FRACTAL SHAPED MICROSTRIP COUPLED LINE BAND PASS FILTERS FOR SUPPRESSION OF 2ND HARMONIC

Il Kwon Kim, Nickolas Kingsley, Matt Morton, Ramanan Bairavasubramanian,
John Papapolymerou, Manos M. Tentzeris, and Jong-Gwan Yook

ABSTRACT — **In this paper, microstrip coupled line band pass filters using Koch fractal curves are proposed for the first time. These filters are fabricated on Liquid Crystal Polymer (LCP) substrate for Ku Band. Conventional microstrip coupled line filters are very popular for RF front ends because these can be made easily. However, their large 2nd harmonic causes the shape of the pass band to be asymmetric in the upper band and it makes the skirt properties worse. By proper design, the 2nd harmonic of fractal filters can be significantly suppressed through the use of fractal shapes. In LCP, the maximum harmonic suppression is almost 42 dB.**

Index Terms **— Koch Fractal geometry, Fractal shape band pass microstrip coupled line filter, Liquid Crystal Polymer (LCP), 2nd harmonic suppression**

I. INTRODUCTION

Traditionally, microstrip coupled line filters have been used to achieve narrow fractional bandwidth band pass filters due to their relatively weak coupling [1]. However, a parasitic second harmonic contributes to an asymmetric pass-band shape and degrades upper band skirt properties. In addition, a large 2nd harmonic signal can degrade the performance of system components, such as mixers. Due to the large difference between the even and odd mode effective dielectric constants of microstrip coupled lines, the phase velocity between two modes is significantly different. This problem is more pronounced when filters are fabricated on high dielectric constant materials, such as silicon or GaAs [2]. To overcome this problem, in this paper, Koch fractal geometry has been applied to the coupled sections of the filter.

I.K. Kim and J.G. Yook are with Department of Electric and Electronic Engineering, Yonsei University, Seoul, Korea.

N. Kingsley, M. Morton, R. Bairavasubramanian, J. Papapolymerou and M. Tentzeris are with the Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA.

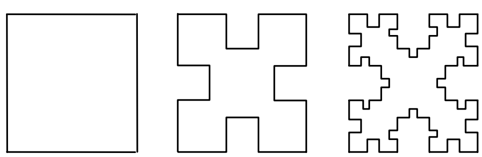
Several fractal geometries (Koch curve, Sierpinski gasket, and Hilbert curve, etc.) have been widely studied to develop various microwave devices, such as antennas, frequency selective surfaces (FSS) [3], and photonic band gap (PBG) devices [4]. All of these fractal shape devices have several advantages, including reduced resonant frequencies and broad bandwidth. These characteristics give the fractal shape two unique properties: space filling and self similarity. A fractal shape can be filled on a limited area as the order increases and occupies the same area regardless of the order. This is due to the space filling property. By self similarity, a portion of the fractal geometry always looks the same as that of the entire structure.

Predominantly, fractal research in microwave engineering is concentrated on antennas because the above properties enable the development of miniaturized, multi-band antennas [5-8].

Conventionally, there are two methods to solve the second harmonic problem in microstrip coupled line structures: making the phase velocity of even and odd modes the same or compensating different electrical length of both modes. To date, researchers have further added reactive components such as photonic band gap (PBG) and defect ground structures (DGS) [9]. However, in these cases, the components become complicated and have a leaky wave problem due to discontinuities in the ground plane. The second configuration involves making optimum line structures by inserting periodic shapes, such as grooved, wiggly and inter-digitized lines into conventional coupled lines [10-12]. These periodic structures can be used to create Bragg reflections to suppress the second harmonic. In this paper, Koch fractal shaped microstrip band pass filters are proposed for the first time. These fractal shape filters are fabricated on 8-mil liquid crystal polymer (LCP) substrate. The center frequency of the designed fractal shape filter is approximately 13 GHz. It has been found that by applying the Koch fractal geometry into a coupled line microstrip band pass filter (BPF), the second harmonic can be greatly suppressed.

II. KOCH FRACTAL SHAPE AND ITS APPLICATION ON COUPLED LINE BPF

Koch fractal geometry, named after the mathematician Helge von Koch, is a well known procedure which has been applied to miniaturize various conventional antennas [6-8]. This is characterized by two properties: the iteration factor and the iteration order. The iteration factor represents the construction law of the fractal geometry generation, and the iteration order depicts how many iteration processes are carried out. Fig.1 shows the configuration of a Koch island, which consists of a Koch curve. Due to its space filling property, the Koch geometry is principally used to miniaturize antennas [6-7]. These geometries exhibit well-known features that have been used to construct miniaturized monopole, loop, and patch antennas. However, when it is applied to RF devices for miniaturization, there is some limitation on the fractal order because the variation of the electrical length is relatively smaller compared to that of the operating frequency [8].



