Reduced Size Harmonic Suppressed Fractal Dipole Antenna with Integrated Reconfigurable Feature

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ABSTRACT: *The presence of harmonics are undesirable in many applications as the overall system performance will be significantly degraded. By employing the fractal technology into an antenna, it is possible to provide reduction on the physical size, increment of its operating bandwidth and directivity. However, the technique can cause significant undesired harmonics problems associated with higher order modes of the antenna. This paper presents the design of a reduced size Koch fractal meander dipole antenna that has tunable capability of a reconfigurable operation within the observed range of 400 MHz to 3.5 GHz. The work involves both simulation and measurements. Each undesired harmonic is removed using one or two stubs. A microwave switch-able dipole antenna concept using Koch curve integrated with open circuit stubs is presented. The structure employed fractal technology that can eliminate higher order modes. With the utilization of Koch curves, it is shown that the antenna size is reduced, but the number of higher order modes has proportionally increased. The size of the proposed antenna is small with regards to the operating frequency. The incorporation of the stub has improved the antenna performance as desired.*

Keywords: Harmonic suppressed antenna, Frequency reconfigurable antenna, Fractal dipole antenna, Stubs-flter

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1. Introduction

Future wireless systems such as cognitive radio (CR) are placing demands on antenna designs. Recently, CR system has been introduced as a new feature for radio communication system such as mobile handset unit [1]. This enables users to share the spectrum frequency that is allocated from other sources such as unused TV spectrums. Several techniques have been used to develop reconfigurable antenna for CR applications [2]-[9]. Among the reported techniques are two antennas with wideband and narrow band features of omni-directional and directional patterns for sensing and frequency agile purposes [2]-[3]. L-shaped monopole antennas were designed with interchangeable interband frequency using a PIN diode, while DC voltage is used to control the reactance of a varactor diode for frequency tuning purposes covering UHF band, mobile radio and wireless LAN [4]. A single patch antenna integrated with parasitic elements via RF switches to create tunable feature from 550 MHz to 1500 MHz has been proposed [5]. Recent studies of reconfigurable antennas include vivaldi antenna [6], log periodic dipole antenna [7], and monopole antenna [8]-[9] which can operate in wideband and narrowband mode.

Harmonics are undesirable in many applications. The incorporation of fractals into antenna structures can cause significant undesired harmonic problems associated with higher order modes of the antenna. This paper presents the simulation and measurement work of a reduced size Koch fractal meander dipole antenna as shown in Figure 1. It has tunable capability of a reconfigurable operation within the observed range of 400 MHz to 3.5 GHz. The structure is an integration of Koch fractal dipole antenna, stubs and wideband taper balun as explained in section 2. The results are presented and discussed in section 3, while concluding remarks are given in section 4.

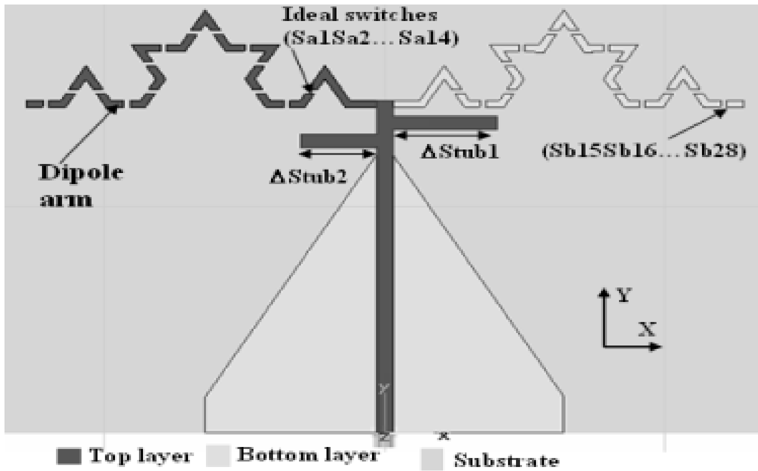


Figure 1. Geometry of the proposed reconfigurable fractal antenna. The ideal switches are ON and OFF to vary the radiating arm length e.g. Band 1 (all switches are ON, Band 2 (Sa2 to Sb27 are ON) and Band 15 (all switches are OFF) while ?Stub1 and ?Stub2 are changed from 19 mm minimum to 42 mm maximum, and 16 mm minimum to 30 mm maximum, respectively

