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SHORT COMMUNICATION

Design and fabrication of a novel hexagonal reconfigurable antenna with RF switches for mobile terminal

P. Chawla* and R. Khanna
Department of Electronics and Communication Engineering, Thapar University, Patiala, Punjab, India.

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Abstract: In this study a hexagonal reconfigurable fractal shaped antenna has been made using radio frequency micro-electromechanical systems (RF MEMS) switches. The proposed design offers miniaturization of antenna by using hexagonal fractals as the patch of antenna. The fractal shape offers multiband resonance of antenna. Hexagonal fractal has been considered up to 2 iterations and the second iteration of antenna offers multiband resonance as required in modern-day wireless devices. The effect of photonic band gap (PBG) on the hexagonal antenna performance has also been studied. The reconfigurable nature of the proposed antenna is demonstrated by applying RF MEMS switches within the hexagonal patch after providing the appropriate slots. The proposed antenna is fabricated on FR4 laminate (d = 1.6 mm, $\varepsilon_r = 4.7$ and tanδ = 0.019) and analyzed in the frequency range 1.5 GHz to 7.5 GHz. The antenna is simulated using a high frequency structure simulator (HFSS) and verified by fabrication results. Both simulated and fabricated results show a considerable degree of agreement. The novelty in the design offers miniaturization of the size, multiband behaviour in comparison to antennas described in literature and the utility of such antenna in mobile RF front section.

Keywords: Antenna design, meta-materials, photonic bandgap structures, RF-MEMS, MOEMS.

INTRODUCTION

The intensive use of multiple wireless service standards usually requires integrating various radiating elements in a single device. The realization of such devices becomes more challenging to antenna designers when multiband operation as well as high degree of miniaturization is required. In literature, a number of fractal shapes are discussed for designing miniaturized antenna while supporting multiband operations of wireless devices (Puente *et al.*, 1996; Werner *et al.*, 1999; Werner & Gangul, 2003; Bayatmaku *et al.*, 2011; Chawla & Khanna, 2012). Hexagon fractal shape was proposed for the first time by Tang and Wahid in 2004. The overall performance of the proposed antenna has been improved by introducing a photonic band gap (PBG) (Boutayeb *et al.*, 2006; Habib *et al.*, 2007) on the substrate surface. For achieving a multiband behaviour, the integration of radio frequency micro-electromechanical systems (RF MEMS) switches along with Sierpinski gasket antenna was introduced by Anagnostou *et al.* (2006). The application of RF MEMS switches with fractal planar antennas always produces good results. The proposed design has 36 hexagons and they are connected by 8 RF MEMS switches. In this paper, the antenna is optimized for side length of the patch using finite element method based quasi-Newton optimization approach, which helps to reduce the mathematical computation complexity as well as to find out the appropriate location of RF switches. Different on-off combinations of switches are considered for changing the physical dimensions of the patch to analyse the antenna in 1.5 to 7.5 GHz frequency range. The complete process of the final proposed reconfigurable antenna has been described by a flow chart diagram as shown in the appendix.

METHODS

In this paper, the hexagon geometrical shape having equal sides (r) is considered as a fractal patch antenna element. The iterated function system (IFS) approach is applied to hexagon geometry. The self-similarity property of the proposed design has been used to obtain multiple resonances, also called as multiband support. The total number of iterations and the scale factor for the proposed design was 2 and 3, respectively. Puente *et al.* (1996)

* Corresponding author (paras.chawla@jmit.ac.in)

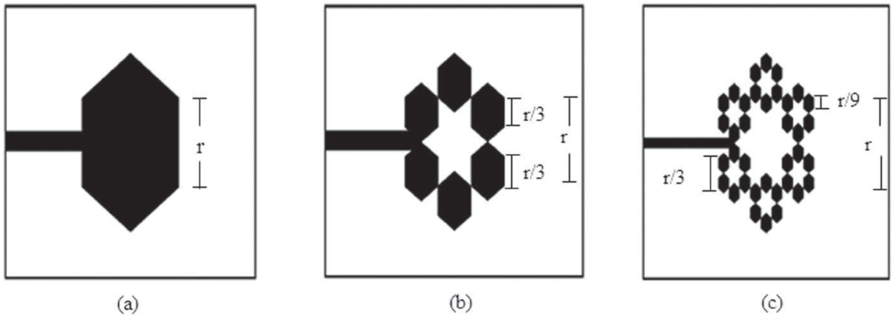

Figure 1: Hexagonal geometry (a) iteration 0; (b) iteration 1; (c) iteration 2

used a scale factor of 2 to achieve multiband behaviour. Initially, two hexagonal geometries are placed in a manner such that their corner vertices do not touch each other, without providing any conducting path between them. The proposed geometry of the hexagonal fractal antenna can be expressed in matrix form. The ideal IFS transformation coefficients (Tang & Wahid, 2004) for the hexagonal fractal can be given by:

$$w\_r\begin{bmatrix}x\\y\end{bmatrix} = \begin{bmatrix}a\_11 & a\_12\\a\_21 & a\_22\end{bmatrix}\begin{bmatrix}x\\y\end{bmatrix} + \begin{bmatrix}b\_11\\b\_21\end{bmatrix}$$

Where

w_r: affine transformation

a_11, a_22: controls scaling

a_12, a_21: controls rotation

b_11, b_22: control linear translation

Different iterations of the hexagonal fractal antennas are shown in Figure 1. In this proposed design the second iteration of the hexagonal patch antenna is used for multiband operation.

The approximate frequency resonance relationship is considered for the hexagonal type of fractal planar antenna, where 'r' is the side length of hexagonal patch, 'ε_r' is the dielectric constant, loss tangent tanδ = 0.019, and 'd' is the thickness of the substrate (Saidatul *et al.,* 2007) as;

$$r = \frac{F}{\sqrt{\left[1+\frac{2d}{\pi\varepsilon_r F\left[\ln\left(\frac{\pi F}{2d}\right)+1.7726\right]}\right]}}$$

Here

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}}$$

Further, the gap equivalent to the dimension of RF MEMS switch is provided between the consecutive vertices of the hexagons. Due to the presence of RF switches, such proposed microstrip line feed hexagonal fractal antenna shows the reconfigurablity in frequency. The current distributions on the hexagon patches change as switches change their position, which is provided through DC biasing pads.

RESULTS AND DISCUSSION

The hexagonal antenna was first simulated and the electromagnetic results were compared with the help of vector network analyser as shown in Figure 2. The magnitude of current distribution on the hexagonal patch is shown in the same plot. The proposed antenna is working on three bands 2.9, 5.95 and 7.13 GHz, respectively. Both simulated and fabricated return loss results show a considerable degree of agreement. Further, to improve the bandwidth, gain and suppression of the side lobes a photonic band gap (PBG) was introduced in the structure. A side of a hexagon in the fractal antenna is 3 mm. The diameter, number of holes and complete geometry of the hexagonal antenna with PBG are shown in Figure 3.

The hexagonal planar antenna with PBG results was simulated using high frequency structure simulator (HFSS) software at a solution frequency of 5.95 GHz. A significant increase (12 %) in the bandwidth and peak realized gain as compared to without PBG was noticed. The surface waves and harmonics are also supressed due to the introduction of PBG.

The PBG holes on the substrate change the value of current distribution on the hexagon patches, and consequently the proposed antenna gain is increased (Table 1).

The radiation pattern performances for both hexagonal antennas (with and without PBG) discussed above are included next. The simulated normalized relative power patterns, i.e., Y-Z and X-Y cut patterns