(a) (b) (c)

Fig. 1. Koch fractal island shape whose iteration factor is ¼ : (a) zero iteration order (b) 1st iteration order (c) 2nd iteration order

Fig. 2 shows 1-pole Koch shape band pass filters. The edges of the filter coupled sections have a Koch curve shape. According to Fig.1, the iteration factor is ¼ and the orders are zero, 1st and 2nd. All 1-pole fractal filters considered in this paper have the same configuration as Fig. 2 (iteration factor is ¼ and fractal order is extended to 2nd order). Also, these filters were extended to 2-pole and 3-pole configurations to investigate their properties. The Koch zero iteration filter is designed by using conventional coupled line theory. The electrical length of all coupled lines is λ/4 and the line width and gap dimensions are determined as in [1]. In Table 1, all even mode and odd mode impedances are smaller than 50 Ω due to LCP fabrication tolerances. Therefore, these filters need to be matched at the end of filter. This was realized by using a λ/4 transformer.

The 1st and 2nd order iteration filters were designed by applying the relative order of the Koch shape to conventional coupled sections. For the 1st iteration, the Koch shape represents a rectangular slit engraved on the center of the coupled microstrip lines. The slit length can be calculated by multiplying the iteration factor by the length of the coupled line and the slit width can be calculated by multiplying the iteration factor by the width of the coupled line. For the 2nd iteration, the slits were positioned on the center of every edge and their length was calculated the same way as that of the previous order. The minimum feature size was 100 um due to fabrication tolerances.

Figure 2 Layout on proposed geometry (1-pole case);K0: zero iteration, K1: the first iteration, K2: the second iteration.

Table.1. Physical parameters of coupled line

	N	W	S	Ze	Zo
1 pole	1	844.2	108.3	39.4	29.78
2 pole	1	789.9	107.5	41.5	31.0
	2	991.3	450.2	32.67	30.11
	3	789.9	107.5	41.5	31.0
3 pole	1	718.2	102.9	44.79	32.77
	2	990.7	246.1	33.57	28.82
	3	990.7	246.1	33.57	28.82
	4	718.2	102.9	44.79	32.77

* N: filter order, W: width of line (um), S: gap space (um), Ze: even mode impedance (Ω), Zo: odd mode impedance (Ω).

III. THE PROPERTY OF KOCH FRACTAL SHAPE COUPLER

To investigate the Koch fractal shape filter property, the Koch fractal shape coupler is introduced and its characteristics are evaluated using IE3D, a Method of Moments simulation tool. Fig.3 shows the configuration of the fractal shaped couplers. These couplers are designed on LCP whose permittivity is 3.1.

(a) zero (b) first (c) second

Fig.3. Koch fractal shape coupler

All of these coupled lines have ¼ fractal iteration factor and zero, 1st and 2nd iteration orders. The electrical length of each coupled section is λ/4 and the center frequency is 13 GHz. Simulated results of these are shown in Fig. 4.

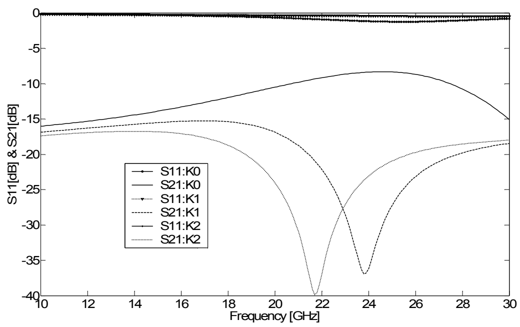
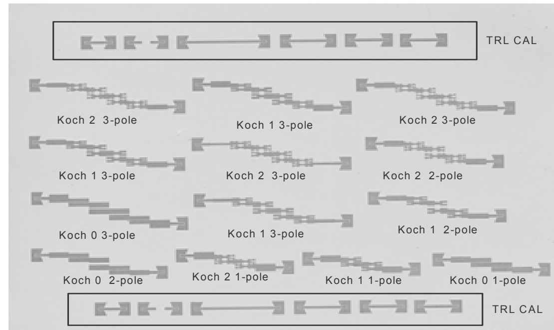


Fig.4. Simulated Insertion and return loss of fractal shape coupler.