2. Proposed Fractal Dipole Antenna Design

The configuration of the proposed planar antenna is illustrated in Figure 1. It has advanced features of harmonic suppressed and reconfigurable [10]. The antenna is first designed to operate at 0.9 GHz as a linear Koch dipole on a low-cost lossy FR-4 substrate. The substrate has dielectric constant, ε_r, of 4.6 and substrate thickness, *h*, of 1.6 mm. When the Koch fractal iteration is zero, the antenna is the same as a conventional linear dipole. Then, it is iterated until $N = 2$ which has input impedance of 34.78 Ω + j6.249 Ω. The antenna is then fabricated. The proposed antenna consists of a double-sided Koch curve radiating element that operates at a lower frequency and higher order modes as expected. It is verified by measurement that records operating frequency of 680 MHz and two higher modes, within the observed range, The modes are named as first higher order mode, 1^{st} HM and second higher order mode, 2^{nd} HM. The radiating element has length = 124 mm and vertical width = 20 mm) with indentation angle of 60^{o}, and line thickness of 1.5 mm. It is fed by a parallel terminal (length = 74 mm, width = 3 mm) and triangular tapered balun (maximum height, H = 64 mm and maximum width, W = 64 mm). The feed line and tapered balun are used to locate the stubs-filter for filtering the antenna's higher order mode and impedance matching purpose, respectively. The balun has 1:1.47 electromagnetic transition with linear structure. To suppress the higher order modes of the antenna, one or two open-circuit stubs (stub 1 with length = 19 mm minimum to 42 mm maximum and width = 3 mm, and stub 2 with length = 16 mm minimum to 32 mm maximum and width = 3 mm) are used as depicted in the figure. The length of the stub depends on $\lambda/4$ of a higher order mode in free space while the width is approximately 3 mm. The line width of the parallel terminal, and stubs-filter is equal to the width of the 50 Ω microstrip line. The total dimension of the antenna is equal to a length of 132 mm and width of 97 mm.

For achieving reconfigurability, the antenna needs to be able to change its radiating arm length so that it can resonate at the desired frequencies. The optimized dimensions of the single band antenna are tabulated in Table I while Figure 2 presents the antenna photograph for band 1 and its equivalent return loss response.

The length of the resonant elements are found to be 128 mm, 120 mm, 112 mm, 104 mm, 96 mm, 88 mm, 84 mm, 76 mm, 68 mm, 60 mm, 52 mm, 44 mm, 36 mm, and 28 mm. Each is controlled by removing the ideal switch. Twenty-eight switches are located on its arms at the middle of each Koch section. The bands, switches condition and the stubs length were reported in [10]. Besides that, the terminal length, stub width, and stubs location need to be optimized for better performance. These parameters could provide sufficiently small reflections and avoid the appearance of higher order modes. The configuration is proposed since it exhibits omni-directional radiation pattern with very low level of cross-polarization, as well as it can suppress higher order modes, although with a simple structure. The fractal technology applied allows minimization of the antenna size. Open circuit stub has been used to trap the higher order mode that acts as stub-filters. This antenna is simulated using numerical simulations, and cross-checked by using the FEM (Finite Element Method) based simulations. Good agreement is observed between both simulation results obtained [11].

Parameter	Value	Parameter	Value
Total size	128 X 97 mm2	Terminal	10 X 3 mm2
Dipole arm	Length =124 mm, width =1.5 mm	Transmission line	70.5 X 3 mm2
Stub 1	42 X 3 mm2	Tapered Balun	64 X 64 mm2
Stub 2	32 X 3 mm2	Indentation Angle	60^o

Table 1. Optimized dimensions of the single band antenna

3. Simulation and Measurement Results

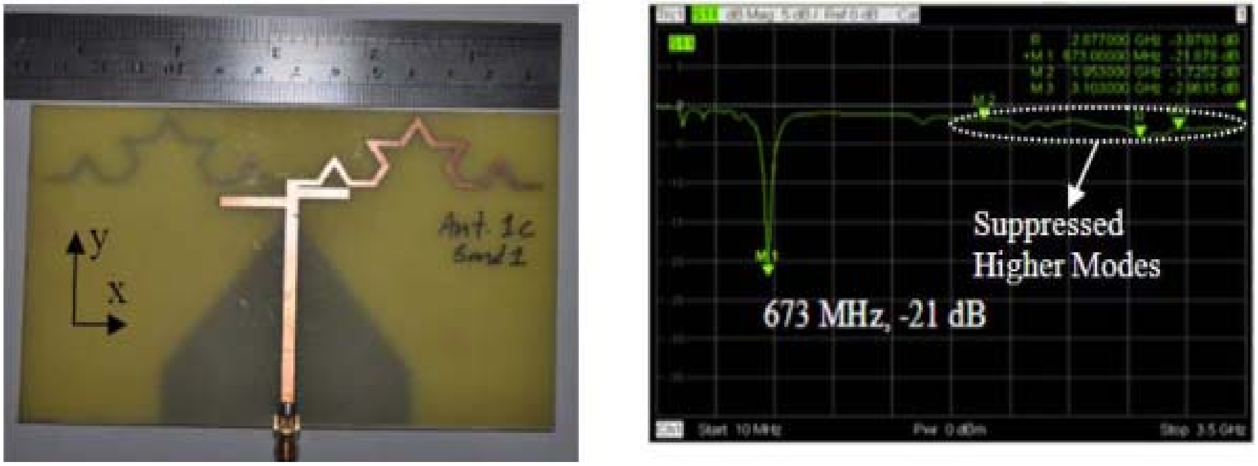
3.1 Harmonic Suppressed Fractal Dipole Antenna

