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Research paper

A Slotted Microstrip Antenna with Fractal Design for Surveillance Based Radar Applications in X- Band

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Abstract

This paper proposes a unique micro-strip patch antenna which has a hexagonal fractal pattern which can mainly be used for ground based surveillance radar applications. To further optimize the functioning of the antenna, multiple slots have been added to the ground plane, and a stepped pattern has been implemented to increase the current density and the gain. A detailed study of the stages of development of the antenna has been made, illustrating the effect that various design elements have on the operating characteristics of the final design. There is specific emphasis on the use of slots in the ground plane. Variations in return loss, gain, VSWR, operating frequency and bandwidth with changes in the design of the ground plane have been documented. The antenna is designed to perform in the X-band, more specifically around 9 GHz, making it well suited for short range search. The final iteration of the antenna design, including various stages of slotting in the ground plane, works at 8.7 GHz, which is well within the X-band range, and has a return loss of around 30 dB.

Keywords: *David Antenna; hexagonal; Voltage Standing Wave Ratio (VSWR); fractal; surveillance radar; return loss; X band*

1. Introduction

Microstrip antennas have become very popular for various applications. These antennas are low profile, physically robust, and have very less manufacturing cost owing to modern printed-circuit technology. Additionally, the versatility of these antennas can be judged with respect to resonant frequency, impedance matching, and polarization pattern, and are used to with designs of MMIC (Monolithic Microwave Integrated Circuit) [1]. Hence, these antennas are specifically compatible with both mechanically rugged and subsystems which are light in weight such as those that are used for radars which demand a low profile.

The Microwave Region contains X-band that falls within the frequency range of 8.0 to 12.0 GHz, as per the IEEE. This band is used for a variety of applications like weather monitoring, defence and space communications, and high resolution imaging. The radar operating in the X band is well suited for high resolution search where light weight and mobility are prioritized over long range as described in [1]. Good target resolution is achieved through wide bandwidth and narrow beam width allocations as detailed in [2] and [3].

The term “fractal” has been coined by Mandelbrot, and is explained in [5]. Fractals are often used to model complex natural objects, and their applications to antenna engineering allow for implementing several new and innovative designs, as explained in [6]. Symmetric fractal patterns significantly increase the surface current path length compared to a conventional patch antenna of similar dimensions. The use of a fractal design allows us to achieve conformity and low profile with a compact size. Fractal antennas are implemented through the repetition of a shape over two or more scale sizes, or "iterations". The feed network of the proposed antenna contains two iterations of self-repeating hexagonal patterns.

A slot antenna includes a flat metallic surface with a hole or “slot” cut out. The slot mimics a dipole antenna in the way it radiates electromagnetic waves. The major factors influencing the radiation distribution pattern involve the shape and size of the slot and also it's driving frequency. Slotted antennas have been useful when there is a requirement of more control of radiation pattern, and are thus are used in radar antennas, where directivity is essential. As suggested in [7] and [8], slots have been added to the ground plane for optimizing the antenna, and their effect on the bandwidth and the gain, is also analyzed in this paper.

2. Methodology

The size of the feed pattern and the antenna are estimated by approximating them to the length and width of a simple, rectangular patch antenna at the same frequency. While increasing the substrate thickness directly increases the operating frequency, it can also cause undesired radiation patterns. Thus, this trade-off between bandwidth and radiation pattern must be taken into consideration while sizing.
Generally the relative dielectric constant of the substrate lies in the range $2.2 \leq \varepsilon r \leq 12$. The fringing effect changes the dielectric constant and the length of the substrate [4] as a lot of waves too travel

via air. Therefore effective dielectric constant ε_{reff} and effective length L_n are given by:

For $\varepsilon_r = 4.3$

$$\varepsilon_{r'eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} + [1 + 12\frac{t}{w}]^{\frac{-1}{2}} \quad (1)$$

And

$$L_n = L + 2\delta L \quad (2)$$

where t is the substrate thickness and δL is given by

$$\frac{\delta L}{h} = 0.412\frac{(\varepsilon_{r'eff}+0.3)(\frac{W}{t}+0.264)}{(\varepsilon_{r'eff}-0.258)(\frac{W}{t}+0.8)} \quad (3)$$

And length L and width W are given by:

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{r'eff}\,\mu_o\,\epsilon_o}} - 2\Delta L \quad (4)$$

$$w = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (5)$$

where, c: light's speed f: frequency.
These formulae yield the dimensions of the substrate to be 44mm X 44mm. The design and dimensions are illustrated in the following section. Fig. 1 depicts the design of the antenna proposed. It is similar to the David antenna proposed in [8], where on the design of hexagonal patch the fractals are made which as a result leads to increase in the bandwidth of the antenna. Modifications to the design are inspired from the configurations proposed in [1], [2], and [3].
The antenna is etched on an FR4-epoxy substrate since it is very economical to use. It has a thickness of 1.6mm, permittivity of 4.4, and a loss tangent of 0.002. The sides of the antenna proposed, depicted in Table 1, ensure its working in the X-Band. The system is fed with a rectangular feed line of 50Ω, with dimensions 22mmX1.66mm.

