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Koch Fractal Shape Microstrip Bandpass Filters on High Resistivity Silicon for the Suppression of the 2nd Harmonic

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Abstract

In this paper, the fractal shape is applied to microstrip band pass filters and integrated on a high-resistivity Si substrate to solve conventional 2nd harmonic problem. Conventional microstrip coupled line filters are popular in RF front ends, because they can be easily fabricated and integrated with other RF components. However, they typically have large second harmonics that can cause unwanted interference in interested frequency bands. Without any additional filters, the proposed Koch shape filters have suppressed the 2nd harmonics by about −40 dB, so they can be used in systems such as direct conversion receiver with stringent harmonic suppression requirements.

Key words : Koch Fractal Geometry, Space Filling Property, Microstrip Bandpass Filter, The 2nd Harmonic Suppression, High Resistivity Silicon.

Ⅰ. Introduction

Conventionally, microstrip coupled line filters have been utilized in developing relatively narrow fractional bandwidth band pass filters due to their relatively weak coupling[1]. These filters have desirable advantages, such as low fabrication cost and ease of integration. However, despite of these advantages, this type of filter has the inherent large 2nd harmonic problem and it makes the shape of filter band asymmetric. This parasitic second harmonic contributes to an asymmetric pass-band shape and degrades the upper band skirt properties. In addition, a large 2nd harmonic can degrade the performance of other nonlinear active component, such as mixers. The large 2nd harmonic is generated because of the large difference between the even and odd mode effective dielectric constants of the microstrip coupled lines. The phase velocity for each mode is significantly different due to the inhomogeneous characteristics of the microstrip structure. The large 2nd harmonic is generated by the large difference between the even and odd mode effective dielectric constants of the microstrip coupled lines. The phase velocity for each mode is significantly different due to the inhomogeneous characteristics of the microstrip structure. This problem is more pronounced when filters are fabricated on high dielectric constant materials, such as silicon or GaAs[2].

Therefore, conventionally, there are two kinds of methods used to overcome this problem in microstrip coupled line structures: one method is to equalize the phase velocity difference of even and odd modes and the other is to compensate the different electrical lengths of both modes by modifying the line shape. Traditionally, several researchers have added reactive components, lumped loads, defect ground structures(DGS), and dielectric overlays to alleviate this problem[3]. An approach where both of the above methods were used together has also been reported[4]. However, in these cases, the components become complicated and have a leaky wave problem due to discontinuities in the ground plane. To overcome this, the second method was introduced which involves making optimum line structures by inserting periodic shapes, such as grooves, wiggly lines and inter-digitized lines into conventional coupled lines[5]~[7]. These periodic structures can be used to create Bragg reflections to suppress the second harmonic. Alternatively, further zero transmission or transmission modulation can be performed by adopting additional parasitic capacitances or PBGs.

As the frequency of RF applications increase, radio-frequency integrated circuit(RFIC) designs on silicon substrates become a key factor for low-cost, highly integrated circuits. However, the substrate loss in CMOS-grade silicon (resistivities between 1 and 30 Ω-cm) emerges as a troublesome issue for microwave integrated circuits particularly for passive components. To reduce the silicon substrate loss, high resistivity silicon (HRS) can be used. In this paper, we propose fractal

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shape filter on HRS to suppress the 2nd harmonic by using space-filling property of fractal geometry.

Ⅱ. Fractal Application In RF Passive Components

Several fractal geometries, such as Koch curve, Sierpinski gasket, Cantor dirt, and Hilbert curves have been widely researched to be used in design on microwave devices, such as antennas, frequency selective surfaces (FSS), and EBGs. These fractal shapes have unique two properties, such as space filling property and self similarity property. A fractal shape can be filled in 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 has same shape as that of entire structure. Until present, the research on fractal antenna element is concentrated on miniaturized antenna and multi-band antenna. The space filling property is useful to miniaturize physical dimensions and the self-similar property is advantages to designing multiband/broad band antennas[8]~[10]. Although, most researches on fractal electromagnetic have been focused on antenna design but two unique properties of fractal geometry can also be adopted to microwave applications[11]~[13]. In this paper, Koch fractal geometry is applied to suppress the 2nd harmonic of a microstrip coupled line on a high-permittivity substrate. By numerical and experimental methods, it is found that this type of filter can be used in a system required to suppress 2nd harmonic interference.