Three antennas have been successfully simulated and measured. These are antenna without stubs, antenna with stub 1 and antenna with stubs 1, 2 (Figure 2). As can be seen in Figure 3, the return losses of the antennas are plotted using three different colours (blue, red and black) for comparison purposes. The blue colour is for antenna 1 while the red and black colours are for antenna 2 and antenna 3, respectively.

The first simulation results showed that there are three operating frequencies from 0 to 3.5 GHz. The antenna operates at 689 MHz, with two harmonics at 1855 MHz and 2814 MHz, having low return losses of -18 dB, -16.3 dB and -17.3 dB, respectively. The results agree well with the second simulation results. The fractal structure has successfully reduced the first resonant frequency to 710 MHz, but at the same time produced two harmonic frequencies as expected. Stub 1 (length = 42 mm, width = 3 mm) is used to eliminate the undesired 1855 MHz frequency as shown in Figure 4. However the new 2nd HM resonates at 3209 MHz with higher return loss of ~ -8 dB. Stub 2 of 21 mm length is then added to remove the 2nd HM as shown in Figure 3. The antenna hence operates at 710 MHz with very low return loss of -43 dB, indicating minute reflection at the input, and suppressed higher order modes.

On the other hand, the second simulations showed that the antenna without stubs exhibits resonances at 705 MHz, 1910 MHz and 2915 MHz. When stub 1 is added, the antenna has eliminated the 1st HM and has a new 2nd HM at 2989 MHz. Finally, the antenna operates at 731 MHz with very low return loss of -26.2 dB after the insertion of two stubs. The measurements were done using Agilent’s ZVB14 network analyzer, which operates in the 10 MHz to 14 GHz range. There are three operating frequencies observed from 0 to 3.5 GHz. The antenna operates at 680 MHz, with two harmonic frequencies, 1916 MHz (1^{st} HM) and 3008 MHz (2^{nd} HM), having low return losses of -13 dB, -22 dB and - 16 dB, respectively. The results agree well with the two simulations. The fractal structure has successfully lowered the first resonant frequency to 673 MHz, but at the same time produced two undesired HMs as expected. Stub 1 (length = 42 mm, width = 3 mm) has effectively eliminated the 1969 MHz frequency. Despite the elimination of the 1^{st} HM, the new 2^{nd} HM with wideband feature resonates within 2.9 GHz to 3.2 GHz with lowest return loss of -32 dB. Stub 2 (length = 30 mm, width = 3 mm) is then added to filter out the 2nd HM. The antenna with the two stubs is observed to operate at only 673 MHz with sufficiently low return loss of - 22 dB, and absence of undesired higher order modes.

Corresponding simulated and measured VSWRs are shown in Figure 4 with good agreements observed. Besides the factor of efficiency, the increasing appearances of higher order modes indicate that the selection method to reduce the antenna size (e.g. fractal technology) is a critical issue. In this work, simple antenna design has effectively produce good harmonic suppression as well as good impedance matching. Notice that the effectiveness of the open-circuit stubs to suppress the higher order modes (suppression level) in this study is proved based on the realized gain, total efficiency and 3-D realized gain patterns, comparing before and after the incorporation of the stubs. These are plotted in Figures 5, and 6 , respectively.



(a) (b)

Figure 2. (a) Photograph of fractal dipole antenna with stubs 1, 2 for band 1 and (b) return loss

