Design and Analysis of a Koch Snowflake Fractal Monopole Antenna for Wideband Communication

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Abstract **─** In this article a compact wideband monopole antenna with constant high gain has been designed and fabricated for wideband microwave communication. Koch fractal geometry has been applied for design of this antenna structure. A wide bandwidth of 3.3 GHz (3.0 GHz to 6.3 GHz) has been obtained, which covers the IEEE 802.11 WLAN bands (5.2 GHz and 5.8 GHz) and WiMAX bands (3.5 GHz and 5.5 GHz). The proposed antenna is characterized by its high gain which remains constant throughout the entire operation bandwidth. An average gain of 5.07 dBi has been realized at all the frequencies of interest. The realized antenna gains are 5.01 dBi, 5.07 dBi, 5.09 dBi and 5.11 dBi at frequencies of 3.5 GHz, 5.2 GHz, 5.5 GHz and 5.8 GHz respectively. Good agreement between simulated and measured results justifies the applicability of the proposed antenna for wideband communication purpose, particularly for the WLAN and WiMAX microwave frequency bands of interest.

Index Terms **─** Constant gain, fractal geometry, wideband antenna, wireless communication.

I. INTRODUCTION

Wideband antennas are gaining huge popularity now-a-days in the field of wireless communication and technology. The conventional patch antenna used in communication technologies suffer from narrow bandwidth and return loss issues. To overcome this disadvantage fractal shapes have been introduced in design of patches in order to improve the impedance-bandwidth and incorporate wideband characteristics. Monopole antennas with various fractal shaped patch structures have shown good return loss characteristics with wide bandwidth, which have fulfilled the need for wideband communication, particularly for the IEEE 802.11 WLAN and WiMAX bands, as available in existing literatures. A fractal hexagonal monopole has been presented in [1] by Fallahi and Atlasbaf, but the maximum available gain is around 3.25 dBi and the average gain is less than 2.5 dBi at the WLAN and WiMAX bands. An H-shaped fractal antenna has been presented in [2] by Weng and Hung, optimized using PSO method for WLAN, but the average gain is much less than 5.0 dBi. A dual band antenna with fractal ground for WLAN has been presented in [3] by Gemio et al. Variable gain less than 5.0 dBi has been obtained as mentioned in the work. Sierpinski carpet fractal antenna with CPW feed has been presented in [4] by Ghatak et al., the average gain obtained is around 4.5 dBi. A wideband fractal loop monopole has been presented in [5] by Chaimool et al., where the realized gain is around 2.0 dBi. Various other slotted and fractal geometries for wideband antennas have been observed in articles [6]-[10], but the realized gain of operation is not constant and falls below the 5.0 dBi margin at some or all the frequencies of interest. In this work we have proposed a fractal shaped monopole antenna with constant high gain ~ 5.0 dBi. It may be noted that the thickness of the proposed structure is kept only 2.00 mm. Koch snowflake fractal geometry has been applied in design of the patch structure along with a slotted ground plane. A wide bandwidth of 3.3 GHz has been observed, which effectively covers the IEEE 802.11 WLAN bands (5.2 GHz and 5.8 GHz) and WiMAX bands (3.5 GHz and 5.5 GHz). The antenna has an average gain of 5.07 dBi at the IEEE 802.11 WLAN and WiMAX bands (5.01 dBi, 5.07 dBi, 5.09 dBi and 5.11 dBi at frequencies of 3.5 GHz, 5.2 GHz, 5.5 GHz and 5.8 GHz respectively). Parametric study of the proposed structure has been elaborated for better understanding of the frequency response characteristics of the proposed structure.

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II. ANTENNA DESIGN PROCEDURE

Koch snowflake fractal geometry has been incorporated in the patch of the proposed radiating structure. Koch first introduced this geometry in 1904. This geometry is generated by an iterative function system (IFS). It is obtained by a set of overlapping equilateral triangles. In Fig. 1, the iterative Koch structure has been displayed. After an iterative transform *n*, there is an increase in the overall geometrical area.