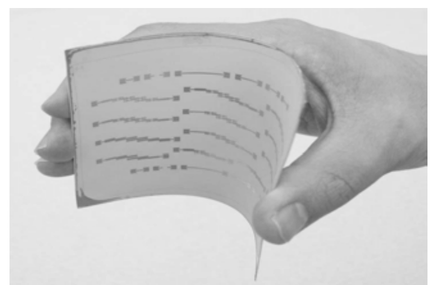
From the insertion loss of the coupler, we observe that the first null point becomes lower as the iteration number increases. For the zero iteration case, the null point is located away from the second harmonic frequency but in the Koch fractal coupler case, its null point is near to the second harmonic and also decreases as the iteration number increases. These properties can be used to suppress the 2nd harmonic of conventional coupled line filters.

IV. FRACTAL SHAPE FILTER ON LCP

LCP is suitable to be applied in microwave and millimeter-wave devices due to its low cost compared to that of low temperature co-fired ceramic (LTCC) and other RF materials. It also has several advantages such as low loss (tan δ = 0.002-0.004 for < 35GHz), flexibility and near hermetic nature (water absorption<0.004%) [14]. All of these advantages make it appealing for high frequency applications where excellent performance is required for minimum cost. The proposed filter is designed on 8 mil thick LCP substrate. Fig. 5 shows fabricated 1-pole, 2-pole and 3-pole LCP fractal shape filters for zero, 1st, and 2nd iteration order, respectively. The filter dimensions are 20.91 mm × 5.504 mm for the 3-pole filter, 17.415 mm × 4.867 mm for the 2-pole filter, and 13.926 mm × 3.281 mm for the 1-pole filter. The Koch zero iteration filter is a conventional filter designed by using traditional Butterworth filter design theory. Its center frequency is 13 GHz and the fractional bandwidth is 10%. The simulated insertion loss and return loss of the 1-pole, 2-pole, and 3-pole fractal shape filters for 0th, 1st and 2nd iteration order are shown in Figs. 6 (a), (b) and (c), respectively. The zero iteration Koch filter has a large second harmonic of 6.79 dB at 26.2 GHz. The simulation results for these filters are summarized in Table 2.



(a) Fabricated fractal filters

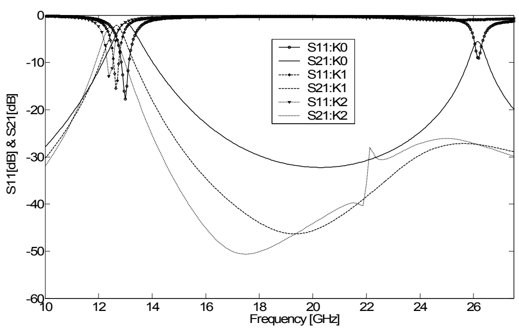


(b) LCP substrate flexibility

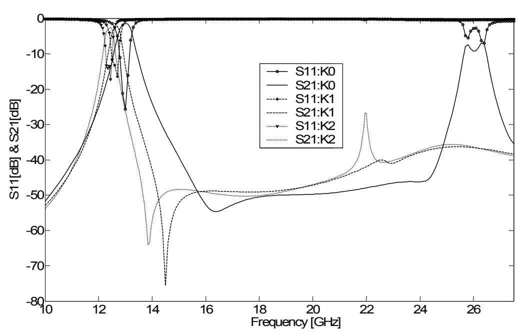
Fig. 5. Fabricated fractal shape filters on LCP substrate.

To verify the simulation results, these filters were fabricated on LCP substrate. The measured insertion loss and return loss results are shown in Fig. 7 and show good agreement with the simulated ones. Measurements were taken on an Agilent 8510 network analyzer using a Thru-Reflect-Line (TRL) calibration to de-embed the cable, probe, and CPW to microstrip transition losses. These measurement results are similar to the simulated ones. For the 1-pole filter, the 2nd harmonic suppression is 7.56 dB for zero iteration, 27.49 dB for the 1st iteration, and 25.75 dB for the 2nd iteration. For the 2-pole filter, the 2nd harmonic suppression is 11.81 dB for zero iteration, 40.47 dB for the 1st iteration and 38.19 dB for the 2nd iteration. Finally, for 3-pole filter, the 2nd harmonic suppression is 15.36 dB for zero iteration, 39.38 dB for the 1st iteration, and 42.59 dB for the 2nd iteration.

