creates a highly detailed and complex fractal geometry that exhibits self-similarity at different scales. The 3rd iteration Koch Snowflake is chosen for its unique ability to provide a large surface area within a compact footprint, which is advantageous for antenna applications operating in the Ku band frequency range.

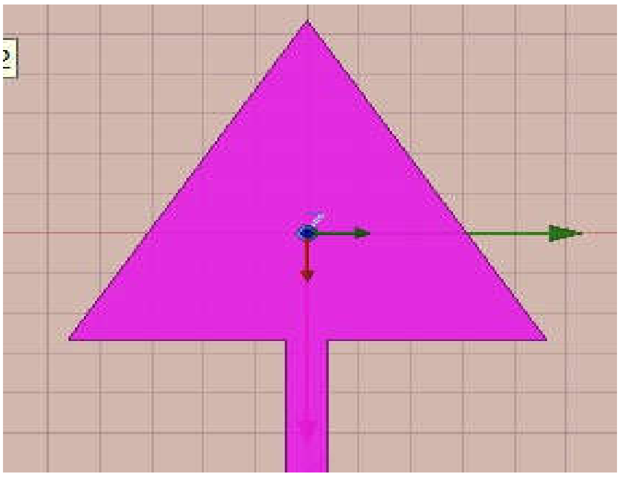

Fig. 1. Zeroth iteration

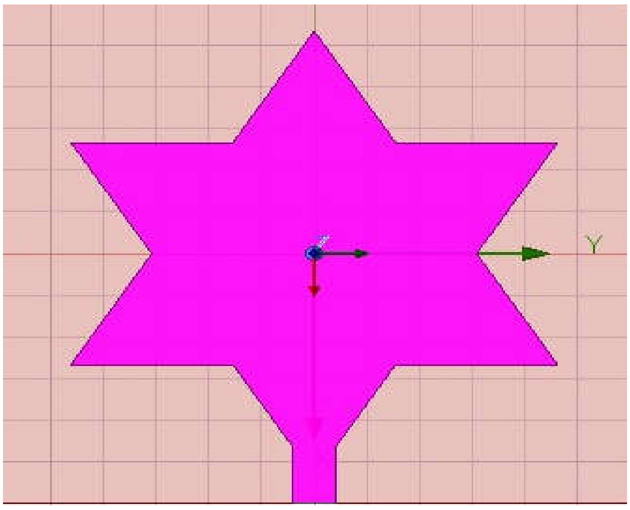

Fig. 2. 1st iteration

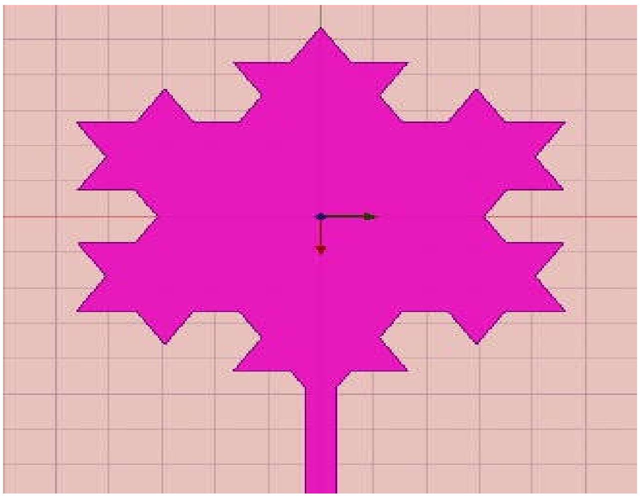

Fig. 3.2nd iteration

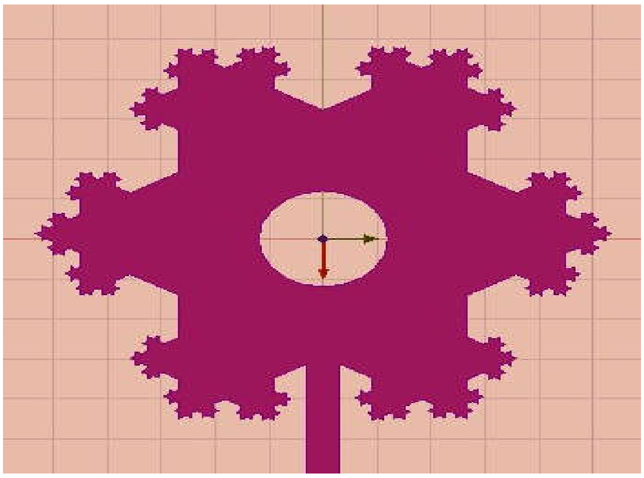

Fig. 4. 3rd iteration

TABLE I. Design specifications

Iteration	Side Length	No of Sides	Perimeter
0th	46.18 mm	3	138.54 mm
1st	15.39 mm	12	184.68 mm
2nd	5.13 mm	48	246.24 mm
3rd	1.71 mm	192	328.32 mm

B. *Effect of Substrate Materials*

The substrate material plays an important role in the performance of the antenna. The results for different substrate materials (keeping the patch material as copper) are summarized as follows:

FR4 Epoxy: Provides a moderate performance with ac-capable S11, gain, and VSWR values. Rogers RT: Offers improved performance due to its lower dielectric loss, resulting in better S11 and gain values. Jeans: Shows comparatively lower performance, likely due to higher dielectric losses. PVC Plastic: Exhibits the best performance when paired with ITO, highlighting the importance of both substrate and patch material properties.

C. *Effect of Patch Materials*

The patch material also significantly impacts the antenna's performance. The results for Copper and Indium Tin Oxide (ITO) as patch materials (keeping the substrate as PVC Plastic) are as follows:

Copper: Provides good conductivity and performance across the metrics. Indium Tin Oxide (ITO): Offers enhanced performance, particularly in S11 and gain, due to its unique conductive and transparent properties.

D. *Equations*

a) Length of each segment

