

# Koch Fractal Shape Microstrip Bandpass Filters on High Resistivity Silicon for the Suppression of the 2<sup>nd</sup> 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 2<sup>nd</sup> 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 2<sup>nd</sup> 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 2<sup>nd</sup> Harmonic Suppression, High Resistivity Silicon.

## 요약문

본 논문에서는 마이크로스트립 대역 통과 필터의 2차 고조파 문제를 해결 하기 위해 프랙탈 형태를 적용하고 고저항성 실리콘에 제작하였다. 일반적으로 마이크로스트립 대역 통과 필터는 쉽게 제작가능하고 다른 RF소자와의 결합이 용이하기 때문에 RF 전단에 많이 사용된다. 하지만, 일반적으로 커다란 2차 고조파 대역을 가짐으로써 관심대역에서 원하지 않는 간섭을 주는 원인이 된다. 제안된 프랙탈 형태의 필터는 약 -40 dB 정도의 고조파 억제를 보임으로써, 이러한 필터는 직접변환 수신기 등과 같이 고조파 억압이 요구되는 시스템에서 추가적인 고조파 억압필터 없이 사용되어 질수 있다.

## 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<sup>[1]</sup>. 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 2<sup>nd</sup> 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 2<sup>nd</sup> harmonic can degrade the performance of other nonlinear active component, such as mixers. The large 2<sup>nd</sup> 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 2<sup>nd</sup> 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<sup>[2]</sup>.

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<sup>[3]</sup>. An approach where both of the above methods were used together has also been reported<sup>[4]</sup>. However, in these cases, the components become complicated and have a leaky wave problem due to discontinuities in the ground plane. To

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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<sup>[5]~[7]</sup>. 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 shape filter on HRS to suppress the 2<sup>nd</sup> 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<sup>[8]~[10]</sup>. 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<sup>[11]~[13]</sup>. In this paper, Koch fractal geometry is applied to suppress the 2<sup>nd</sup> 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 2<sup>nd</sup> 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 1/4 on HRS are shown in Fig. 2. The electrical length of each coupled line section is λ/4 and the center frequency is about 40 GHz for HRS. The gap distance between the coupled sections is 46.6 μm, the width of line is 66.5 μm, and the length of line is 609.9 μm.

### 3-2 Transmission Zero Shift Property

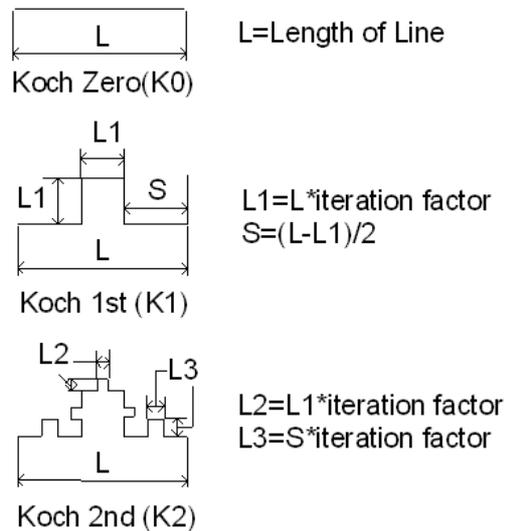


Fig. 1. Koch fractal curves.

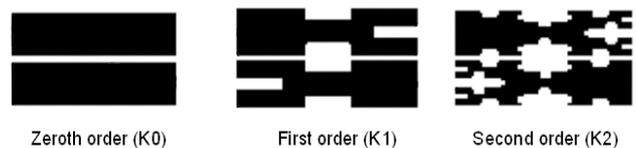
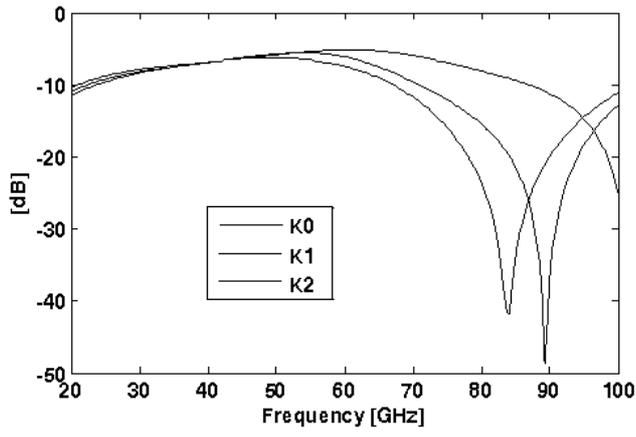


