Koch Fractal Antenna Application in Monopulse Antenna Array

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***Abstract*—This paper addresses the design and evaluation of monopulse antenna array used in UAV on-board collision avoidance radar. The antenna array use the advantages of the fractal geometry. The inverted Koch square patch fractal antenna has been modified in order to gain more control over the efficiency degradation originating from production difficulties and to meet the requirements of a monopulse collision avoidance radar. Simulation and measurement results show the applicability of fractal geometry in antenna arrays.**

***Index Terms*—monopulse radar, fractal antenna, inverted Koch fractal, fractal antenna array**

I. INTRODUCTION

This paper addresses the application of Koch fractal geometry in small sized antenna arrays. When it comes to designing antenna systems, it is essential to properly set the spacing between antenna elements. The interelement spacing should not exceed one wavelength to avoid grating lobes (multiple main beam) [1]. However, the physical size of single elements are commensurable with half wavelength or quarter wavelength in general. Therefore, the realization of the antenna system could easily come up against problem. On of the possible solutions to size reduction is the application of fractal antennas. The goal of this paper is to present the design and evaluation of an antenna system that takes advantage of fractal antennas. The design considerations and the characterization of single element are discussed in detail. The efficiency of Koch fractal geometry using in antennas has been widely proved so far [4],[5],[6],[3]. At the same time, proper fabrication of inverted Koch square patch antennas can be difficult due to the required sharp edges. In this paper we describe our fractal geometry which is a modification of the standard inverted Koch square fractal. Design methodology has been presented along with the simulation and measurement results comparison.

II. DESIGN CONSIDERATIONS

Collision avoidance radars can use the monopulse principle to detect nearby targets and determine those position. According to the measurement results the UAV could execute the necessary maneuvers to avoid the collision. In order to perform the right maneuvers the UAV must have three dimensional information about the targets position, thus it is necessary to measure both azimuth and elevation angles. So the antenna system must consist of four receiver and a transmitter antenna to produce the two delta and the sum channels. The distance between receiver antenna elements should be kept around half a wavelength to evaluate wide enough beams in the monopulse beampattern. However, receiver elements should be placed maximum a wavelength away from each other to prevent grating lobes appear and measurements uncertainty. Since the separation of the transmitter and receiver antennas is not feasible due to the small space the layout presented on figure 1 has been designed. Other benefit of this antenna layout is the nearly symmetrical electromagnetic field distribution on the different antenna elements. The operating frequency of the experimental radar is in the F-band, while the relative bandwidth of the system is approximately 4%.

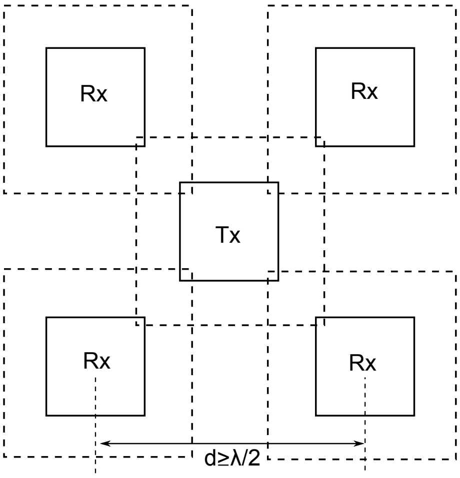


Figure 1. Schematic layout of the monopulse antenna array

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} \tag{1a}$$

$$L = \frac{1}{2f_r\sqrt{\epsilon_{eff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \tag{1b}$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-\frac{1}{2}} \tag{1c}$$