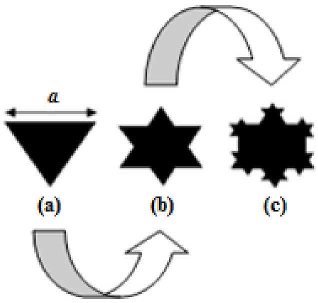

Fig. 1. Koch fractal geometry in successive iterations: (a) basic geometry, (b) 1st iteration, and (c) 2nd iteration.

If S_n be the area at each iteration *n*, then the overall area of the successive iteration can be obtained as:

$$S_{n+1} = S_n + (\sqrt{3}/12)\,.(4/9)^{n-1}\,.a^2, \qquad (1)$$

where *a* is the length of the side of an equilateral triangle, whose area is equal to:

$$S_o = (\sqrt{3}/4)\,.a^2. \qquad (2)$$

Figure 2 shows the comparison plot of basic geometry, 1st iteration and 2nd iteration stages of Koch fractal geometry. Best result has been achieved in the final or 2nd iterative stage. As observed from Fig. 2, a wide impedance-bandwidth of 3.3 GHz (3.0 – 6.3 GHz) has been obtained in the 2nd iterative stage. Our objective is to design a compact high gain wideband antenna. The task has been achieved in the 2nd iterative stage. All other standards for wideband communication have been successfully achieved. Therefore the 2nd iterative stage has been chosen as the final stage of the design. Figure 3 shows the complete structure of the proposed antenna along with side view. The proposed antenna is a unique combination of fractal and slotted structures, incorporated in a monopole configuration, in order to achieve wideband characteristics along with constant high gain at the frequency bands of interest. The patch and the ground plane are composed of copper (annealed). The patch is designed using Koch snowflake fractal geometry, fed by a feed line of width 1.5 mm in order to match the characteristic impedance, which has been explained in the next section

Fractal structures help in implementing large electrical length within a small surface area. The nearly spaced resonant frequencies come closer with the increase in the number of iterations of the fractal structures. The ground plane is etched from the top and a rectangular slot is cut midway. The low-cost substrate (Arlon AR 600) having a dielectric constant ε_r of 6.0 is sandwiched between the fractal patch and the slotted ground plane. The substrate thickness is kept equal to 1.0 mm. The reason is, thicker substrates increases the impedance-bandwidth but generates surface waves, which have a negative effect on antenna radiation. The overall thickness of the structure is 2.0 mm including the thickness of the patch (0.5 mm) and the ground plane (0.5 mm). For the proposed design parameter *a* is taken as 6.0 mm. The design has been kept compact, for the antenna to be easily incorporated in wireless devices. The detailed dimensions of the structure are provided in Table 1.

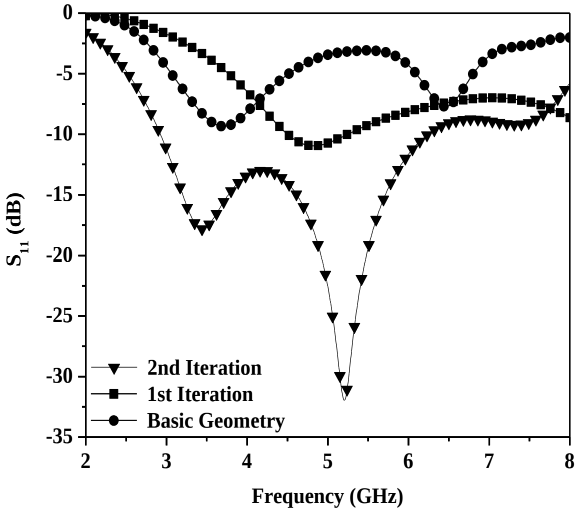

Fig. 2. Comparison plot of various iterative stages.