Ⅲ. Koch Shape Two Port Coupled Line

In this section, the Koch fractal shape 2-port coupled lines are introduced and designed on HRS. The Koch fractal shape 2-port coupled lines can be obtained by applying the Koch fractal curves shown in Fig. 1 into the conventional coupled line sections. The characteristics of the proposed coupled lines are evaluated using a method of moments(MOM) based commercial simulation tool.

3-1 Design Procedure

HRS has a permittivity of 11.7 and 100 μm thicknesses. Three different iteration order coupled lines with ¼ on HRS are shown in Fig. 2. The electrical length of each coupled line section is $\lambda/4$ and the center frequency is about 40 GHz for HRS. The gap distance between the coupled sections is 46.6 um, the width of line is 66.5 um, and the length of line is 609.9 um.

3-2 Transmission Zero Shift Property

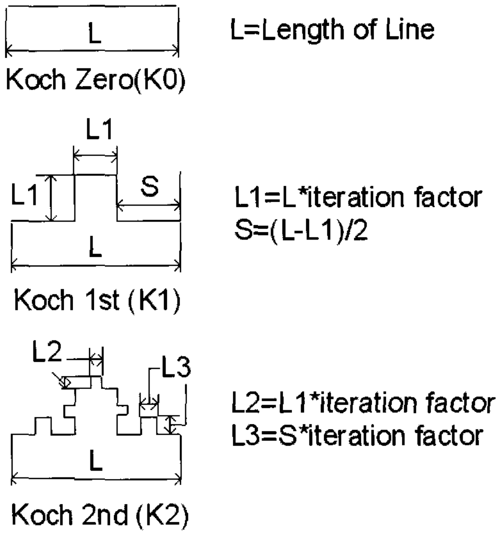
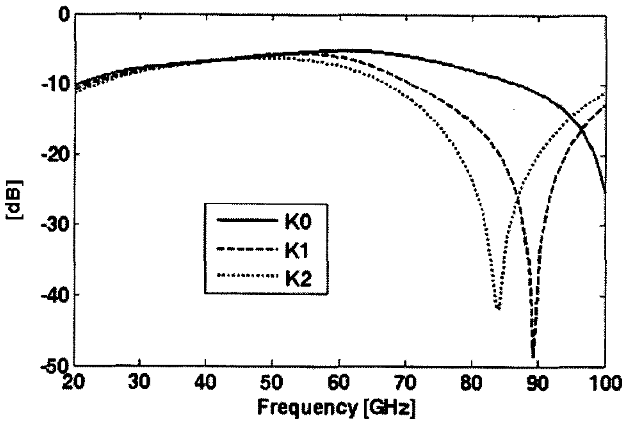


Fig. 1. Koch fractal curves.

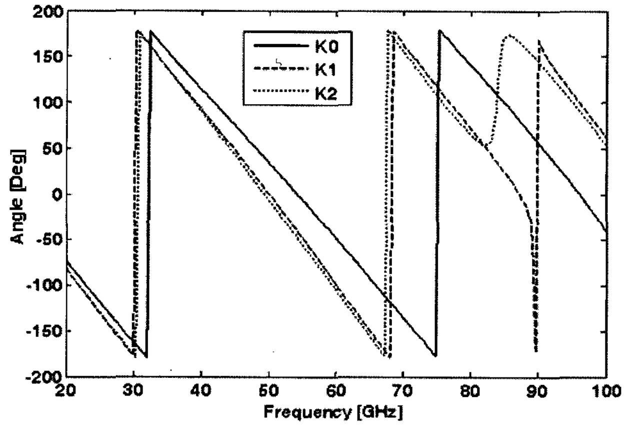
Zeroth order (K0) First order (K1) Second order (K2)

Fig. 2. Two port Koch fractal shape coupler.