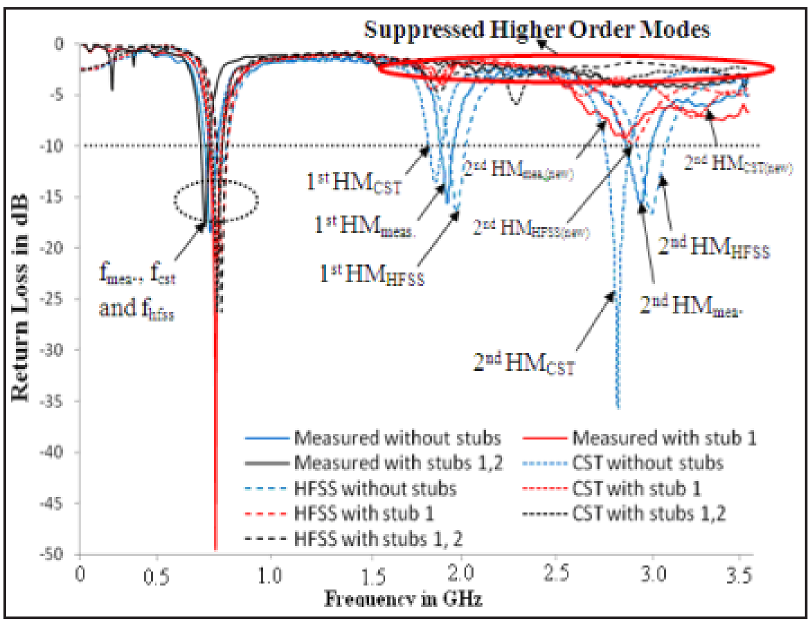


Figure 3. Simulated and measured return loss responses

3.2 Harmonic Suppressed Reconfigurable Fractal Dipole Antenna

The VSWR performances of the antenna that exhibits tunable feature and presence of higher order modes are presented in Figure 7. Operating band is referred as fr. The operating bands are divided into three groups. The first group covers bands 1 to 6, having 1st HM and 2nd HM. The second group consists of bands 7 to 10 having single higher order mode, 1st HM, while group three with no higher order mode.

The bands in group three are colored to indicate that they are considered to be single operations which do not need any stub. Only their first resonances exist within the observed range of frequencies. Besides that, the figure clearly highlights the objective of the work that relates to avoiding higher order modes interfering with the upper band frequencies (e.g. fr13 to fr15). All resonant frequencies and their equivalent higher order modes are given in the figure. To eliminate these higher order modes, one or two open circuit stubs are used depending on the $\lambda/4$ wavelength. The results obtained are shown in Figure 8.

Table II presents simulated and measured return loss and corresponding VSWR performances of the antenna for each band. It can be observed that the antenna can be tuned at 732 MHz, 756 MHz, 787 MHz to 2971 MHz, at a time. The stubs have effectively reduced the input reflections and thus corresponding VSWRs. Channel operating bandwidths obtained are 2239

MHz. The length of stub 1 obtained is from 19 mm minimum to 42 mm maximum, while stub 2 is 16 mm minimum to 30 mm maximum to eliminate higher order modes. It can be inferred that the proposed reconfigurable antenna works well in the CR standard frequency regulation which is allocated by FCC in the TV band, cellular radio band and ISM band (e.g. 400 MHz to 3.5 GHz) with return loss better than -10 dB, and corresponding VSWR of < 2.0. In addition, Table III gives the bandwidth for each channel, % BW, E-HPBW, realized gain and total efficiency. The channel bandwidth is from 54 MHz (band 1), 58 MHz (Band 2), to 670 MHz (band 15). Corresponding acceptable BWs are 7.65% (band 1), 7.9% (band 2), to 21.5% (band 15), respectively. The realized gain is fairly flat for band 1 to band 9 while the value is slightly high for other bands. In fact, they vary between a minimum value of 1.563 dB and a maximum value of 3.515 dB.