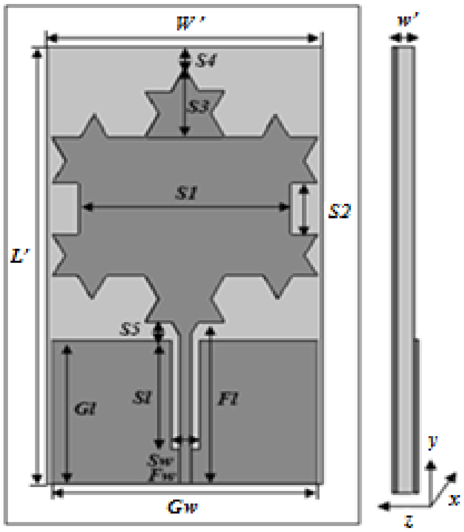

Fig. 3. Proposed fractal monopole antenna along with side view.

Table 1: Parameter dimensions (in mm)

Parameters	Dimensions	Parameter	Dimensions
W'	26.50	*Fw*	01.50
L'	47.00	*Fl*	16.50
S1	20.50	*Gw*	25.50
S2	06.00	*Gl*	16.00
S3	06.25	*Sw*	02.50
S4	02.50	*Sl*	12.00
S5	02.00	*w'*	02.50

III. PARAMETRIC STUDIES AND DISCUSSION

In this section, keeping the substrate parameter same, i.e., Arlon AR 600, the effect of other design parameters of the antenna such as the feed length (*Fl*), slot width (*Sw*) and slot length (*Sl*) of the rectangular slot in the ground plane, the ground width (*Gw*) and ground length (*Gl*) of the ground plane are observed and the results are discussed sequentially.

The feed line width (*Fw*) should be carefully selected. It is an important parameter which affects the impedance matching between the current source and the radiating element, i.e., the antenna. There should be an impedance match between the source element and the load resistance for maximum power to be transferred. The feed line is designed to match the 50 Ω characteristic impedance using Equations (3) and (4). For the proposed design, substrate dielectric constant, $\varepsilon_r = 6.0$ (Arlon 600), substrate height, $h = 1.0$ mm and width of feed line, $Fw = 1.5$ mm.

$$\varepsilon_{eff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[\sqrt{1 + 12\,(h/Fw)}\right]^{-1}, \tag{3}$$

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon eff}\left[\frac{Fw}{h} + 1.393 + 0.667\,ln\left(\frac{Fw}{h} + 1.444\right)\right]}, \tag{4}$$

for $Fw/h \geq 1$. Zo is the aracteristic impedance and ε_{eff} is the effective dielectric constant of substrate [9].

An optimum feed line width *Fw* of 1.5 mm has been selected to approximately match the 50 Ω input impedance and to obtain desired bandwidth and return loss level. Our next aim is to obtain an optimum dimension for the length of the feed line. Therefore, keeping the other parameters fixed the feed length *Fl* has been varied. The optimized feed length obtained is 27.75 mm (Fig. 4). The overall feed line dimension is therefore given as *Fw* x *Fl* = 1.5 x 27.75 mm.

The dimensions of the ground plane has an effect on the impedance-bandwidth as well as on the available resonant modes of the designed structure. A portion of the ground plane has been etched. Etching a portion of the ground plane yields improved S_{11} characteristics. Keeping the other design parameters constant, the width of the ground plane *Gw* is varied. The optimized dimension obtained for *Gw* is 25.50 mm (Fig. 5). Next, the ground length *Gl* is varied keeping the other parameters unchanged. As is observed from Fig. 6, there is an increment in bandwidth when the length of the ground plane *Gl* increases from 21.5 mm to 23.5 mm. But on further increment of the length of the ground plane, *Gl* beyond 24.00 mm, it has been observed that though there is an increment of impedance-bandwidth, there is a decrement in $|S_{11}|$, which provides a negative effect on antenna response. The effect of ground plane length *Gl* on frequency response of the structure is well illustrated in Fig. 6. The optimized dimension for ground length *Gl* is therefore kept equal to 24.00 mm. The ground plane dimension is given as, *Gw* x *Gl* = 25.50 x 24.00 mm. The effect of slot in the ground plane is discussed in the next section.