From the insertion loss of the 2 port coupled lines in Fig. 3, it is observed that the first null point becomes lower as the iteration number and fractal iteration factor increases. For the zeroth iteration case which is conventional coupled line, the first transmission zero point is located far away from the second harmonic frequency, but in the Koch fractal coupler case, the null point is located near the second harmonic, and it also shifted down as the iteration number increases. This is due to the space filling property of the fractal geometry. The electrical length at higher frequencies is adversely affected by this property(space-filling property). As the iteration order increases, the length around the perimeter increases. Also, as the frequency increases and the wavelength decreases, the physical perimeter length remains constant, but the effective electrical length increases. This causes the transmission zero point to shift lower to a low value as the iteration order increases. This can be further demonstrated by evaluating the phase for each iteration order. As the electrical length decreases the corresponding phase should also decrease. This is indeed the case, as shown in Fig. 3(b). These properties can be used to suppress the 2nd harmonic of conventional coupled line filters by controlling the location of the first null point. As shown in Fig. 3(a), the position of the null point can be located at the 2nd harmonic, thus, crea-



(a) Amplitude



(b) Phase

Fig. 3. Simulated insertion loss.

ting a stop band. These results show that the space-filling property of fractal geometry can be adapted to suppress the 2nd harmonic.

Ⅳ. Koch Shape Filters for 2nd Harmonic Suppression

4-1 The Design of Proposed Koch Filter

To check the possibility of application of proposed filter in high dielectric materials, the permittivity of high resistivity silicon(HRS) considered here is 11.7 and the substrate thickness is 100 um. The resistivity of silicon is approximately 300 Ω-cm. The fractal shape filter configurations are same with Fig. 4 and the physical dimension of filters are shown in Fig. 5. The properties of these filters are investigated by using a commercial method of moments(MOM) based simulator. The simulation results for proposed filter on silicon are shown in Fig. 6. In Fig. 6, the 2nd harmonic of proposed filter for 3 configurations have been suppressed strongly and the first zero point is shifted down to improve upper skirt property. The discontinuity at the around 70 GHz for 2nd iteration fractal filter is due to the generation of transmission coupled line at the lower than the 2nd harmonic frequency. The simulated return loss for 3-pole filter is not matched, however, the 2nd harmonic suppression property can be found in that also the result. All simulated results shows the similar tendency with that of LCP case, therefore, the proposed filter geometry can be used in high dielectric constant material without any significantly degradation of RF performance to suppress the 2nd harmonic of conventional filters.

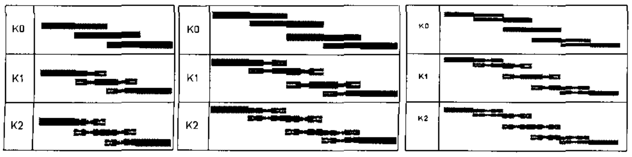


Fig. 4. The configurations of proposed filters.

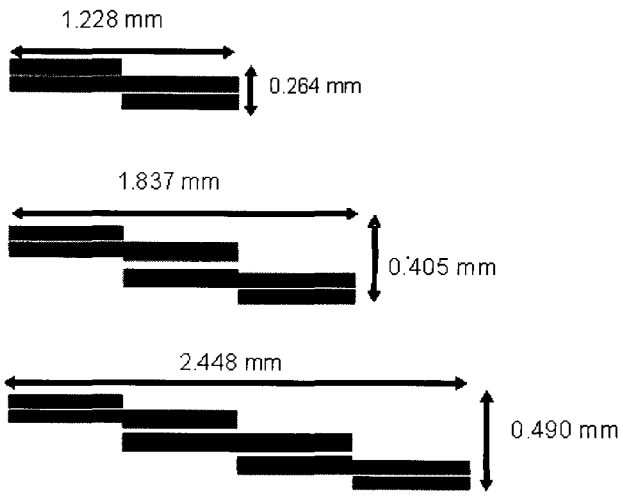
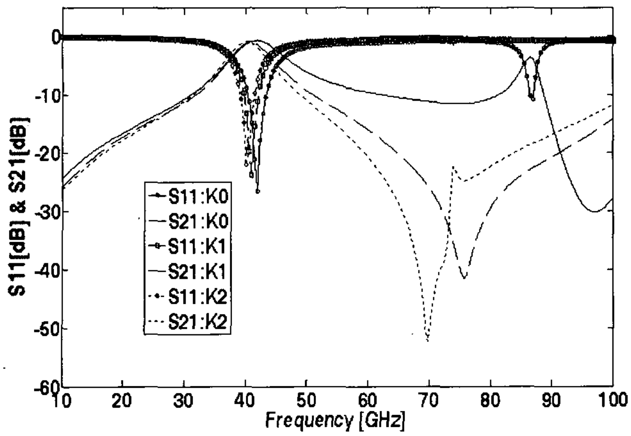