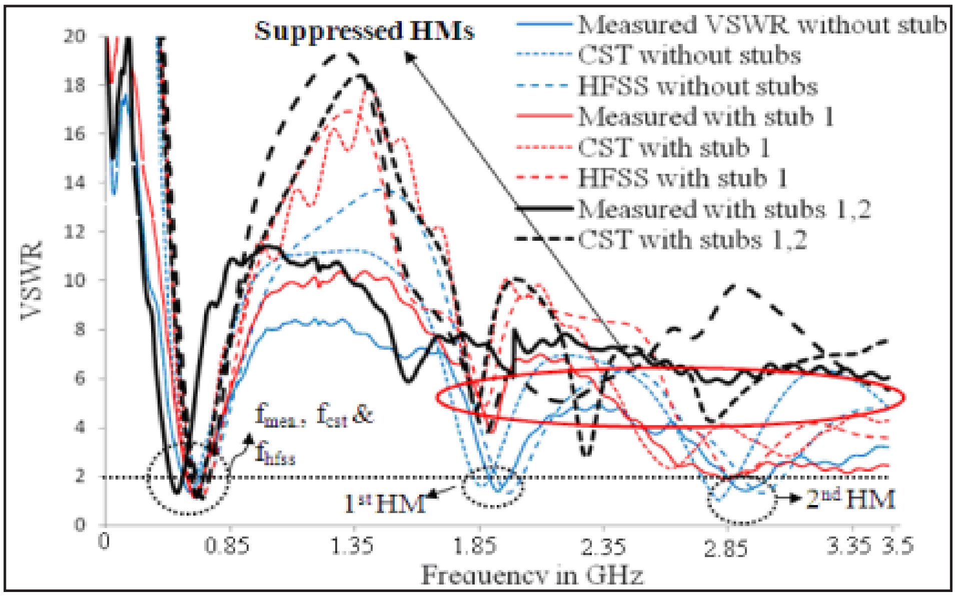


Figure 4. Simulated and measured VSWR responses

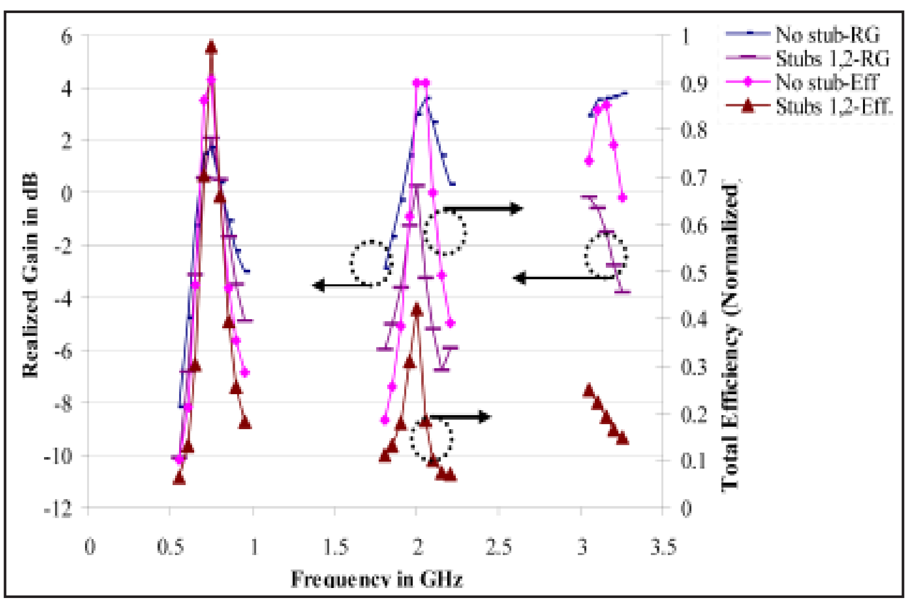


Figure 5. Realized gain (RG) and total efficiency (Eff.) as a function of frequency. The effectiveness of the stubs to suppress the higher order modes is highlighted

The antenna exhibits near ominidirectional H-plane (x-z) radiation patterns and figure-of-eight for E-plane (z-x) patterns as presented in Figure 9. Bands 1, 2, 3, and 15 have wide beamwidth of 87.7°, 92.5°, 90° and 50.9°, respectively, as tabulated in table III. The qualitative results by means of E- field patterns have been computed with the higher bands of 11, 12, 13 to 15 to be slightly different than the measured radiation pattern (bands 13, 15, and 15) as reported in [12] - [14]. This might be due to the tapered balun size that is relative to its operating wavelength.

Finally, Figure 10 depicted the realized gain of the 1st HM (band 1 to band 10) and 2nd HM (band 1 to band 5) for the antenna without stubs and the antenna with stubs as well. This figure clearly shows that the stubs have successfully eliminated these unwanted frequencies by means of reduction of the realized gain and the efficiency to a low value, and the antenna is not in a radiating mode at these frequencies.