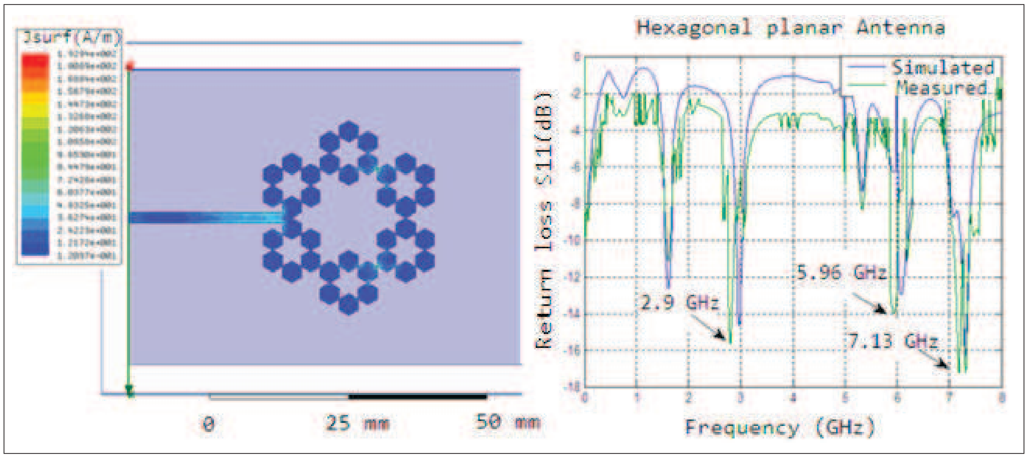

Figure 2: Measured and simulated return loss S_{11} (dB) of the hexagonal antenna

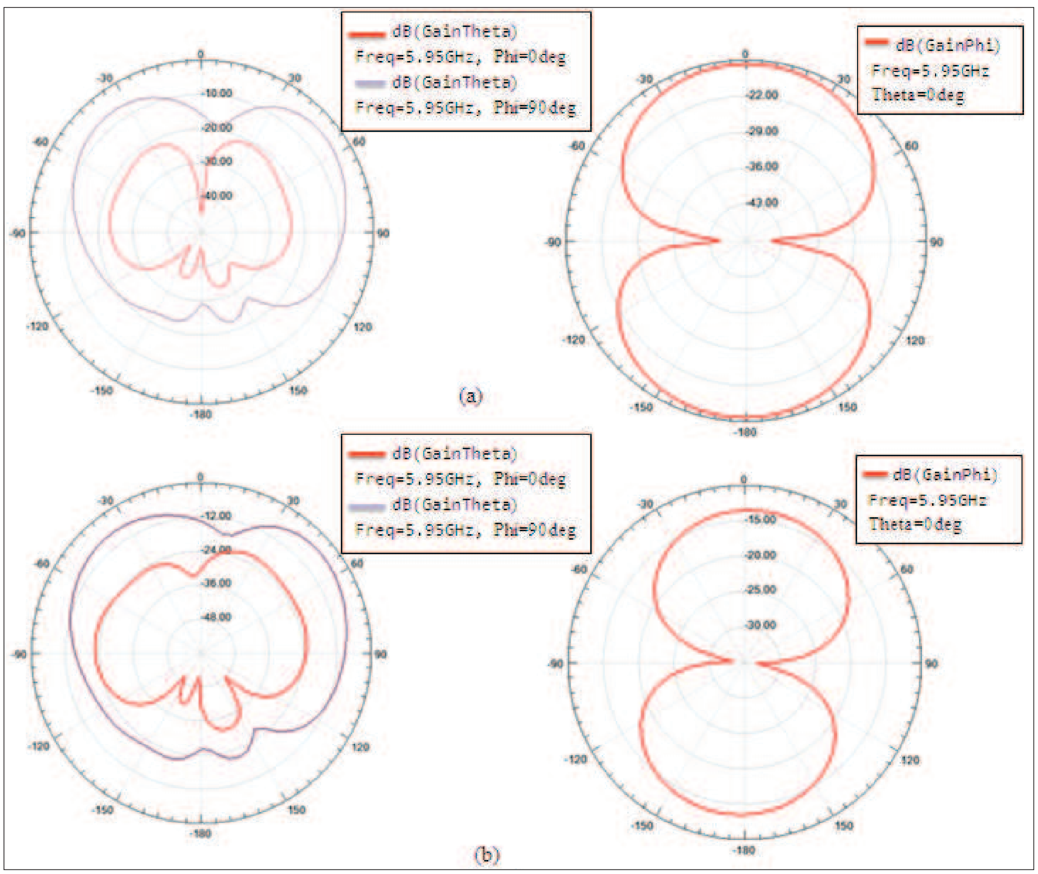

Figure 4: Co- and cross-polar radiation patterns of hexagonal antenna at 5.95 GHz in E-plane (Y-Z plane, phi = 90, phi = 0) and H-plane (X-Y plane, theta = 0) (a) without PBG (b) with PBG

are shown in Figures 4(a) and 4(b) at 5.95 GHz obtained from the HFSS. The left plot of Figures 4(a) and 4(b) shows the elevation plane i.e. E-theta component, which corresponds to co-polarization (Y-Z plane, phi = 90) and cross polarization (X-Z plane, phi = 0) cut planes and the right plot of Figures 4(a) and 4(b) shows azimuth plane i.e. H-phi component in co-polarization (X-Y plane, theta = 0) cut planes. A figure-eight pattern in the