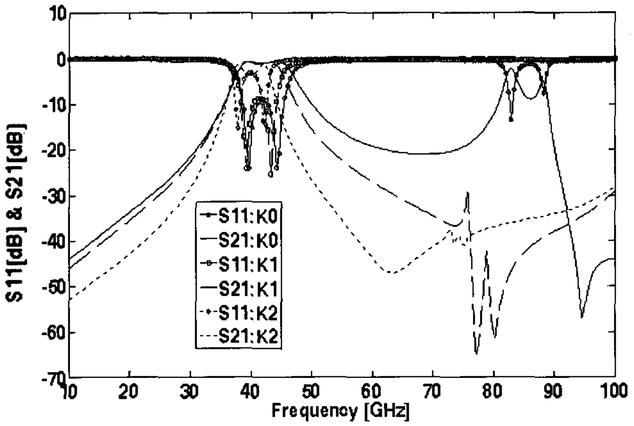
Fig. 5. The physical dimensions for proposed filters.

4-2 The Fabrication of Proposed Koch Filter

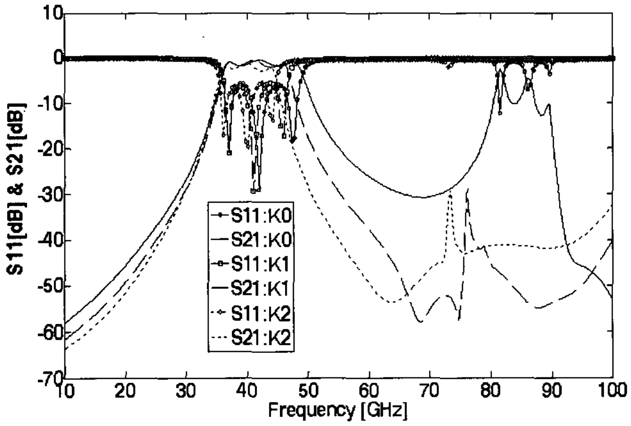
To verify the simulation results, the designed filters were fabricated and measured. A photo of the fabricated filters is shown in Fig. 7 and 8 for detail. Copper was electroplated to a thickness of 2 μm on a 100 μm thick wafer and the fabrication process for filters is shown in Fig. 9. The measured S-parameters are shown in Fig. 10 verifying that the resonant frequency of the fractal shape filter is almost the same as the conventional filter (Koch zero case), Fig. 10 also shows that first or second iteration geometries are sufficient for a 2nd harmonic suppression around or below 30 dB's even for 1-pole designs. In measurement, TRL calibration methods are used with 150 μm GSG pitch probes to obtain good calibration results. Without an additional matching circuit, the insertion loss at the center frequency



(a) 1-pole



(b) 2-pole



(c) 3-pole

Fig. 6. Simulated return and insertion loss.

is slightly larger than the conventional one. However, the 2^{nd} harmonic insertion loss is approximately 40 dB larger than the conventional one even for higher permittivity substrates, as in the case of silicon. This result clearly demonstrates that the fractal shape filter can be used to suppress the 2^{nd} harmonic. As the fractal iteration order increases, the suppression becomes larger

Fig. 7. Fractal shape filters.

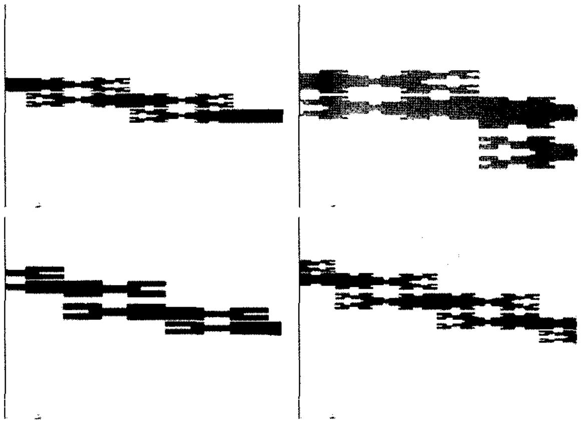


Fig. 8. Fabricated fractal shape silicon filters(detail).