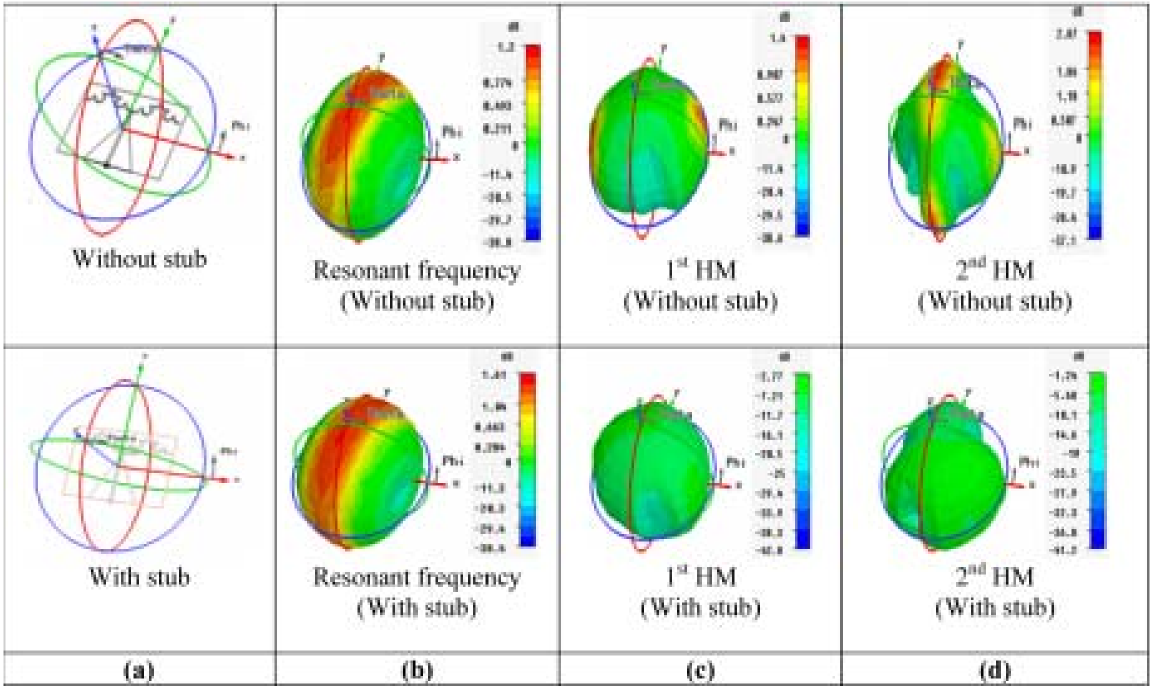


Figure 6. Realized gain patterns of the fractal dipole antenna in the passband mode and stopband mode. (a) Perspective view of the antenna without stubs (top) and perspective view of the antenna with stubs (bottom) in spherical coordinates system, (b) resonant frequency (without stubs), 689 MHz (1.2 dB) and resonant frequency (with stubs), 710MHz (1.61 dB), (c) 1st HM (without stubs) (1.4 dB) and 1st HM (with stubs) (-2.77 dB), and (d) 2nd HM (without stubs) (2.87 dB) and 2nd HM (with stubs) (-1.24 dB)

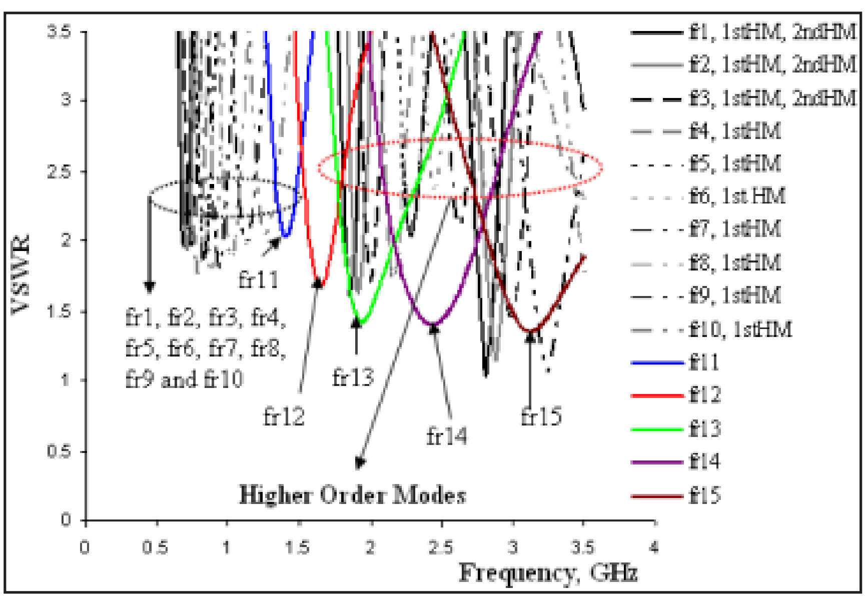


Figure 7. Simulated VSWRs of the tunable antenna with higher order modes

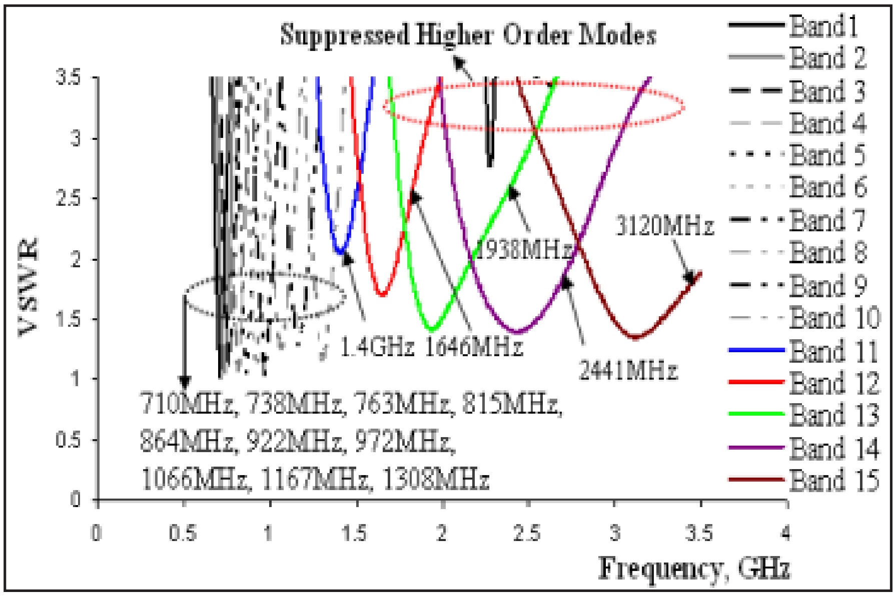


Figure 8. Simulated VSWRs of the tunable antenna with suppressed higher order modes