Table 1: The effect of PBG on the hexagonal antenna performance

Type of hexagonal antenna	Maximum power density per unit solid angle (W/Sr)	Peak directivity	Peak gain	Peak realized gain	Radiated power (W)	Accepted power (W)	Radiation efficiency
Without PBG	0.020	0.944	0.314	0.257	0.273	0.819	0.333
With PBG	0.024	0.981	0.349	0.301	0.306	0.863	0.355

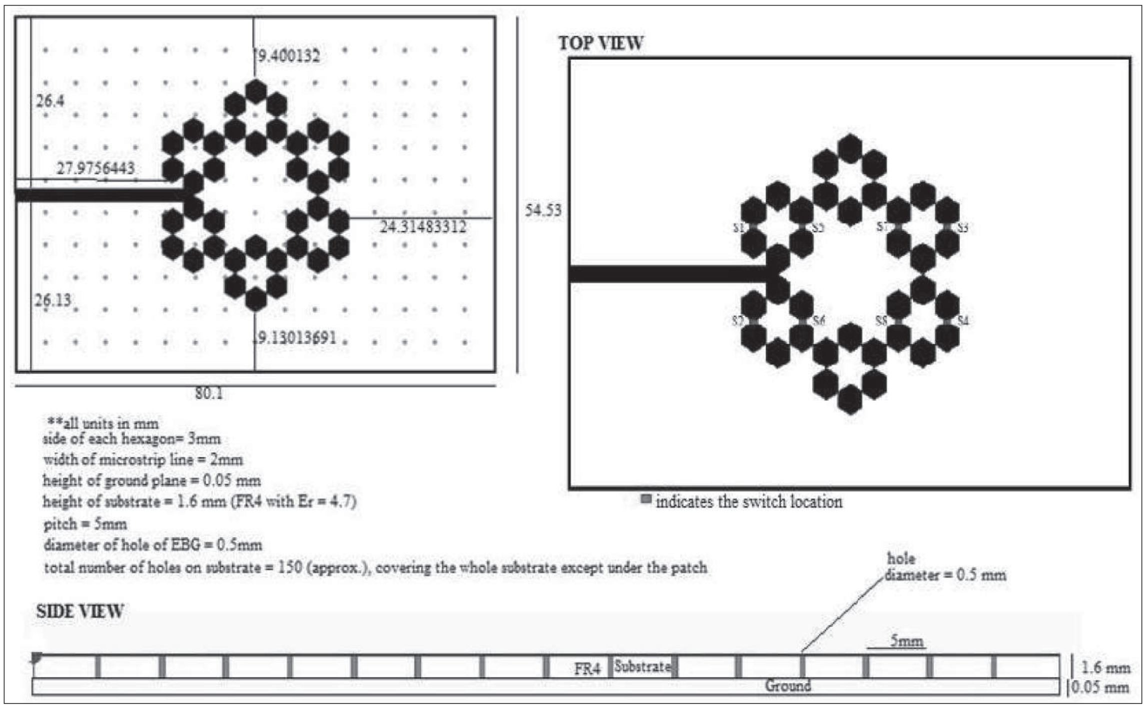

Figure 3: Location of RF switches on hexagonal antenna with PBG

X-Y plane signifies a dipole type of radiation pattern. Both antennas achieving a fairly omni-directional and normalized patterns as expected are supported by the simulated 3D realized gain radiation patterns, which show that the pattern quality is nearly omni-directional as concluded. Further, both antennas have well-behaved linearly polarized as axial ratio (E_y/E_x) is more than one at theta value equal to zero.