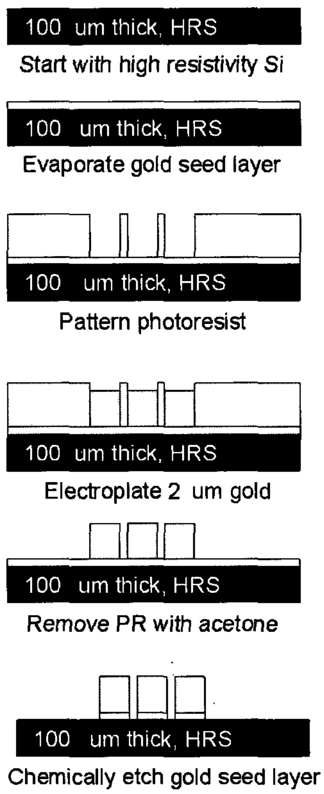
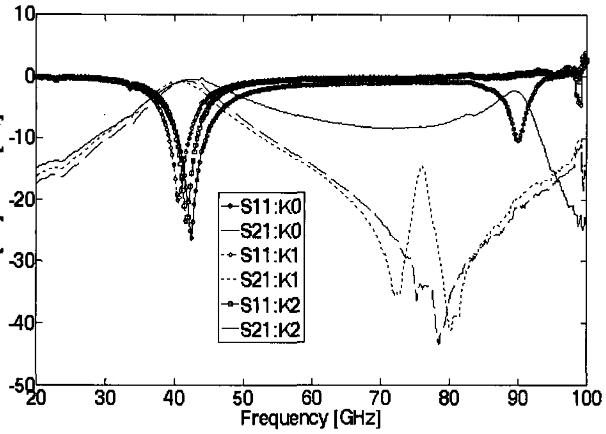
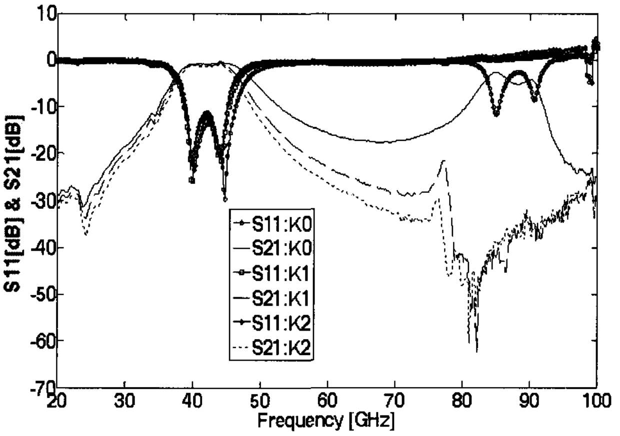


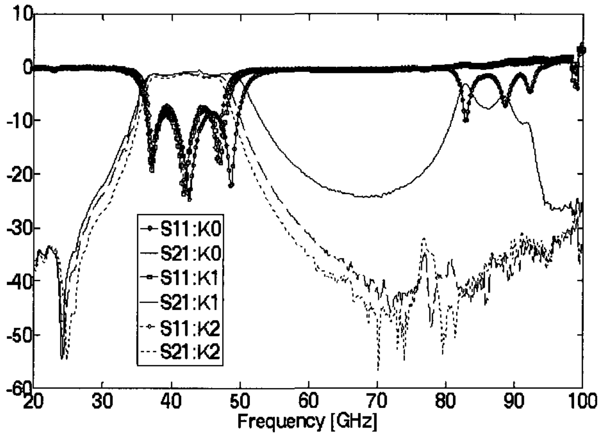
Fig. 9. Fabrication process for HRS.



(a) 1-pole



(b) 2-pole



(c) 3-pole

Fig. 10. Measured return and insertion loss.

Table 1. Summary of results(HRS).