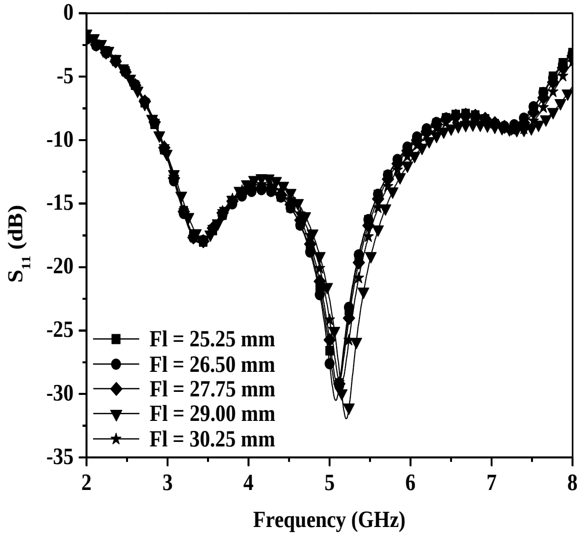

Fig. 4. Feed length effect on antenna response.

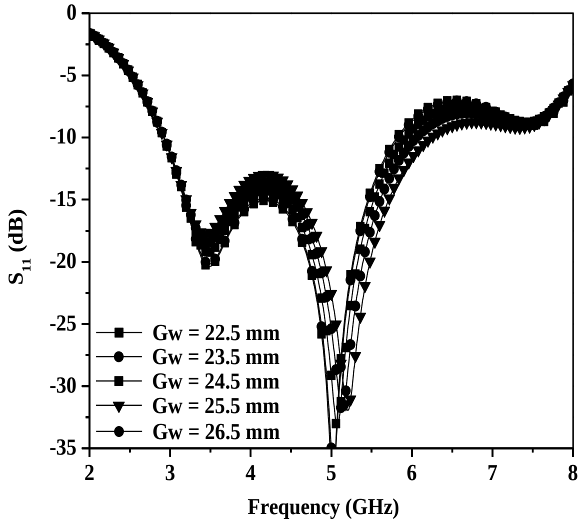

Fig. 5. Ground width effect on antenna response.

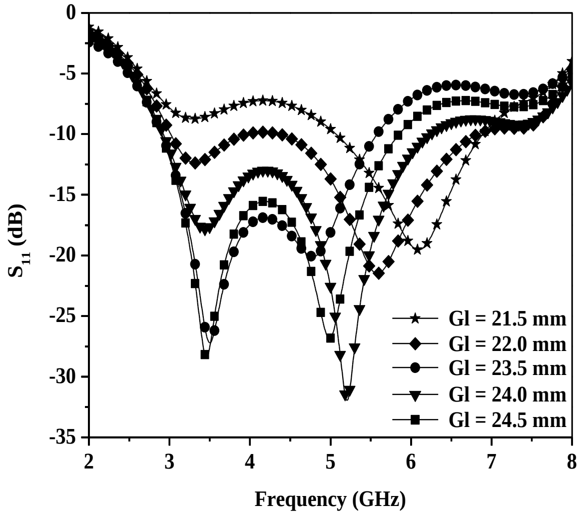

Fig. 6. Ground length effect on antenna response.

The current density is mainly concentrated near the ground slots and sparsely distributed elsewhere, which has an effect on the impedance bandwidth of the antenna. Slots in the ground plane reduces the ground effect by the suppression of currents in the ground plane at the operating frequency in the lower end. It also plays a significant role in impedance matching. Such ground plane structures are regarded as defected ground structures (DGS) in antenna engineering. A rectangular slot has been incorporated in the ground plane of the proposed structure. Figure 7 shows the variation of slot width *Sw* with frequency of the proposed structure, when the other design parameters have been kept constant. Increase in slot width increases the $|S_{11}|$. Optimized response has been obtained when the slot width is kept as 2.5 mm. Figure 7 and Fig. 8 justify the optimized set of dimensions for the ground plane slot.