The length of each segment at a given iteration n is given by:

$$L_n = \frac{L\sigma}{3^n} \qquad (1)$$

Where:

- L_n is the length of each segment at iteration n.
- $L\sigma$ is the length of the initial triangle's side.
- n is the iteration number.

b) Number of Sides:

The total number of sides at a given iteration n is calculated as:

$$N_n = N\sigma * 4^n \qquad (2)$$

Where:

- N_n is the number of sides at iteration n.
- $N\sigma$ is the initial number of sides.
- n is the iteration number.

c) Total Length of the Perimeter:

The total length of the perimeter at iteration n can be calculated by:

$$P_n = L_n * N_n * 4^n * \frac{L\sigma}{3^n} = N\sigma * L\sigma * \left(\frac{4}{3}\right)^n \quad (3)$$

Where:

- P_n is perimeter length at iteration n.
- L_n is the length of each segment at iteration n.
- N_n is the number of sides at iteration n.
- N_σ is the initial number of sides.
- L_σ is the initial side length of the triangle.
- n is the iteration number.

IV. SIMULATION AND RESULTS

The simulation setup and the performance parameters such as the S11 Parameter, Gain and Voltage Standing Wave Ratio (VSWR) are compared with different patch and substrate materials below:

A. *Simulation Setup:*

The Koch Snowflake fractal antenna was designed and analyzed using Ansys HFSS, which is a software primarily used for simulating high-frequency electromagnetic fields. The simulations were conducted for the Ku band frequency range (8 GHz to 12 GHz). The following setup parameters were used.

- Substrate materials:FR4 Epoxy, RT-Duroid, Jeans, PVC
- Patch materials: ITO (Indium Tin Oxide), Copper
- Frequency range: 8GHz to 12GHz (PML)
- Excitation: Lumped port.

B. *S11 Parameter analysis:*

The S11 parameter, also known as the reflection coefficient, was measured to evaluate the antenna's return loss. The results for different substrate and patch material combinations are summarized in Table II.

