A Miniaturized Wide-Band LTCC Based Fractal Antenna

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Abstract: A Sierpinski carpet fractal antenna design is realized for the first time in low temperature co-fired ceramic (LTCC) medium. An aperture coupled LTCC topology is utilized, which is highly suitable for multi-layer system-on-package (SoP) concept. This paper presents a comparison between a conventional patch antenna and the fractal antenna, both designed at 24GHz, on the LTCC substrate. The results demonstrate that the bandwidth of fractal patch antenna is 7.3 % as compared to 1.9% for the conventional patch antenna. In comparison to the conventional approach, the size of the fractal patch antenna has been reduced by 57%. With such a large bandwidth, the design is quite suitable for high data rate applications. A detailed sensitivity analysis has been performed which reveals that the design is quite robust to typical LTCC fabrication tolerances.

Keywords: LTCC (Low Temperature Co-fired Ceramic), SoP (System on Package), Fractal Antenna.

1. Introduction

The explosion of wireless devices in the last decade has revived the antenna engineering. Miniaturization, large bandwidth, and efficiency of the antenna have been the key performance parameters for the new generation of antennas. Microstrip patch antennas are one of the most commonly used topology because of their low-cost, low-profile, light-weight, and easy fabrication. These advantages of the patch antennas make them a suitable choice in applications such as WLAN, satellite communications, and international mobile telecommunication [1]. Despite the advantages mentioned above, a major drawback is the small bandwidth of the patch antennas. Several papers have demonstrated the methods to improve the bandwidth performance of patch antennas while maintaining the performance of gain and beam width such as two port excitation of the antenna [2], use of shorting posts between the antenna and ground plane [3]. These techniques are effective in terms of enhancing the bandwidth performance but they introduce additional components or fabrication steps to achieve these goals. An alternate approach can be the use of fractal geometries which inherently have large bandwidth, due to their multi resonant structures [4,5].

The term fractal was introduced by 'Madelbrot' to define a new geometry of shapes which can be defined as complex structures that have self similarity [5]. The fractals are composed of numerous small units of non integer dimensions which stack up together to give rise to a complete structure which has the similar shape as that of the unit structure. This unique property of fractals has been exploited to develop antennas that are compact in size and have large bandwidths [6]. The fractals can have multi-resonances; hence, provide greater bandwidths as compared to the conventional antennas [7]. In addition to their larger bandwidths, fractal antennas are compact in size relative to the conventional antennas because of their efficient volume filling nature. The self affine and space filling properties of fractal antenna increases the effective electrical length of antenna to reduce the size of the antenna and hence, making them compact.