P	Iteration	Simulation Results			
		CF	IL	FB	2H
1	K0	41.60	0.62	9.04	6.74
	K1	40.60	1.08	8.30	30.57
	K2	39.80	1.04	7.82	26.64
2	K0	42.00	1.21	13.70	4.71
	K1	41.00	1.45	12.89	49.97
	K2	40.00	3.70	11.83	36.93
3	K0	41.80	0.56	9.89	9.11
	K1	41.20	0.70	9.13	43.63
	K2	39.80	1.66	8.65	42.47

P	Iteration	Measurement Results			
		CF	IL	FB	2H
1	K0	42.80	0.48	12.37	5.15
	K1	41.80	0.71	11.92	28.97
	K2	41.00	0.81	11.90	34.02
2	K0	43.00	0.80	14.12	3.45
	K1	42.20	1.08	14.26	44.57
	K2	42.00	1.32	13.09	41.46
3	K0	44.00	0.49	10.61	5.76
	K1	42.40	1.13	8.38	43.25
	K2	41.80	1.27	9.49	41.78

* 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: 3 dB Fractional Bandwidth [%], 2H: 2nd Harmonics Insertion Loss [dB].

than that of the previous iterations. This is due to the space filling property of the fractal geometry. The electrical length at higher frequencies is more affected by this property. As the fractal iteration order increases, the length around the perimeter increases, the physical perimeter length remains constant, but the effective electrical length increases. This causes the transmission zero point to shift to a lower value as the iteration order increases.

All results are summarized in Table 1, where it is clearly demonstrated that fractal shape filters can be used to suppress the 2nd harmonics in high permittivity substrates for suppression of the 2nd harmonics.

V. Conclusions

In this paper, the Koch fractal shape is applied for the first time to mm-wave microstrip band pass filters integrated on a high-resistivity Si substrate. From simulation and experimental results, it was found that the 2nd harmonic of fractal shape filters can be suppressed as the fractal factor increases reaching a level of 40 dB, while maintaining the physical size. These fractal shape filters can be easily integrated with RF systems which require a highly reduced 2^{nd} harmonic component. From all of numerical and fabrication results, it is found that the proposed filters can suppress the 2^{nd} harmonic without any significant degradation; therefore, the proposed methods can be used in high dielectric constant materials.

References

[1] David M. Pozar, *Microwave Engineering*, 2nd Ed., pp. 474-485, 1993.

[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, pp. 440-442, Oct. 2003.

[3] Jen-Tsai Kuo, Meshon Jiang, "Enhanced microstrip filter design with a uniform dielectric overlay for suppressing the second harmonic response", *IEEE Microwave and Wireless Component Letters*, vol. 14, no. 9, pp. 419-421, Sep. 2004.

[4] 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, Mar. 2004.

[5] 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 Theroy and Techniques*, vol. 49, no. 9, pp. 1593-1598, Sep. 2001.

[6] 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, Nov. 2004.

[7] B. S. Kim, J. W. Lee, and M. 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, Sep. 2004.

[8] I. K. Kim, J. G. Yook, and H. K. Park, "Fractal shape small size microstrip patch antenna", *Microwave and Optical Technology Letters*, vol. 34, no. 1, pp. 15-17, Jul. 2002.

[9] D. H. Werner, P. L. Wener, "Frequency independent features of self-similar fractal antennas", *Radio Science*, vol. 31, no. 6, pp. 1331-1343, Nov. 1996.

[10] C. Punete-Baliarda, R. Pous, "Fractal design of multiband and low side-lobe arras", *IEEE Trans. on Antennas and Propagation*, vol. AP-44, pp. 730-739, May 1996.

[11] V. Crnojevic-Bengin, Budimir, "Novel compact resonators with multiple 2-D hilbert fractal curves", *the Proceeding of 35th European Microwave Conference*, pp. 205-208, 2005.

[12] Hani Ghali, Tarek A. Moselhy, "Miniaturized fractal rat-race, branch-line and coupled-line hybrids", *IEEE Trans. on Microwave Theory and Techniques*, vol. 52, no. 11, pp. 2513-2520, Nov. 2004.

[13] I. K. Kim, *Koch Fractal Shape Microstrip Coupled Line and Its Application on RF Passive Devices for Wireless Communications*, Ph.D Thesis, Yonsei University, 2006.

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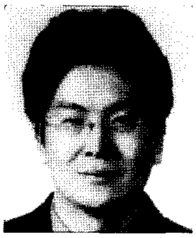

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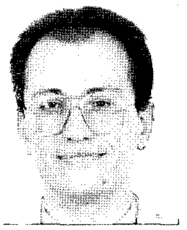

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