Reconfigurable antenna with RF switches

The proposed reconfigurable antenna designing and measurement setup contains four sections: hexagonal planar antenna, RF switches, power supply circuit to control switches and vector network analyzer (VNA). The resistive RF MEMS switch selected for the antenna was taken from a previous study (Garg *et al*., 2013), which shows excellent electromagnetic characteristics. For proof of the concept, its equivalent absorptive SPDT ceramic RF switch (CSWA2-63DR+) having almost similar insertion, isolation loss and 50 ohm matching was considered. The typical applications of CSWA2-63DR+ switch is cellular, PCN, WCDMA, WiMAX, ISM, military and automated switching networks. It consumes a very low power (in μW) and the typical supply current range is 18 μA. It is a low profile, small size (4 x 4 x 1.2 mm) hermetic package having an internal CMOS driver circuit. Further, the RF switch used here has a wide bandwidth varying from 0.5 – 6.5 GHz. A separate PCB of RF switches including DC bias lines and pads was designed on Roger RO4350 material. The dielectric constant and the thickness of Roger sheet is 3.5 and 0.508

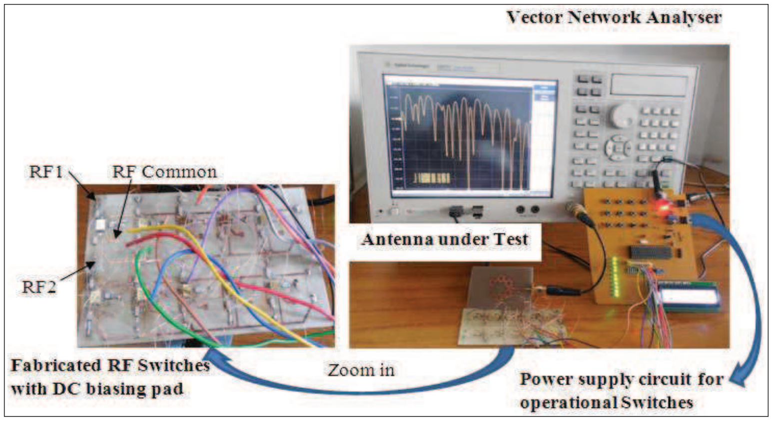

Figure 5: Reconfigurable antenna measurement setup for return loss characterization