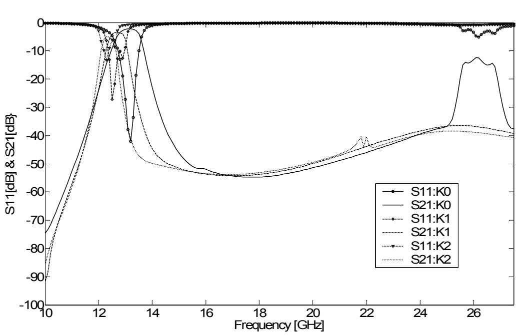
As shown in Figs. 6 and 7, as the iteration order of the fractal increases, the second harmonic frequency shifts slightly lower and their 2nd harmonic suppression becomes greater than that of a lower fractal order filter because, as shown in Fig. 4, the first null point of coupled section shifts lower. Additionally, the filter bandwidth becomes narrower as the iteration number increases due to weak coupling. These filters suppress the second harmonic by 20 dB or more compared to that of the zero iteration filters. In addition, the first zero frequency of the filter becomes closer to the center frequency (fundamental) as shown in Figs. 6 and 7. As a result, the skirt property of the filter improves in the frequency region of interest. The center frequency also becomes slightly lower than that of the conventional filter. From these results, as the iteration order increases, the second harmonic of the fractal shape filter can be suppressed and the distance between center frequency and first zero point narrows, improving the upper skirt performance.



(a) 1-pole

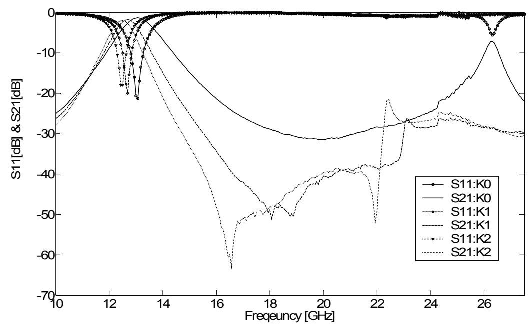


(b) 2-pole

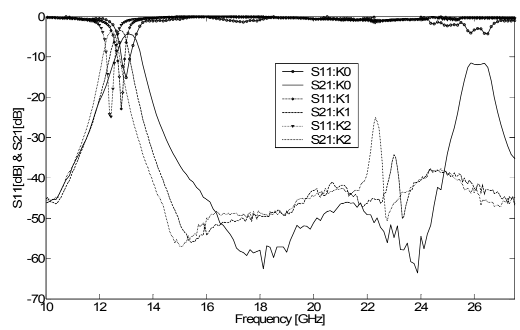


(c) 3-pole

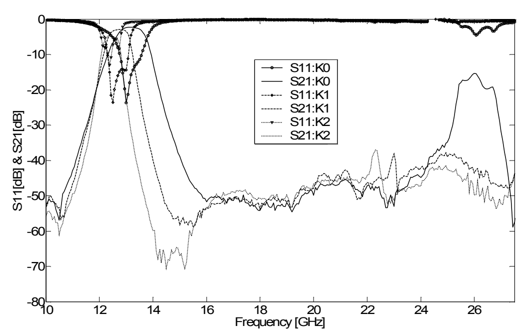
Fig. 6. Simulation results.



(a) 1-pole



(b) 2-pole



(c) 3-pole

Fig. 7. Measurement results.

Table 2. Summary of the results

P	Iter.	Simulation Results			
		CF	IL	FB	2H
1	K0	13.0	1.64	6.15	6.79
	K1	12.7	2.16	4.74	27.22
	K2	12.4	2.64	4.80	26.15
2	K0	13.0	1.45	4.20	9.25
	K1	12.7	2.18	3.15	25.40
	K2	12.4	2.69	2.73	35.88
3	K0	13.2	2.2	6.51	14.53
	K1	12.7	3.49	4.72	36.42
	K2	12.4	5.12	4.07	38.56

P	Iter.	Measurement Results			
		CF	IL	FB	2H
1	**K0**	13.1	1.33	9.80	7.56
	K1	12.7	1.74	7.64	27.49
	K2	12.5	1.94	6.40	25.75
2	**K0**	13.1	4.36	4.95	11.81
	K1	12.8	3.45	3.90	40.47
	K2	12.4	3.89	3.29	38.19
3	**K0**	13.2	2.29	8.38	15.36
	K1	12.7	2.93	7.29	39.38
	K2	12.4	4.45	4.84	42.59

* P: Pole number, Iter.: Iteration order, K0: Koch zero order, K1: Koch first order, K2: Koch 2nd order, CF: Center Frequency [GHz], IL: Insertion Loss [dB], FB: 3dB Fractional Bandwidth [%], 2H: 2nd Harmonics Insertion Loss [dB]

VI. CONCLUSION

In this paper, Koch fractal shape coupled filters have been proposed and investigated using numerical and experimental methods for the first time. It was shown that the 2nd harmonic of fractal shape filters can be suppressed as the fractal factor increases. The maximum suppression is 27.5 dB for 1-pole, 40.5 dB for 2-pole and 42.6 dB for 3-pole filters. It has also been determined that as the iteration number of the fractal geometry increases, the 2nd harmonic insertion loss increases. The proposed method can also be applied on high dielectric constant materials to suppress the 2nd harmonic. Fractal shape filters could be an ideal solution for RF systems which require a reduced 2nd harmonic component.