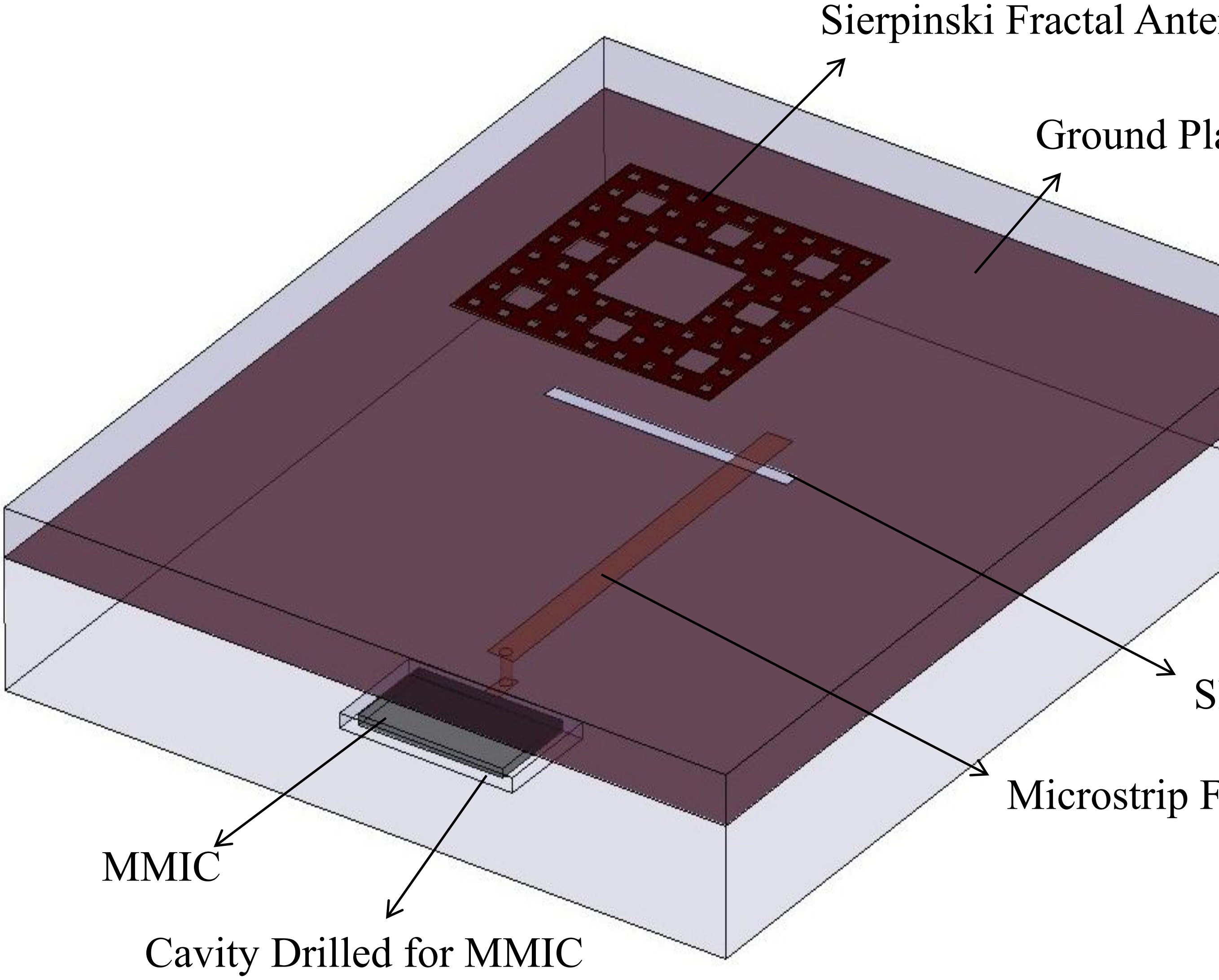
Fractal antennas have been designed previously, but they are implemented on PCB based substrates [4,7] rather than LTCC. LTCC has now become a popular medium for wireless applications, such as sensors and microsystems [8,9]. The rationale for the use of LTCC is its multilayer technology which allows vertical stack up. This vertical stack up helps in isolating the RF circuits from the antenna radiations. In addition, it helps to decrease the horizontal area of the system by allowing the components to be integrated vertically. The paper, for the first time, presents LTCC as a platform for the development of fractal antennas.

2. Concept and Design

A. *SoP Concept*

The multi layer nature of LTCC permits vertical stacking of the active and passive components. This is an ideal medium for aperture coupled antenna design. The RF driving circuits can be placed in a cavity below the ground plane and the antenna can be realized on the top layer as shown in figure 1. The bottom substrate is five layers thick with a four layer thick cavity to accommodate the microwave and millimeter-wave integrated circuit (MMIC). The MMIC is a flip-chip, which rests on the solder balls in the cavity. The output of the MMIC, placed in the cavity, is connected to the microstrip feed line through a bond wire or solder ball. One layer thick substrate is placed between the microstrip feed line and the ground plane. The ground plane contains a slot which is excited by the microstrip feed line. The added advantage of this design technique is the shielding of RF circuits from the antenna radiation due to the presence of a ground plane in between the two. However, one drawback of this technique is the backward radiation from the slot which is present in the ground plane. This radiation can be reduced by adjusting the length of the slot and by placing the slot in a way that the active circuits don’t lie beneath the slot [10].