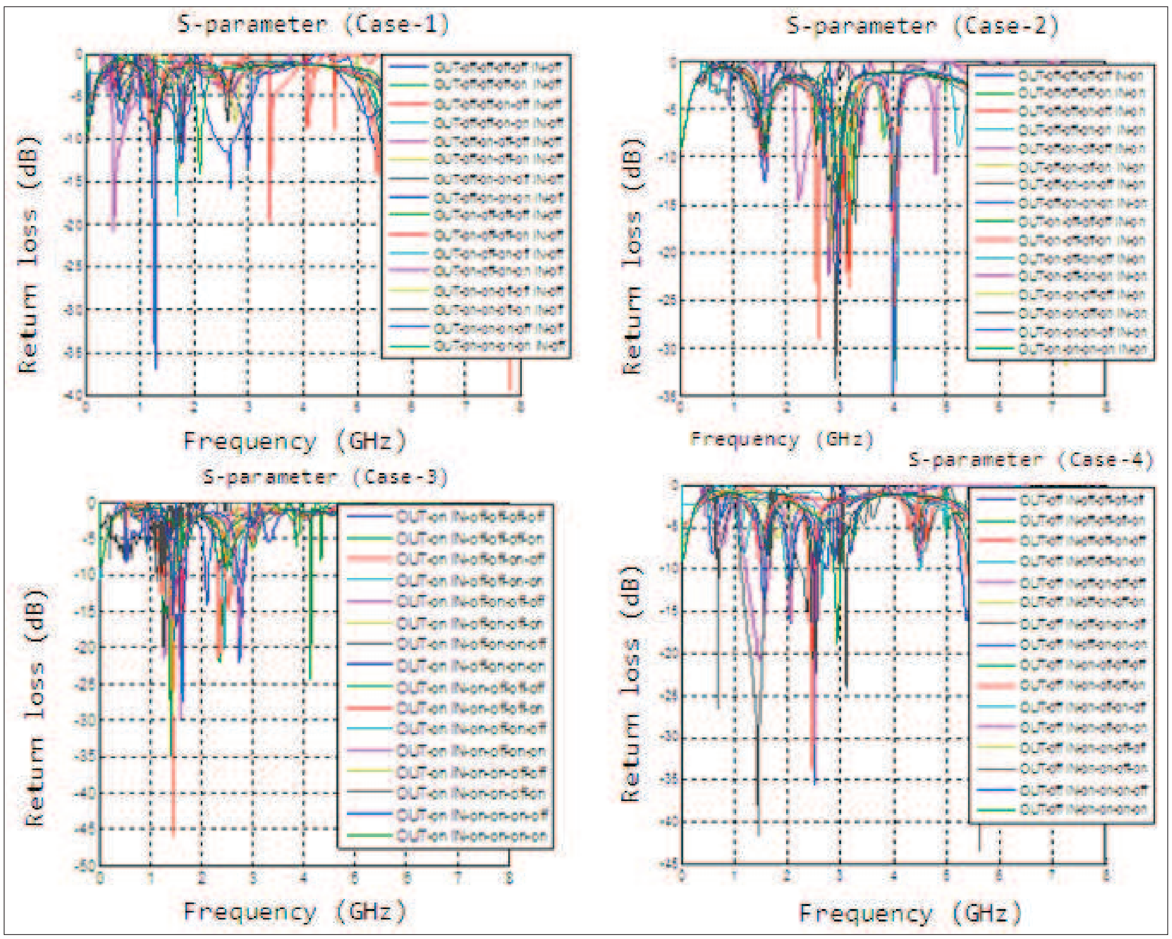

Figure 6: Simulated return loss of hexagonal reconfigurable antenna (16 × 4 = 64 selected cases)

mm, respectively. The highly stable on-chip capacitor dielectrics C0G (NP0) ceramics having a value of 47 pF was used for the biasing circuit. A variable DC regulated power supply, which varies from 1.3 – 4.92 V was designed to control RF switches. The RF1, RF2 and RF common (as shown in Figure 5) from RF switches PCB are directly connected to hexagonal antenna through high quality thin copper wires having diameter 0.025 mm. The return loss of such reconfigurable antenna with RF switches was measured with the help of Agilent Technologies E5071C. The complete set up of measurement is shown in Figure 5.

Out of 256 (= 2^8) different combinations of RF switches, 64 selected cases of reconfigurable antenna were simulated. These configurations cover almost all the present as well as future mobile and wireless communication bands lying between 1.5 – 7.5 GHz as shown in Figure 6.

Further, the total gain pattern in elevation plane i.e. E-theta component at phi = 90 degree of reconfigurable antenna with RF MEMS switches has been considered. For illustrating the effect of switches on antenna, two extreme cases i.e. when all switches are in ON and OFF position are considered. The radiation pattern result include the dielectric losses, reflection or mismatch loss and ohmic losses associated with antenna and RF MEMS switches. The effects of DC biasing and connection pads are not considered in this study, which may affect the characteristics of radiation pattern.

CONCLUSION

A novel self-similar multiband hexagonal antenna has been designed using the iterated function system (IFS) approach. The photonic band gap (PBG) technique applied on the substrate showed a considerable reduction in side lobes and an increase in the maximum power density. Further, we have designed, fabricated and tested a novel reconfigurable multiband antenna using a fractal hexagonal shaped geometry and RF switches. Quasi-Newton method was used to find out the location of RF MEMS switches. For all possible RF switching states, during designing and measurement of proposed multiband reconfigurable structure needs to be well-matched at all measured frequencies lying between 1.5 to 7.5 GHz. From an industrial application point of view, the proposed compact reconfigurable antenna with RF switches is considered in mobile RF front end terminal, which cover all present as well as future wireless and mobile communication bands.