Table 1: Dimensions of the proposed antenna

Parameters	Value (mm)
Length of Substrate	44.000
Width of Substrate	44.000
Horizontal Length of Slot	25.329
Horizontal Width of Slot	1.690
Vertical Length of Slot	20.329
Vertical Width of Slot	2.250
Ladder Step	1.000
Hexagonal Length	1.667

3. Antenna Designs

The antenna proposed has been simulated in Ansoft High Frequency Structure Simulator (HFSS v13.0). The work done previously in [1] has been taken as a base and further improvements have been done on the same design. Major results including the radiation patterns, return loss, gain and VSWR have been depicted of the proposed antenna. A parametric study has been conducted which investigates the effects of different parameters of the proposed antenna and the S11 parameter rectangular plots of the designs have been shown.

3.1. Antenna 1

This is the basic design of the antenna without a ground plane, and with hexagonal fractal feed. Its corresponding rectangular plot is given below. The two major peaks in the graph correspond to a return loss of -8 dB at 8.1 GHz and 21.95dB at 9.5 GHz.

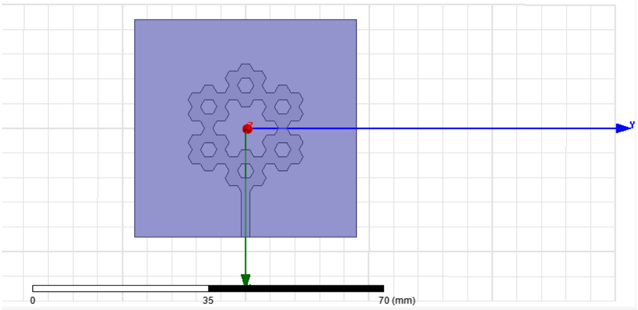

Fig.1. Hexagonal fractal antenna with no ground plane, and its corresponding current density distribution

3.2. Antenna 2

This design contains the antenna with a regular square shaped ground plane of side 44mm, which is the same size of the substrate. It yields a return loss of -11.15 dB at 7.3 GHz.

3.3. Antenna 3

This design is similar to Design 2, but contains vertical slots in the ground plane of dimensions 14mm X 1mm. The changes in the return loss can be seen from the ensuing rectangular plot.

3.4. Antenna 4

This design contains horizontal slots instead of vertical ones in the ground plane. The slots have dimensions 25.33mmX1mm each, and are symmetrical, as shown in the following figures.

3.5. Antenna 5

In this iteration, the previous design has been modified keeping current density gains in mind. The upper slot has been extended iteratively to form a stepped pattern, keeping the lower slot intact. The step size is 1mm, and the length of each consecutive slot in the stepped design increases by 2mm. This design generates a favorable result, as has been concluded in [2].

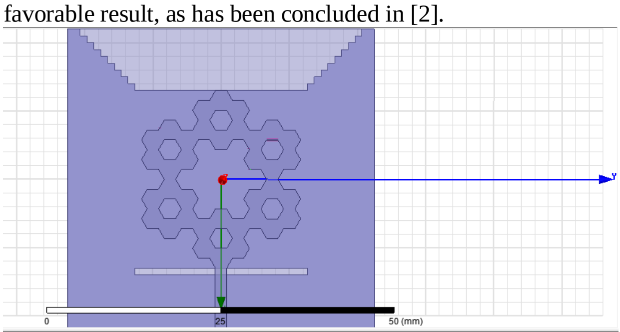

Figure 2: Design 5

3.6. Antenna 6

Two horizontal slots being added in the ground plane towards the bottom have led to an incremental improvement upon the previous, keeping the stepped pattern as it is. This increases the current density around both the bottom slots and improves upon the results of the previous design.

3.7. Antenna 7

This is an upgraded design of the proposed antenna. The vertical slots seen in Design 3 are added back to the ground plane, but their dimensions have been tweaked to obtain an optimum operating frequency in the X-Band. The obtained results have been included thereafter.

3.8. Antenna 8

In this design, the stepped pattern has been combined to form one big slot. The horizontal and vertical slots of the previous design have been kept the same. The S 11 is obtained to be more negative at the same frequency.

3.9. Antenna 9

The horizontal slots have been made symmetrical and of an equal number. The vertical slots are symmetrical too, are half of the horizontal slots.

3.10. Antenna 10

An equal number of horizontal and vertical slots have been introduced, with 2 slots on either side.