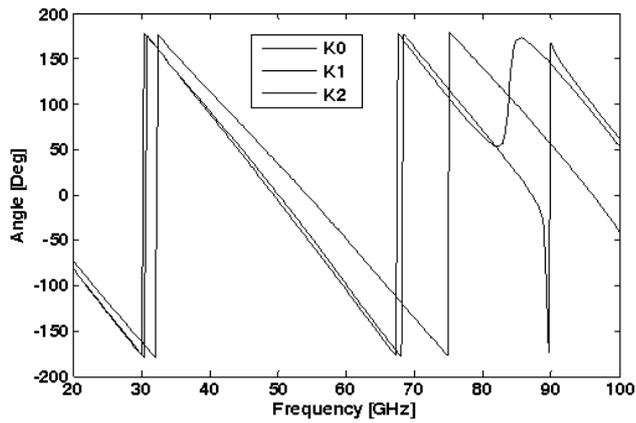
Fig. 2. Two port Koch fractal shape coupler.

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 2<sup>nd</sup> 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 2<sup>nd</sup> 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 2<sup>nd</sup> harmonic.

#### IV. Koch Shape Filters for 2<sup>nd</sup> 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  $\mu$ m. The resistivity of silicon is approximately 300  $\Omega$ -cm. The fractal shape filter configurations are same with Fig. 4 and the physical dimension of filters are shown in Fig. 5. The properties

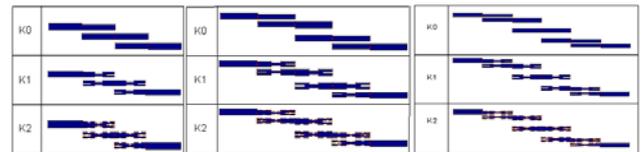


Fig. 4. The configurations of proposed filters.

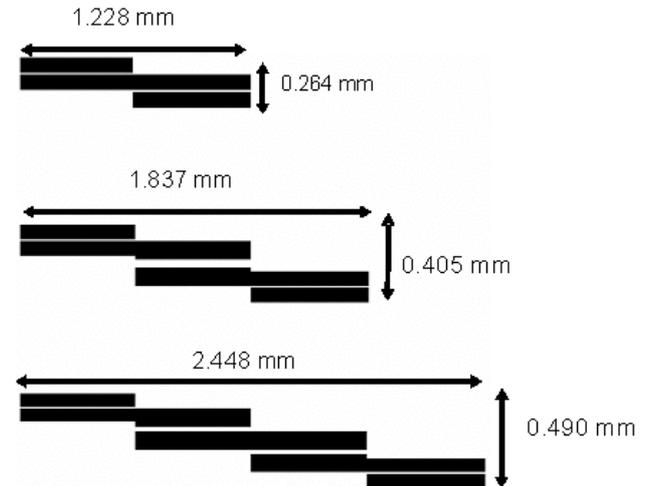


Fig. 5. The physical dimensions for proposed filters.

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 2<sup>nd</sup> 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 2<sup>nd</sup> iteration fractal filter is due to the generation of transmission coupled line at the lower than the 2<sup>nd</sup> harmonic frequency. The simulated return loss for 3-pole filter is not matched, however, the 2<sup>nd</sup> 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 su-

ppress the 2<sup>nd</sup> harmonic of conventional 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  $\mu\text{m}$  on a 100  $\mu\text{m}$  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 2<sup>nd</sup> harmonic suppression around or below 30 dB's even for 1-pole designs. In measurement, TRL calibration methods are used with 150  $\mu\text{m}$  GSG pitch probes to obtain good calibration results. Without an additional matching circuit, the insertion loss at the center frequency