Figure 1: Aperture coupled fractal antenna design in



B. *Conventional Aperture Coupled Patch Antenna*

The patch antenna is designed on eight layers of CT707 substrate having a permittivity of 6.39 and loss tangent of 0.001 with each layer of thickness 100 um. The 50 Ω feed line of dimension 0.14 mm is designed on the bottom of the first layer with a ground plane on the top of the third layer. A slot of dimension 0.1 mm x 1.68 mm has been positioned in a way that it lies at the centre of the patch. The length of the slot is optimized to adjust the resonant frequency of the patch antenna to be 24 GHz while the width of the slot is tunes the input impedance of the antenna. The patch of dimension 2.39 mm x 3.42 mm is placed on the top of the eighth layer. The simulations have been performed in Ansoft HFSS$^{\text{TM}}$.

The return loss of patch antenna demonstrates a bandwidth of 460 MHz which is 1.9 % of the centre frequency as can be observed in figure 4. The simulated radiation pattern of the patch, shown in figure 2 above, exhibits a gain of 4.6 dB and beam widths of 55° and 120° in the H plane and E plane, respectively.

C. *Fractal Aperture Coupled Patch Antenna*

The construction of a square Sierpinski carpet fractal antenna is carried out by successive iterations applied on a simple patch 3(a). A square of dimension equal to one third of the main patch is subtracted from the centre of the patch giving rise to structure of Figure 3(b). The next step is etching of squares which are nine times and twenty seven times smaller than the main patch as demonstrated in Figures 3(c) and 3(d), respectively. The second and third iterations are carried out nine and sixty three times respectively, on the main patch. This fractal can be termed as third order fractal as it is designed by carrying out three iterations. In this particular design, the iterations are of dimensions 0.6 mm, 0.2 mm and 0.0667 mm, respectively. The number of iterations can be increased but due to the fabrication tolerance of 50um the design was kept till the third iteration.

The fractal antenna is designed on the same eight layers of CT707 as in the case of aperture coupled patch antenna to compare the performance of the two. The feed line and the slot have the same dimension as in the case of patch antenna due to the presence of same number of layers. The fractal antenna has a dimension of 1.8 mm x 1.8 mm which is 57% smaller than the conventional patch at the same frequency of 24 GHz. The simulated bandwidth of the fractal antenna, as shown in Figure 4, is 1.7 GHz (7.3% of 24GHz) of the centre frequency which is 3.84 times higher than that of the conventional patch which is 460MHz (1.9% of 24 GHz). The design exhibits a gain of 5.03 dB and beam widths of 50° and 110° in H plane and E plane respectively. The 3D polar plot of radiation from the fractal antenna is quite symmetric about z axis as can be observed from figure 6.

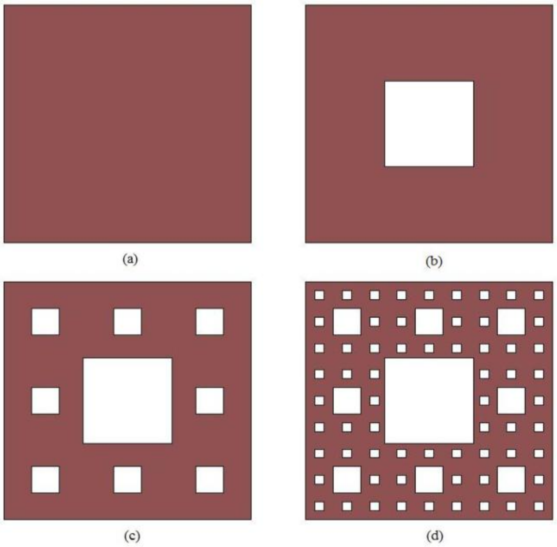
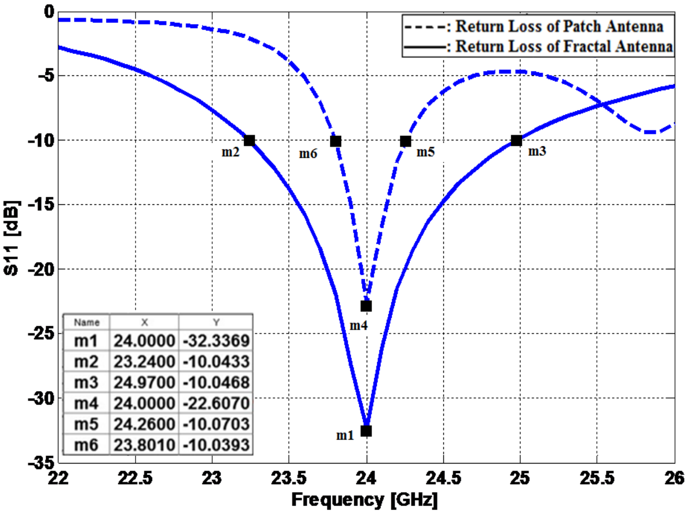