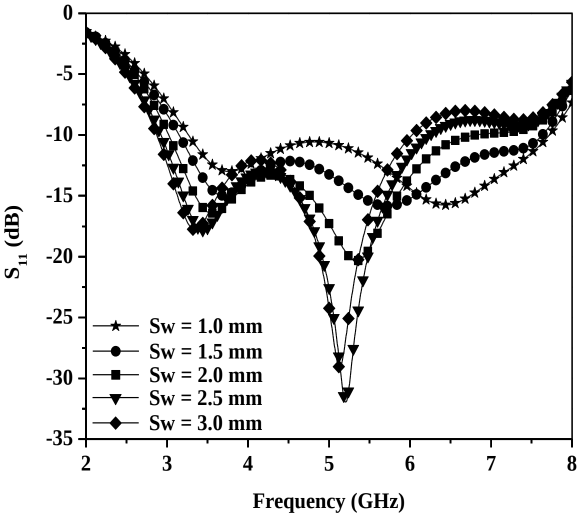

Fig. 7. Effect of slot width on antenna response.

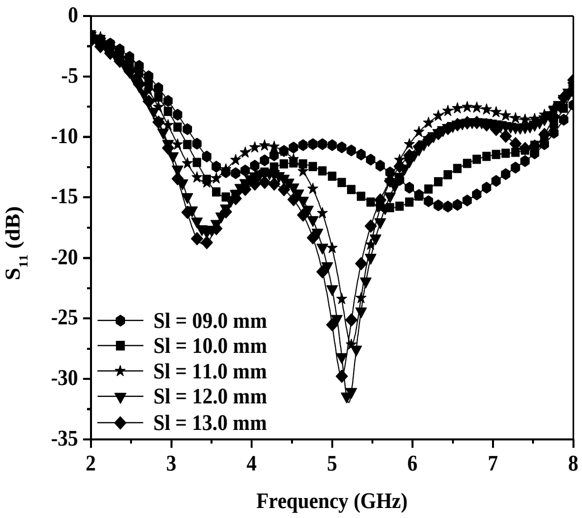

Fig. 8. Effect of slot length on antenna response.

As seen from Fig. 7, the slot width has a direct effect on the variation of $|S_{11}|$, which is minimum when *Sw* is kept equal to 1 mm. Similarly, as observed from Fig. 8, the slot length *Sl* is directly proportional to variation of $|S_{11}|$, when *Sl* is sequentially changed keeping the other design parameters fixed. $|S_{11}|$ increases on increase in slot length, which is kept equal to *Sl* = 12.00 mm (Fig. 8). The dimensions of the rectangular slot in the ground plane is therefore chosen as, *Sw* x *Sl* = 02.5 x 12.00 mm for achieving an optimized frequency response for wideband operation.

IV. FABRICATION AND MEASUREMENT

Prototype of the proposed antenna (as displayed in Fig. 3) has been fabricated (Fig. 9) and tested. The return loss characteristic is measured using 'Vector-Network-Analyzer' or VNA; spec. Agilent Technology N5-230A.

Figure 10 shows the comparison plot of the measured and simulated return losses of the fabricated antenna. The deviation between the VNA measured and CST simulated results is very negligible and it occurs due to the effect of the soldering and fabrication tolerance. The antenna shows an average realized gain of 5.07 dBi at all the proposed IEEE 802.11 WLAN and WiMAX bands, which is depicted in Fig. 11. The measured gain is also in good agreement with the simulated gain. Some discrepancies between simulated and measured results may also occur due to the soldering effect of the SMA connector.

The current distribution pattern of antenna surface is shown in Fig. 12. Analysis of surface current distribution pattern is extremely important in order to get an idea of the antenna characteristics. As observed from Fig. 12, the current originates from the feed and gradually distributes itself towards the edges of the patch, creating nearly spaced resonant frequencies, which results in enhancement of the impedance bandwidth, gain and low variation in the gain parameter at the resonant frequency points. This phenomenon happens due to the self-similarity property of fractals. The maximum surface current is 36.8 A/m and the minimum surface current is 2.30 A/m. The realized antenna gains are 5.01 dBi, 5.07 dBi, 5.09 dBi and 5.11 dBi at frequencies of 3.5 GHz, 5.2 GHz, 5.5 GHz and 5.8 GHz respectively. The average realized gain is 5.07 dBi at the frequency bands of interest (Fig. 11). As observed from Fig. 11, the antenna gain is almost constant around the 5.0 dBi margin. Simulated and measured results are in good agreement.