Band	**Return Loss**				**VSWR**	
	Simulated		**Measured**		**Simulated**	**Measured**
	Frequency	**dB**	**Frequency**	**dB**		
1	732 MHz	-26	673 MHz	-21	1.10	1.21
2	756 MHz	-26	712 MHz	-24	1.11	1.33
3	787 MHz	-31	712 MHz	-26	1.06	1.11
4	837 MHz	-38	760 MHz	-26	1.03	1.08
5	889 MHz	-42	792 MHz	-22	1.02	1.13
6	956 MHz	-19	798 MHz	-22	1.27	1.13
7	1012 MHz	-18	858 MHz	-19	1.30	1.25
8	1113 MHz	-17	858 MHz	-17	1.34	1.32
9	1211 MHz	-17	930 MHz	-20	1.33	1.25
10	1330 MHz	-19	1146 MHz	-24	1.24	1.13
11	1470 MHz	-10	1306 MHz	-42	1.88	1.02
12	1656 MHz	-14	1446 MHz	-9	1.53	2.16
13	1900 MHz	-19	1674 MHz	-9	1.26	2.16
14	2485 MHz	-20	1892 MHz	-12	1.24	1.66
15	2971 MHz	-19	2462 MHz	-20	1.26	1.19

Table 2. Return Losses and VSWR Results

4. Conclusion Future Work

A reduced size reconfigurable fractal dipole antenna has been successfully designed, simulated and tested. It operates in the 400 to 3500 MHz band of the future cognitive radio system. The antenna reconfigurable performance has advanced feature of harmonic suppression capability. The fractal curve is used to miniaturize the antenna size through the reduction of the first