Figure 3: Fractal Design (a) Zeroth order iteration (b) First order iteration (c) Second order iteration (d) Third order iteration



Name	X	Y
m1	24.0000	-32.3369
m2	23.2400	-10.0433
m3	24.9700	-10.0468
m4	24.0000	-22.6070
m5	24.2600	-10.0703
m6	23.8010	-10.0393

Figure 4: A Comparison between the return loss of two antennas

3. Sensitivity Analysis of the Fractal Antenna Design

The sensitivity analysis of Sierpinski carpet fractal design is carried out by varying the size of its inner squares in order to observe the variation in the gain and bandwidth of the antenna. Sensitivity analysis is important to find out the effect of fabrication tolerances on the performance of the fractal antenna. The simulation results show that the variations in antenna dimensions have little influence on the gain and bandwidth of the antenna.

The three iterations of figure 4 (b), (c) and (d) are swept from 0.6 mm to 0.7 mm, 0.17 mm to 0.23 mm, and 0.055 mm to 0.077 mm, respectively, to analyze their impact on the performance of the antenna. These variations in the dimensions are plotted against the gain and bandwidth of the antenna in Figures 7, 8, and 9 below. The results show that the alterations carried out in the dimensions of the antenna changes the gain and bandwidth by a maximum of 0.1dB and 50 MHz (0.2 %), respectively. The results exhibit that the design is quite stringent and independent of these tolerances.