TABLE II. S11 Parameter Analysis

Material combination	Minimum S11 (dB)	Resonant frequency (GHz)
FR4 epoxy & copper	-31.9500	8.9800
RT-Duroid & copper	-17.4600	11.0600
Jeans & copper	-29.4611	9.1000
PVC plastic & ITO	-32.5038	11.2800

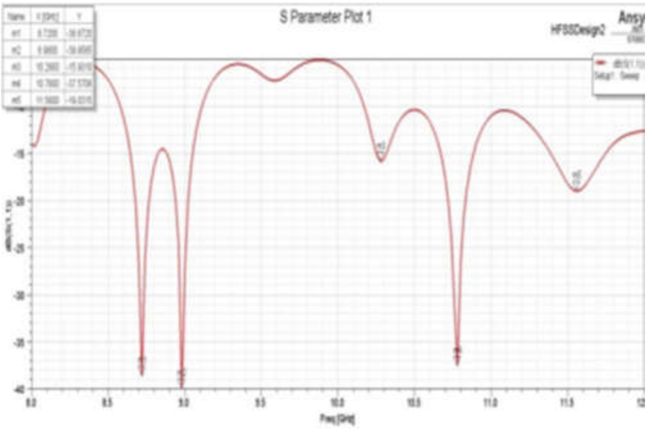

Fig. 5.S11 Parameter of Copper patch with FR4-Epoxy as substrate.

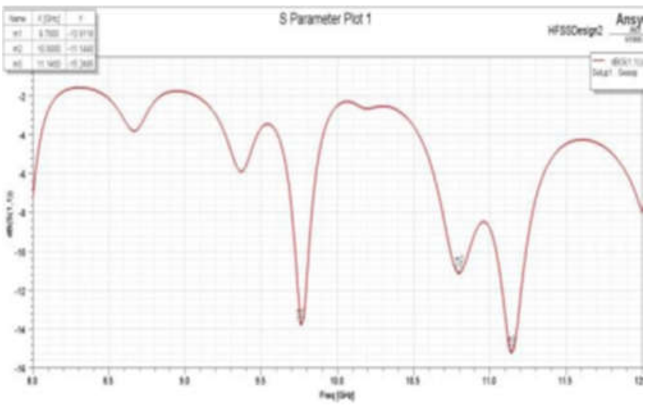

Fig. 6. S11 Parameter of Copper patch with RT-Duroid as Substrate.

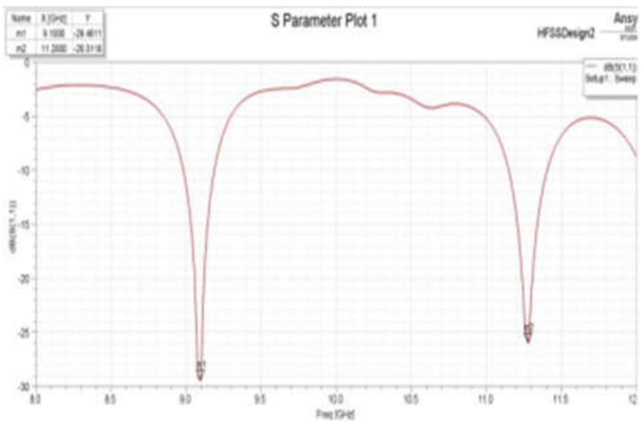

Fig. 7.S11 Parameter of Copper patch with Jeans a substrate.

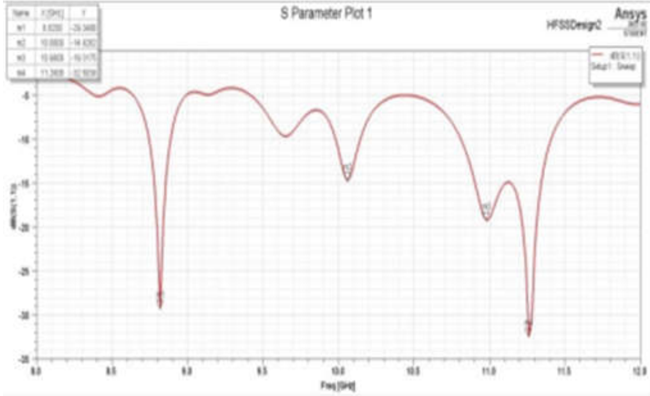

Fig. 8.S11 Parameter of ITO patch with PVC-plastic as Substrate.

The results show that the amalgamation of PVC Plastic and ITO offers the best performance in terms of return loss, with a minimum S11 value of -32.5038 dB at 11.2800 GHz. Additionally, the combination of FR4 Epoxy and Copper achieves a minimum S11 value of -31.9500 dB at 8.9800 GHz.