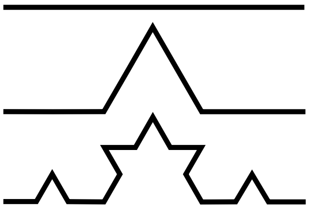


Figure 2. Koch fractal evolution

Using the well known equations above (1 a-c) [1] the physical sizes of a conventional microstrip rectangular path antenna can be calculated. For a standard FR4 substrate with $\epsilon = 4.5$ relative permittivity and $h = 1.5\,\mathrm{mm}$ substrate height we get $W = 30.13\,\mathrm{mm}$ for the width and $L = 36.9\,\mathrm{mm}$ for the length of the patch antenna. While the free-space wavelength is $\lambda_0 = 100\,\mathrm{mm}$. Figure 1 illustrates the structure of the designed antenna array. The interelement spacing of the receiver antennas is half wavelength. The dashed lines illustrates the previously calculated sizes of the antenna elements. As it can be seen from the layout the use of standard microstrip patch antennas is not possible because of inter element overlapping. Consequently the physical size of the antenna elements must be reduced. There are several methods to reduce the size of the microstrip patch antenna such as using substrate with high dielectric permittivity or applying slots. However, higher dielectric substrate can only used in the expense of reducing the antenna bandwidth as it is analyzed in [1]. In order to increase the bandwidth of the antenna the FR4 substrate was extended with $10\,\mathrm{mm}$ height air gap (The height of the FR4 substrate is also decreased from $1.5\,\mathrm{mm}$ to $0.5\,\mathrm{mm}$). Figure 6 illustrates the stack up of a single element.

Using fractal geometry the electrical size of the antenna can be increased without greatly affecting other antenna parameters. Our main goal was to design the above described antenna system using fractal geometry antennas thus the antenna system could meet the requirements.

III. FRACTAL ANTENNA GEOMETRY

Our antenna design utilizes the geometry of inverted Koch square patch. The Koch curve is one of the first published fractal shapes proposed in 1904 by Niels Fabian Helge von Koch [2]. Taking a segment of a straight line as initiator, then substitute the middle third of it with an equilateral triangle, results the so called generator. Repeating the previous step for all the newly obtained segments again and again we get the Koch fractal curve depicted on figure 2. Applying the Koch generator to a regular polygon converge to the Koch island fractal. In case of the base polygon is a square, the fractal is called Koch square fractal. Inverted Koch square fractal geometry can now be constructed with using subtraction instead of complement the initiator with the equilateral triangle in each iteration. Using the above described procedure the fractal illustrated on figure 3 can be generated [3]. Effectiveness of the fractal antenna geometry generated in this manner has been proven so far.

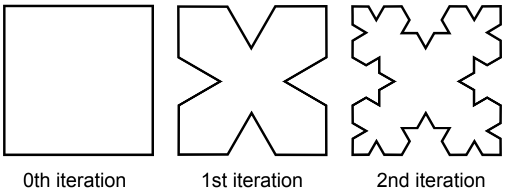


Figure 3. inverted Koch square fractal evolution

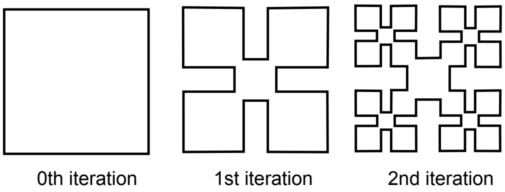


Figure 4. Modified inverted Koch square fractal evolution

At the same time this fractal shape has also some drawbacks. Symmetrical properties of the structure may easily damaged during the etching process in PCB manufacturing. To overcome this difficulty we are proposing a modified inverted Koch fractal geometry. To eliminate the sharp edges of the fractal structure we experimented with using rectangular notches instead of sharp triangles. Figure 4 illustrates the modified inverted Koch fractal patch evolution until the second iteration.

IV. DESIGN METHODOLOGY

For designing the antenna we have developed an inverted Koch square fractal geometry generator program. This program is capable of generating the inverted Koch square patch antenna geometry both with triangle insets and with rectangular insets. The parameters of the insets such as the width and height can be configured in the program. The output of the program is a '.dxf' file which can be used by an EM simulator program. In order to facilitate the manufacturing we only generated antenna geometries until the second fractal iteration.

Feeding of the antenna elements using microstrip transmission lines could not be carried out without affecting the symmetry of the antenna system. L-probe feeding used in [3] was not advisable in our case because of low mechanical stability. Thus, in order to prevent unwanted coupling effects and to achieve stable feeding structure we are feeding the antenna directly with coaxial probe. Figure 6 shows the applied feeding method and the parameters of the antenna stack up.

After the fractal geometry generation the EM performance of the fractal antenna has been evaluated using CST Microwave Studio. Simulations are made using frequency domain solver and tetrahedral mesh. Parameter optimization has also done with CST, such as structure scaling and coaxial probe feeding position. Sweeping with the coaxial probe offset the real part of the antenna radiating impedance can matched to $50\,\Omega$.