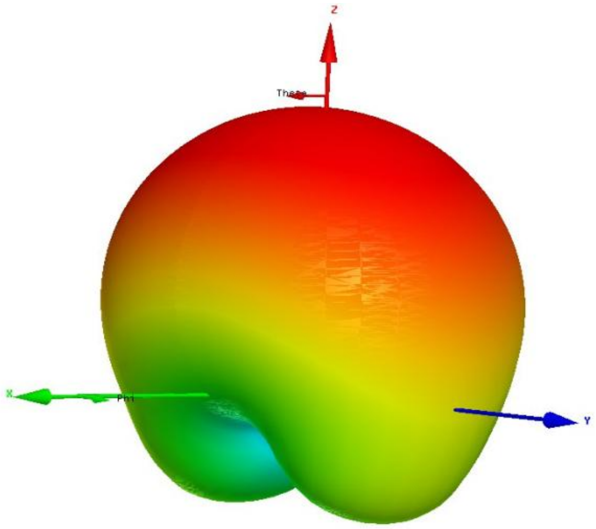


Figure 6: 3D Polar Plot of Radiation from Fractal Antenna

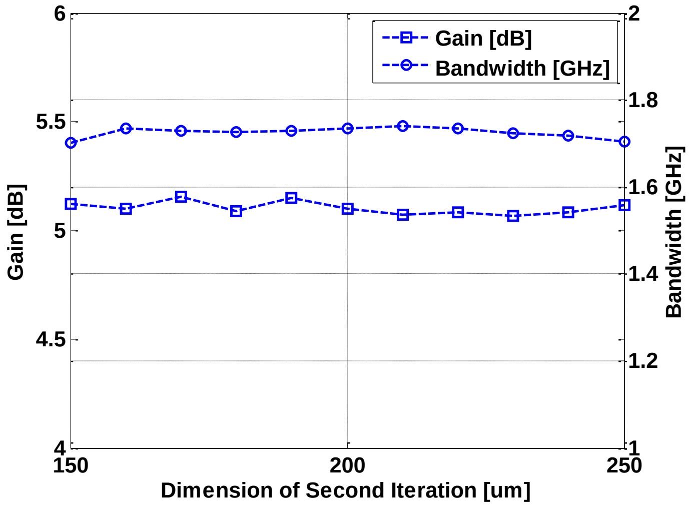


Figure 8: Gain and Bandwidth vs. Dimension of Second Iteration

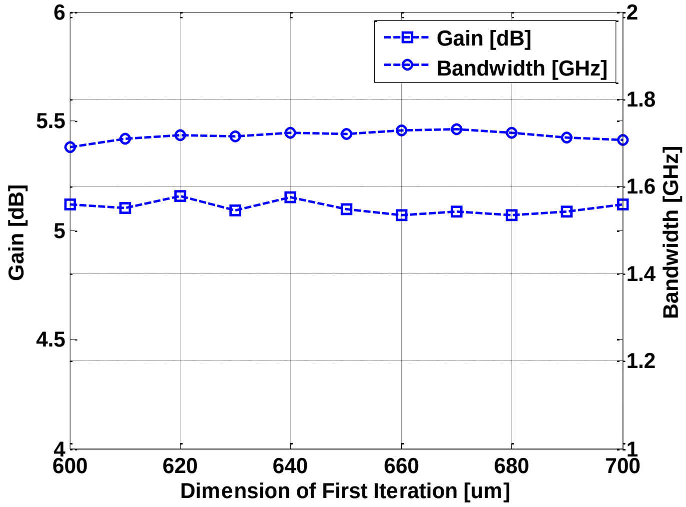


Figure 7: Gain and Bandwidth vs. Dimension of First Iteration

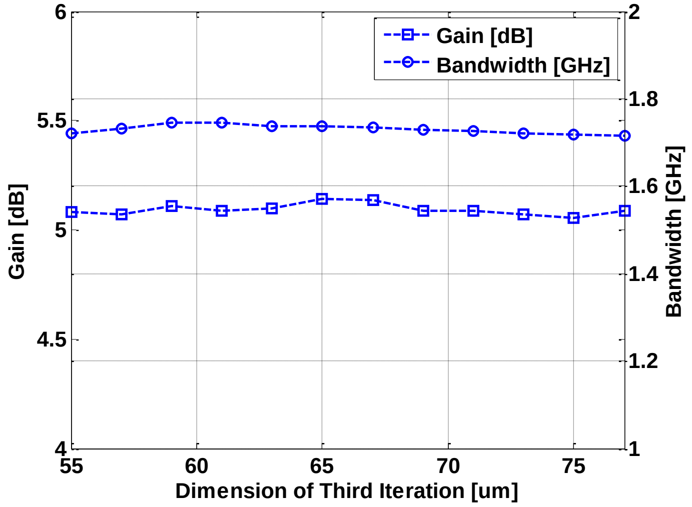


Figure 9: Gain and Bandwidth vs. Dimension of Third Iteration

The dimensions of the slot, in addition to gain and bandwidth, are also, critical for the resonant frequency and input impedance of the antenna. The length of the slot determines the resonant frequency and width of the slot realizes the input impedance of the antenna. The length and width of the slot are varied from 1.65 mm to 1.75 mm and 0.05 mm to 0.15 mm, respectively, to observe their impact on the performance of the antenna. Due to the variations in length, the centre frequency deviated by a maximum of 100 MHz which is of no importance when compared to the bandwidth of the antenna. The return loss of the antenna is observed to vary between 25 dB and 35 dB due to the sweep in width of the slot. In addition to these results, it is also, observed that the maximum fluctuation in gain is 0.1dB and that in the bandwidth is 50 MHz (0.2 %) due to these variations in the dimensions of the slot. All these results exhibit negligible divergence in the overall performance of the antenna due to the tolerances in the slot dimensions.

4. Conclusion

The paper compares the design of a conventional aperture coupled patch antenna with an aperture coupled Sierpinski gasket fractal antenna. Both designs have been simulated on low temperature co-fired ceramic (LTCC) substrate CT707. The results show that fractal antenna is compact in size and has a greater bandwidth than the conventional patch with almost the same performance of radiation pattern. These characteristics of fractal antenna make them suitable for high data rates applications, such as satellite communication and automotive radars. The sensitivity analysis of the fractal antenna indicate that slight modifications in the dimensions of the antenna have negligible effect on the gain and bandwidth of the antenna, hence, making the antenna independent of fabrication tolerances.

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