C. Gain Analysis:

The gain of the antenna was analyzed to determine its ability to direct radio frequency energy. The simulation results for the gain at the center frequency (10 GHz) are shown in Table III.

TABLE III. Gain analysis

Material combination	Gain (dB)
FR4 epoxy & copper	3.9127
RT-Duroid & copper	6.4237
Jeans & copper	5.0000
PVC plastic & ITO	5.2273

D. VSWR Analysis:

The VSWR (Voltage Standing Wave Ratio) is an essential metric that reflects the efficiency of power transmission from the antenna. The VSWR results for various material combinations are summarized in Table IV.

TABLE IV. VSWR analysis

Material combination	Minimum VSWR	Resonant frequency (GHz)
FR4 epoxy & copper	0.1746	8.9800
RT-Duroid & copper	3.0321	11.1400
Jeans & copper	0.5847	9.1000
PVC plastic & ITO	1.0621	11.2800

E. Radiation Pattern Analysis:

A radiation pattern in antenna design indicates how exactly the antenna radiates electromagnetic energy in a particular given space. It shows the relative strength of the radiated fields in different directions from the antenna.

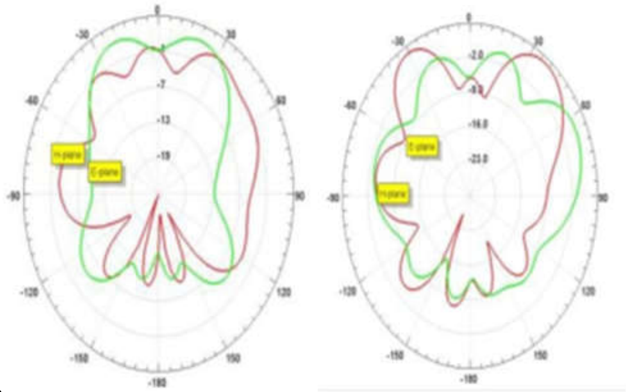

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Fig. 9. Radiation pattern of FR4-epoxy and copper(left), Radiation pattern of RT-Duroid and copper (right).

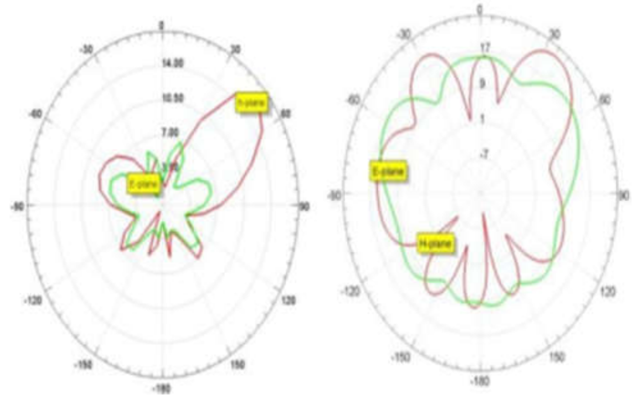

Fig. 9. Radiation pattern of PVC plastic and ITO and copper(left), Radiation pattern of jeans and copper (right).

V. CONCLUSION

This paper presents the design, simulation, and performance analysis of a Koch Snowflake fractal antenna operating in the Ku band (8 GHz to 12 GHz). The antenna was evaluated using various substrate and patch materials combinations, including FR4 Epoxy and Copper, Rogers RT and Copper, Jeans and Copper, and PVC Plastic and Indium Tin Oxide (ITO). Performance metrics such as the S11 parameter, gain, and VSWR were analyzed. The results obtained ascertain to the fact that material plays a vital role in the performance of an antenna. It was observed that the lowest S11 value of -32.5038 dB and a maximum gain of 5.2273 dB, and the best VSWR of 1.0621 was obtained at 11.2800 GHz, the PVC Plastic and ITO combination has outperformed the other tested combinations. The results obtained speak to the potential of high-frequency fractal antenna designs using unconventional materials like ITO and PVC plastic. The Koch Snowflake antenna due to its special geometrical characteristics shows promise as it has been observed to improve performance parameters. This work highlights how crucial the material selection aspect is when designing antennas and also provides opportunities for more research into unusual materials for fractal antenna applications. Furthermore, the impact of various combination of materials on the performance of an antenna for higher frequency bands will be the main focus for further research.

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