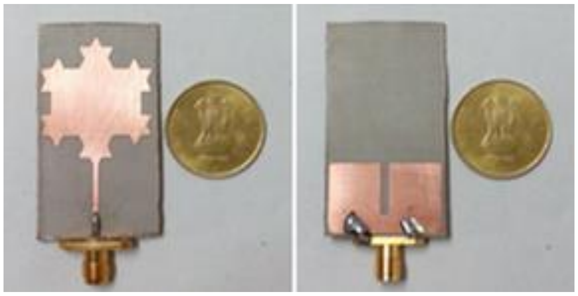

Fig. 9. Fabricated prototype - front and rear view.

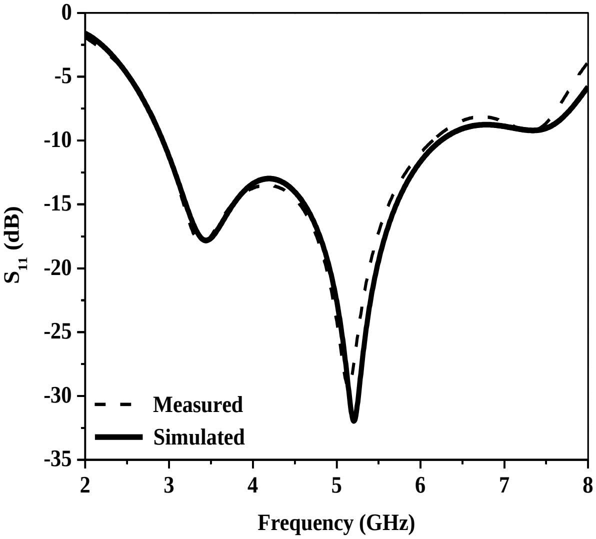

Fig. 10. Response of simulated and fabricated prototype.

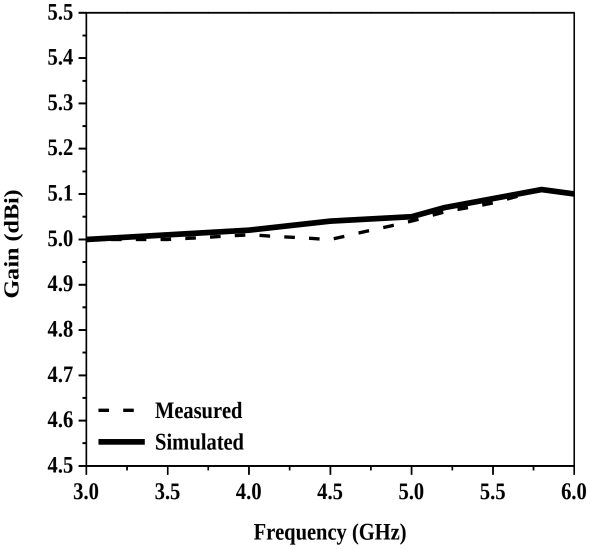

Fig. 11. Measured and simulated antenna gain.

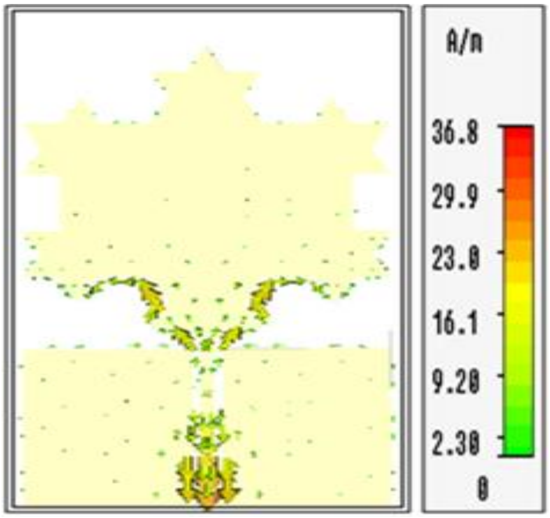

Fig. 12. Current distribution pattern of antenna surface.