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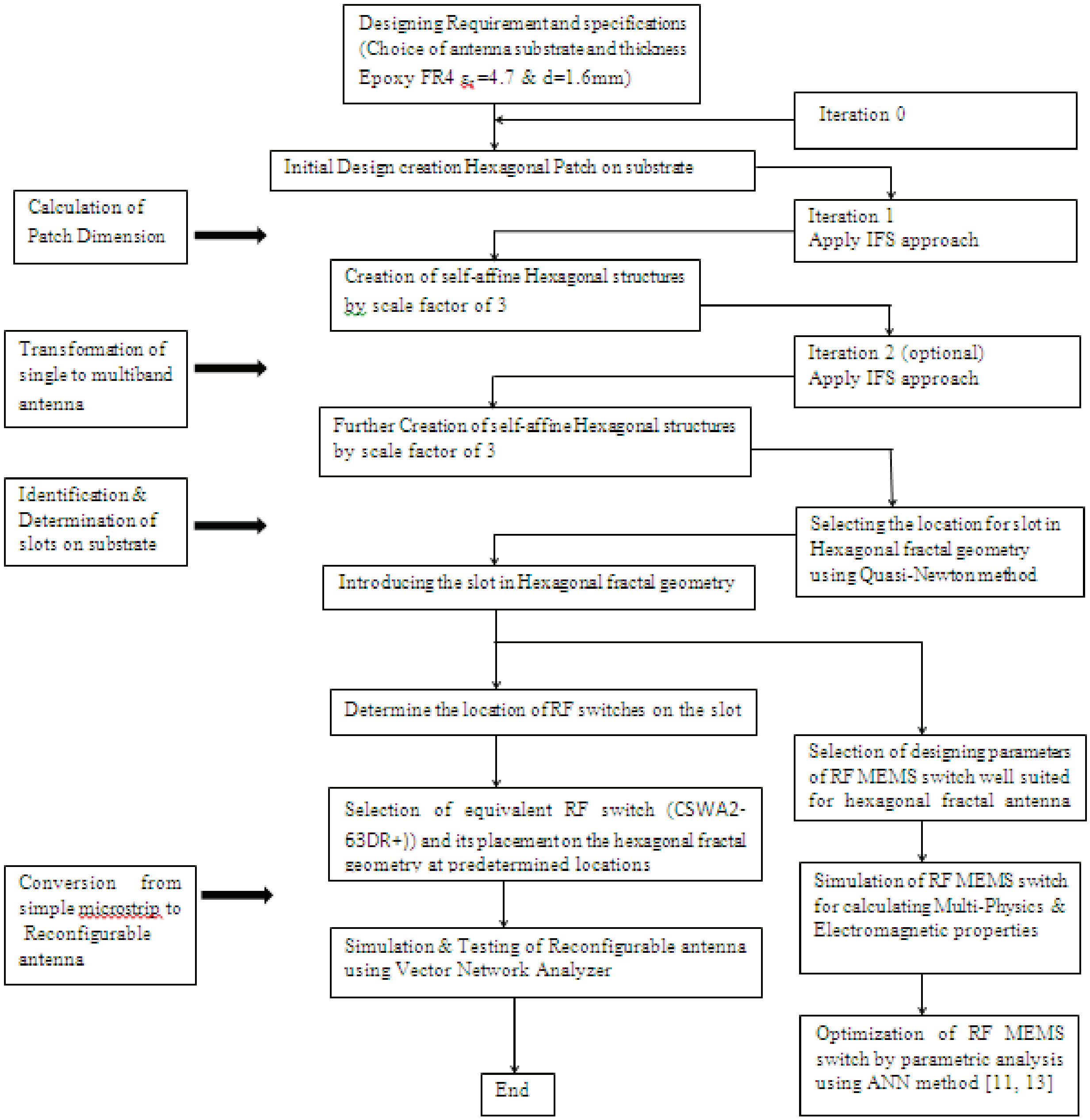
APPENDIX


Designing Requirement and specifications (Choice of antenna substrate and thickness Epoxy FR4 εr =4.7 & d=1.6mm)
Iteration 0
Initial Design creation Hexagonal Patch on substrate
Calculation of Patch Dimension
Iteration 1
Apply IFS approach
Creation of self-affine Hexagonal structures by scale factor of 3
Transformation of single to multiband antenna
Iteration 2 (optional)
Apply IFS approach
Further Creation of self-affine Hexagonal structures by scale factor of 3
Identification & Determination of slots on substrate
Selecting the location for slot in Hexagonal fractal geometry using Quasi-Newton method
Introducing the slot in Hexagonal fractal geometry
Determine the location of RF switches on the slot
Selection of designing parameters of RF MEMS switch well suited for hexagonal fractal antenna
Selection of equivalent RF switch (CSWA2-63DR+)) and its placement on the hexagonal fractal geometry at predetermined locations
Simulation of RF MEMS switch for calculating Multi-Physics & Electromagnetic properties
Conversion from simple microstrip to Reconfigurable antenna
Simulation & Testing of Reconfigurable antenna using Vector Network Analyzer
Optimization of RF MEMS switch by parametric analysis using ANN method [11, 13]
End