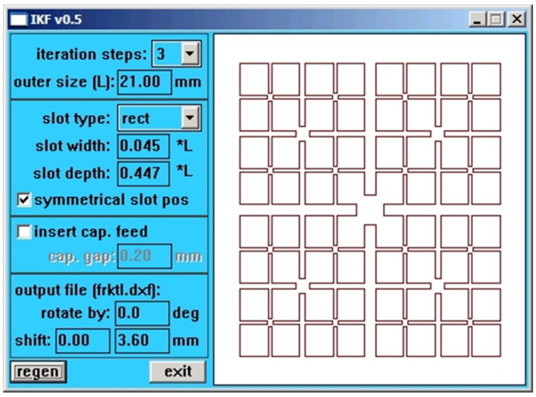
However, care must be taken when placing the coaxial probe close to the center of the antenna. As the probe position is approaching to the center the four main part of the antenna tends to radiate each independently. This kind of radiation pattern can not be accepted in monopulse antenna systems as it may results in uncertainty during target detection.

V. RESULTS

The first experimental prototype of the antenna has designed to operate at $3.3\,\mathrm{GHz}$. In order to gain good enough size reduction and easy manufacturability we have designed the fractal geometry until the second iteration. The physical size of the designed fractal antenna element is $19\,\mathrm{mm}$. Simulation results including the farfield pattern, input reflection can be seen on figure 7, 8. After the simulations had made the antenna array was fabricated (figure 11). Measured input reflection also can be seen on figure 7. The input reflection curve shows similarity between measured and simulated result.

Calculating the standard rectangular patch antenna physical sizes using equations 1 (a-c) with $h = 10\,\mathrm{mm}$ and with air substrate we get $W \simeq 50\,\mathrm{mm}$ and $L \simeq 36\,\mathrm{mm}$, while our designed antenna physical sizes are $19\,\mathrm{mm}$, thus we achieved 62% size reduction.

During the course of optimization a trade-off must be made between the input reflection and the radiation pattern. The better the input reflection is the more the major beam splits into individual sections. To obtain better monopulse like characteristic, the splitting of the major beam can not be accepted. Figure 8 and 9 shows the radiation pattern variation both in E-Plane and H-plane for different feed positions, while figure 10 shows the input reflection for different feeding offset. Thus to satisfy these conditions the radiation pattern of the antenna system has been optimized in the expense of input reflection. The final feed offset has set to $6.8\,\mathrm{mm}$. The simulated monopulse delta channel beampattern is illustrated on figure 12.



iteration steps: 3
outer size (L): 21.00 mm
slot type: rect
slot width: 0.045 *L
slot depth: 0.447 *L
☑ symmetrical slot pos
☐ insert cap. feed
cap. gap: 0.20 mm
output file (frktl.dxf):
rotate by: 0.0 deg
shift: 0.00 3.60 mm

Figure 5. Developed fractal geometry generator program

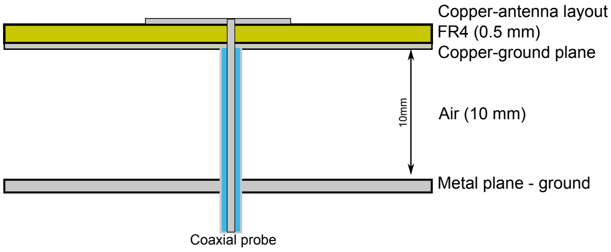


Figure 6. Single antenna element stack up

VI. CONCLUSION

With the presented modifications on inverted Koch fractal geometry almost the same performance can be achieved as with the original one. The achieved 60 percent size reduction proves the applicability of the proposed geometry in antenna array where available space is an important factor. With careful design a reasonable trade-off can be made between the input reflection and the farfield pattern of the antenna.