Effect of co- and cross-polar components at the frequencies of interest have also been considered. Desired co-polar and cross-polar isolation are obtained, which is depicted in Fig. 13 for a beamwidth consideration higher than 90°.

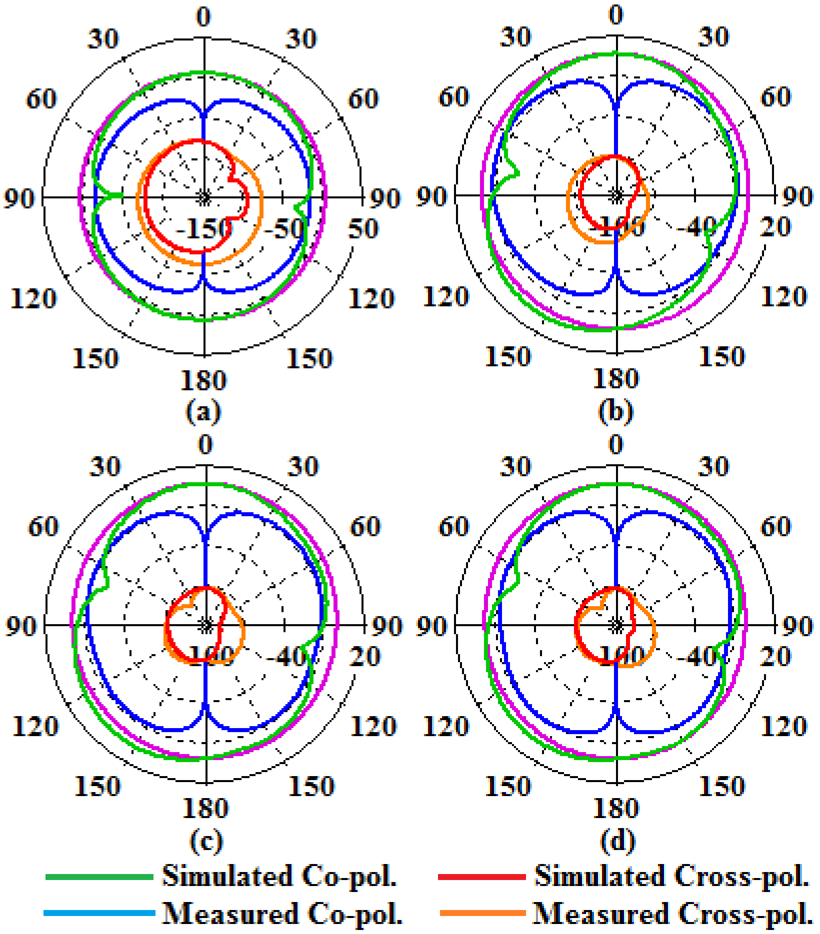

Fig. 13. Radiation pattern of proposed antenna: (a) 3.5 GHz, (b) 5.2 GHz, (c) 5.5 GHz, and (d) 5.8 GHz.

V. CONCLUSION

This article presents a novel approach in monopole antenna design in combination with fractal shaped patch element and slotted ground plane in a monopole configuration. The most significant feature of the antenna is its almost constant high gain which is maintained at all the frequencies of interest. The structure is easy to fabricate and due to its compactness it can be easily incorporated in portable devices suited for wireless communication purposes. The presented structure shows a wide bandwidth of 3.3 GHz (3.0 GHz to 6.3 GHz), which covers the IEEE 802.11 WLAN bands (5.2 GHz and 5.8 GHz) and WiMAX bands (3.5 GHz and 5.5 GHz). The antenna has gain of 5.01 dBi, 5.07 dBi, 5.09 dBi and 5.11 dBi at frequencies of 3.5 GHz, 5.2 GHz, 5.5 GHz and 5.8 GHz respectively. An average gain of 5.07 dBi realized at the proposed WLAN and WiMAX bands is an added advantage in this regard.

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