ACKNOWLEDGEMENT

This work was supported by the International Research Internship Program of the Korea Science and Engineering Foundation (KOSEF) and the Georgia Electronic Design Center (GEDC).

REFERENCES

[1] David M. Pozar, *Microwave Engineering*, 2nd Ed, pp 474-485

[2] Jen-Tsai Kuo, Sin-Ping Chen, and Meshon Jiang," Parallel-Coupled Microstrip Filters With Over-Coupled End Stages for Suppression of Spurious Responses," *IEEE Microwave and Wireless Components Letters*, Vol. 13, No.10, pp440-442, October 2003.

[3] Jordi Romeu and Yahaya Rahmat-Samii, "Fractal FSS: A Novel Dual-Band Frequency Selective Surface," *IEEE trans. on Antennas and Propagation*, Vol. 48, No. 7, July 2000

[4] Jung-Hyo Kim, Il Kwon Kim, Jong-Gwan Yook, and Han-Kyu Park, " A Slow-Wave Structure Using Koch Fractal Slot Loops," *Microwave and Optical Technology Letters*, Vol. 34, No.2, pp 87-88, July 2002.

[5] Steven R. Best," On the Performance Properties of the Koch Fractal and Other Bent Wire Monopoles," *IEEE trans on Antennas and Propagation*, Vol. 51, No.6, pp 1292-1300, June 2003.

[6] N. Cohen and R.G. Hohfeld, "Fractal loops and small loop approximation," *Commun. Quart*., pp 77-78, Winter 1996.

[7] Carles Puente Baliarda, Jordi Romeu, and Angel Cardama, "The Koch Monopole: A Small Fractal Antenna," *IEEE trans on Antennas and Propagation*, Vol. 48, No. 11, pp 1773-1781, November 2000.

[8] Il Kwon Kim, Jong-Gwan Yook and Han-Kyu Park, "Fractal-Shape Small Size Microstrip Patch Antenna," *Microwave and Optical Technology Letters*, Vol. 34, No.1, pp 15-17, July 2002.

[9] Jun-Seok Park, Jun-sik Yun, and Dal Ahn, " A Design of the Novel Coupled-Line Bandpass Filter using Defected Ground Structure With Wide Stopband Performance," *IEEE Trans on Microwave Theory and Techniques*, Vol. 50, No. 9, pp 2037-2043, September, 2002.

[10] Maria del Castillo Velazquez-Ahumada, Jesus Martel, and Francisco Medina, " Parallel Coupled Microstrip Filters With Ground-Plane Aperture for Spurious Band Suppression and Enhanced Coupling, "*IEEE trans on Microwave Theory and Techniques*, Vol. 52, No.3, pp 1082-1086, March 2004.

[11] Txema Lopetegi, Miguel A. G. Laso, Jorge Hernandez, Miguel Bacaicoa, David Benito, Maria J. Garde, Mario Sorolla, and Marco Guglielmi, " New Microstrip " Wiggly-Line" Filters With Spurious Passband Suppression," *IEEE trans on Microwave Theory and Techniques*, Vol. 49, No.9, pp 1593-1598, September 2001.

[12] Texa Lopetegi, Miguel A. G. Laso, Francisco Falcone, Ferran Martin, Jordi Bonache, Joan Garcia, Lteticia Perez-Cuevas, Mario Sorolla, and Marco Guglielmi, " Microstrip "Wiggly-Line" Bandpass Filters With Multispurious Rejection," *IEEE Microwave and Wireless Component Letters*, Vol. 14, No. 11, pp 531-533, November, 2004

[13] Bong S. Kim, Jae W. Lee, and Myung S. Song, "An Implementation of Harmonic-Suppression Microstrip Filters with Periodic Grooves," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No.9, pp 413-415, September 2004.

[14] Dane C. Thompson, Olivier Tantot, Hubert Jallageas, George E. Ponchak, Manos M. Tentzeris, and John Papapolymerou, "Characterization of Liquid Crystal Polymer(LCP) Material and Transmission Lines on LCP Substrates from 30 to 110 GHz," *IEEE trans. on Microwave Theory and Techniques*, Vol. 52, pp. 1343-1352, April 2004.