ACKNOWLEDGMENT

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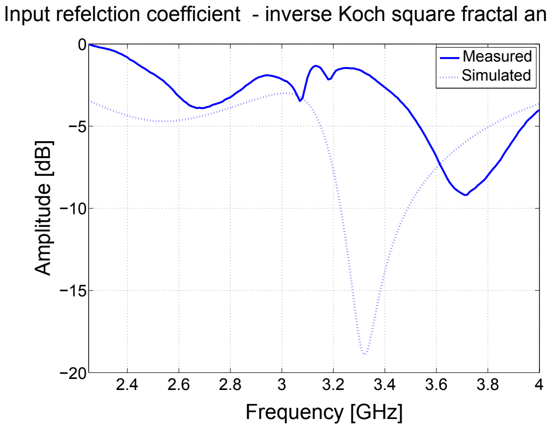

Figure 7. Measured and simulated input reflection

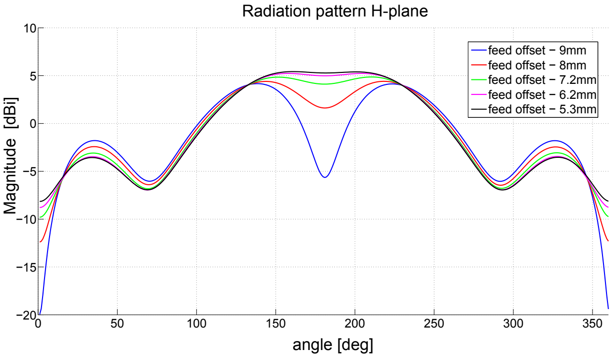

Figure 8. Distribution of the major beam occurs when the antenna is fed close to its center

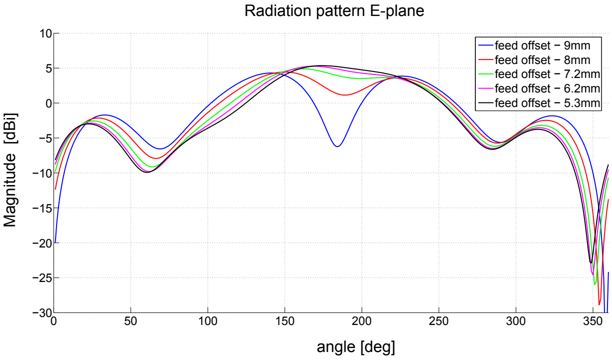

Figure 9. Distribution of the major beam occurs when the antenna is fed close to its center

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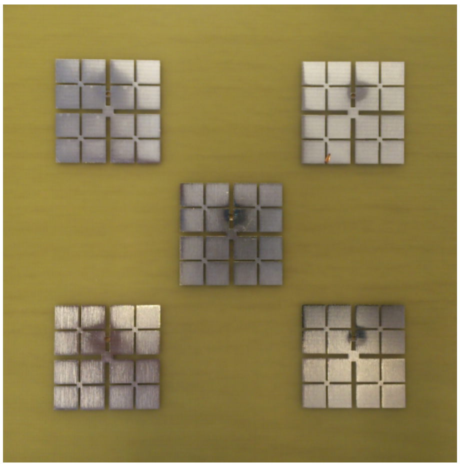


Figure 11. Fabricated fractal antenna array

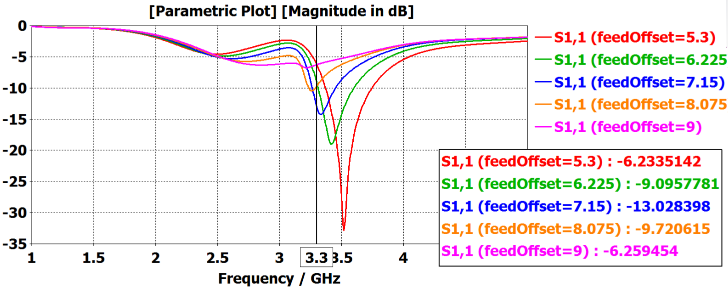
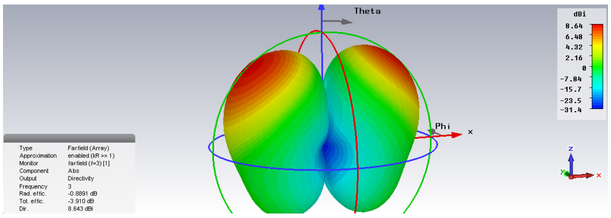


Figure 10. Antenna input reflection with changing the feed position



Type	Farfield (Array)
Approximation	enabled (kR >> 1)
Monitor	farfield (f=3) [1]
Component	Abs
Output	Directivity
Frequency	3
Rad. effic.	-0.8891 dB
Tot. effic.	-3.910 dB
Dir.	8.643 dBi

Figure 12. Monopulse delta channel farfield pattern