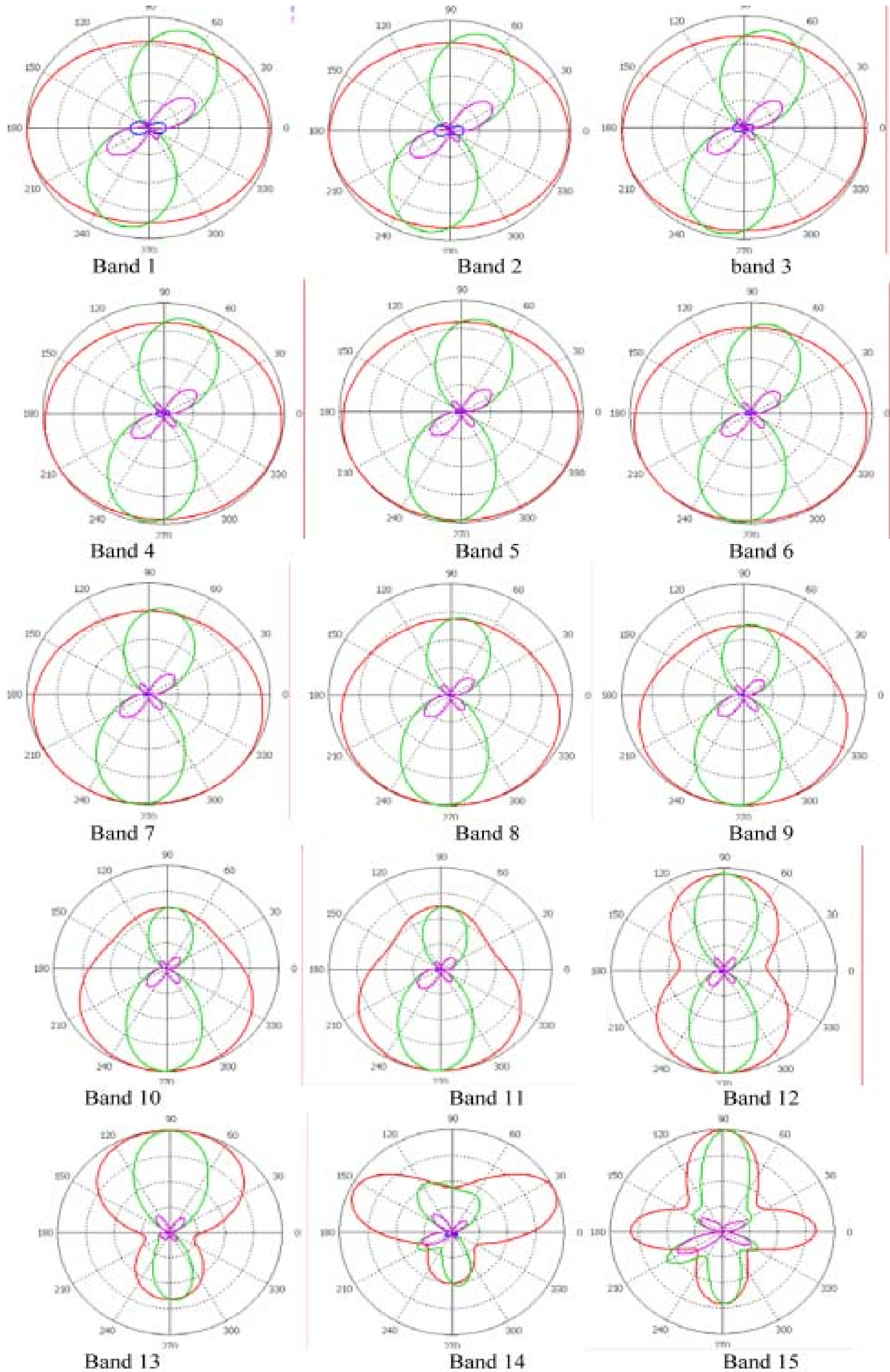


Figure 9. Simulated E-plane (z-x) and H-plane (x-z) radiation patterns for bands 1 to 15. Red indicatesH-plane co-polarization, blue indicates H-plane cross-polarization, green indicates E-plane co-polarization and purple indicates E-plane cross-polarization

resonance frequency. In summary, the optimal design of the reconfigurable harmonic suppression antenna has been studied. The design is feasible for frequency SDR/CR applications. However, its performance can be further enhanced by minimizing the size of the taper balun as well as implementing it on a low loss material such as RT/duroid. The work has shown that the number of bands selected to achieve wideband operation and tunable stubs-filter has a critical impact on the antenna's performance when realizing it using real PIN diodes.

Bands	BWch, (MHz)	BW (%)	E-HPBW (^{o})	Realized Gain (dB)	Total η
1	54	7.6	87.7	1.611	0.8898
2	58	7.9	92.5	1.601	0.8842
3	61	8.0	90.0	1.587	0.8783
4	66	8.1	88.1	1.573	0.8707
5	69	8.0	87.3	1.563	0.8651
6	74	8.0	87.4	1.567	0.8599
7	92	9.5	86.3	1.626	0.8601
8	100	9.4	84.8	1.790	0.8513
9	110	9.4	84.1	1.964	0.8361
10	120	9.2	80.0	2.430	0.8238
11	150	10.7	80.4	1.920	0.7096
12	150	9.1	71.1	2.467	0.7447
13	330	17.0	76.7	3.515	0.7913
14	270	11.1	54.4	2.977	0.7809
15	670	21.5	50.9	2.463	0.7604

Table 3. Simulated Bandwidth, BWch, Percentage BW, %BW, E-HPBW (°), Realized Gain (dB), and Total Efficiency, η

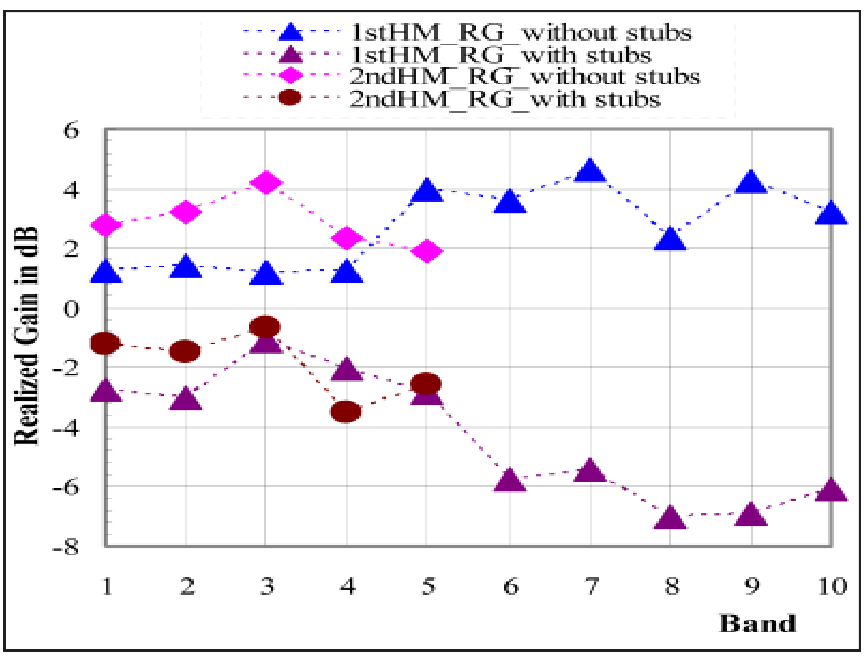


Figure 10. Realized gain (RG) of the 1st HM and 2nd HM as a function of frequency for the reconfigurable fractal dipole antenna

5. Acknowledgment

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