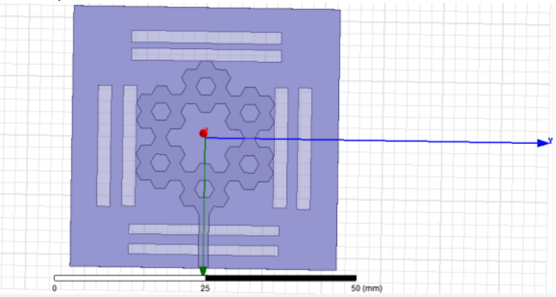

Figure 3: Design 10

4. Results and Discussions

A detailed report of the final design results has been compiled below. As seen from the above comparisons, we can see that Design 7 yields a highly desirable gain when compared to other designs. Moreover, it also offers a high 10dB bandwidth of nearly 340 MHz (8.62 GHz to 8.96 GHz), with the optimum operating frequency of 8.7 GHz. This behavior is well suited for applications in the X-Band. The maximum gain at the operating frequency is -29.56 dB. However, for optimum use in radar applications the radiation efficiency pattern of an antenna is also an important parameter. The radiation pattern must be fairly widespread [3] in order to be able to detect objects in the immediate surroundings of the antenna. High directivity is undesirable.
In addition, the Voltage Standing Wave Ratio (VSWR) of the antenna's emission pattern gives us valuable insight into it's connection to surveillance radar system as to how well the impedance matching is done, and is an important metric in measuring the radiation efficiency of the antenna at a particular frequency. For an ideal antenna with perfect impedance matching, the value of VSWR is 1. As calculated above, this analysis of VSWR parameters concurs with the bandwidth of 340 MHz. A step by step compilation of the various parameters obtained from analyzing the various designs has been presented in Table 2. In Fig. 4, a cumulative parametric analysis of the return loss of the various designs has been presented as a colour coded graph, enabling easier comparison. This will illustrate the effect of various design elements on the result.
From the exhaustive study completed above, the addition of the slots in the ground plane depicts the following trends:

4.1 Adding slots lowers the fundamental resonant frequency.

This is observed in comparing Design 2, Design 3, and Design 4, although the effect is more pronounced in the subsidiary lobes. Designs 5, and 6 show a drastic shift in the operating frequency, which is primarily due to the stepped pattern, which is equivalent to multiple slots.

4.2. Adding horizontal slots increases the gain.

The addition of horizontal slots in Design 3 boosts the gain by about 2 dB. The increase for Designs 5 and 7, which have multiple horizontal slots, is manifold. However, adding slots very close to each other, as in Design 6 decreases gain, possibly due to interference of radiation patterns.

4.3. Increasing slot width increases current density.

This trend is visible in the transition from antenna 5 and 6 to antenna 7. An increase in the thickness of the slots increases the surface current density distribution around the slots and the fractal design feed element. This leads to a net increase in gain.

4.4. The insertion of the slots leads to an incremental improvement in the range of the radar.

Addition of the slots broadens the range of the antenna and hence detects targets in a more diversified range.

4.5. The VSWR value 1 as slots introduced.

The VSWR decreases as the number of the slots in the ground plane increases to reach a desirable value of close to 1. This implies that the antenna's impedance is very well matched with the impedance of the radio and transmission line

4.6. Fractal design increases surface current density.

This is visible in antenna 2, where there is an increase in the current density distribution around the fractal design feed element. The increase is appreciable when compared to a simple patch antenna of similar dimensions.

Table 2: Performance Comparisons of Different Antennas

Name	Frequency(GHz)	Gain (dB)	VSWR
Antenna 1	9.5	-26.2	1.18
Antenna 2	7.3	-11.16	2.10
Antenna 3	7.3	-11.30	1.26
Antenna 4	7.3	-12.94	1.17
Antenna 5	9.2	-20.75	1.12
Antenna 6	9.2	-10.44	1.21
Antenna 7	8.7	-29.56	1.07

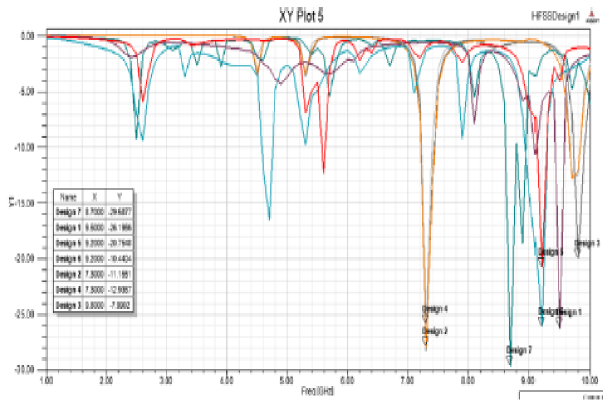

Figure 4: Parameters Rectangular Plots for Various Designs

5. Conclusion

The use of a fractal based antenna design to increase bandwidth has been receiving much interest in recent times. In this paper, an application for such a design in a X-band surveillance radar has been proposed. The design is further optimized by the addition of slots. The suitability of the design for the proposed application is systematically proved by analysing its gain, radiation pattern, VSWR values and operating bandwidth.

It is very well known that introduction of slots in the antenna can improve the performance by a lot. It has been well documented in

[6,7]. We have used S-parameter curves to understand and draw differences in different stages of development when different slots were introduced which modified the existing characteristics.

A detailed comparison with the various other design stages obtained during development has been made, showing the inherent benefits of one design over the other. This helps us obtain some general trends while designing, which have been documented herewith, and would be helpful for further research in this area.

Acknowledgement

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