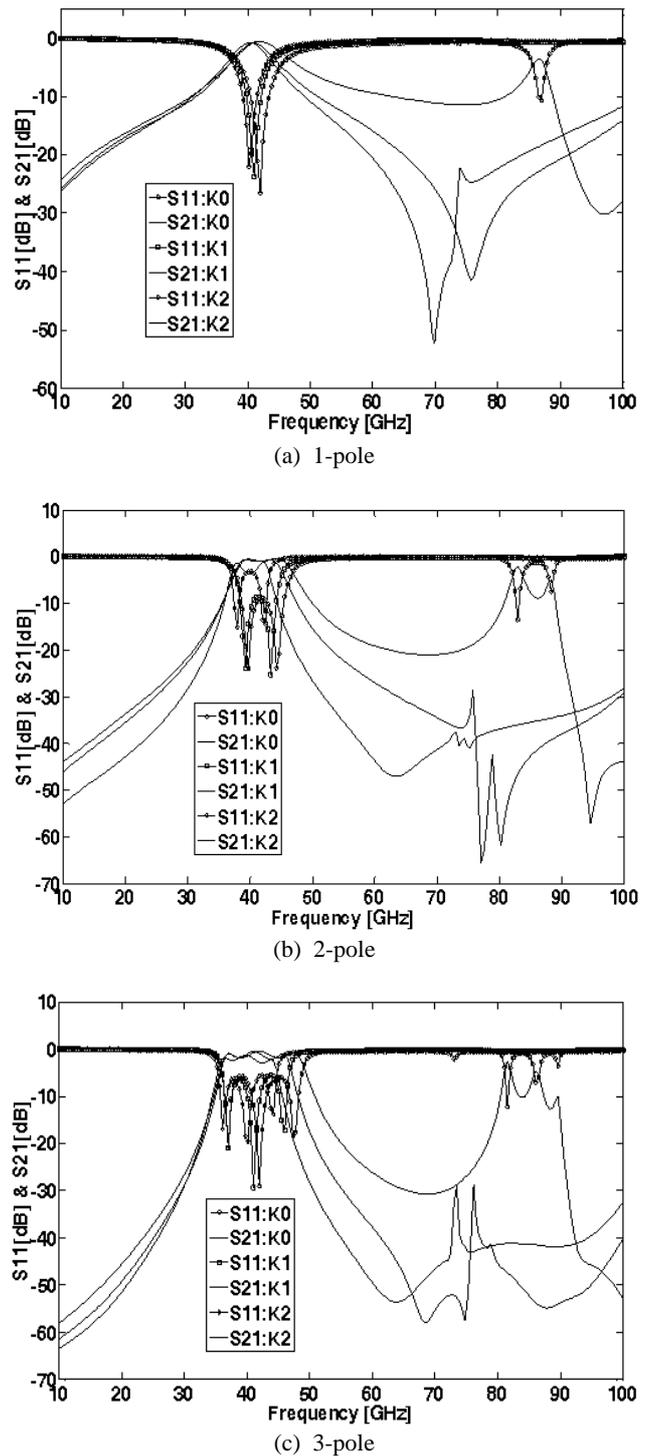


Fig. 6. Simulated return and insertion loss.

is slightly larger than the conventional one. However, the 2<sup>nd</sup> 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<sup>nd</sup> harmonic. As the fractal iteration order increases, the suppression becomes larger



Fig. 7. Fractal shape filters.

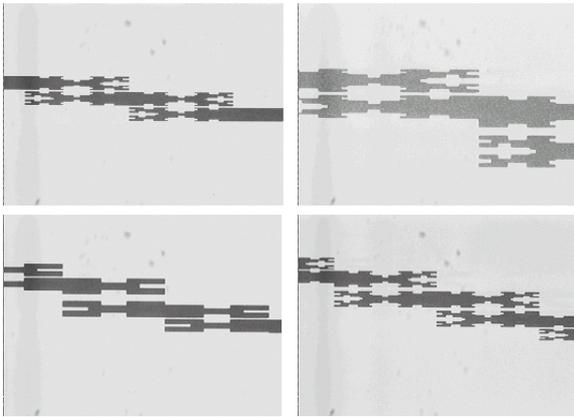


Fig. 8. Fabricated fractal shape silicon filters(Detail).

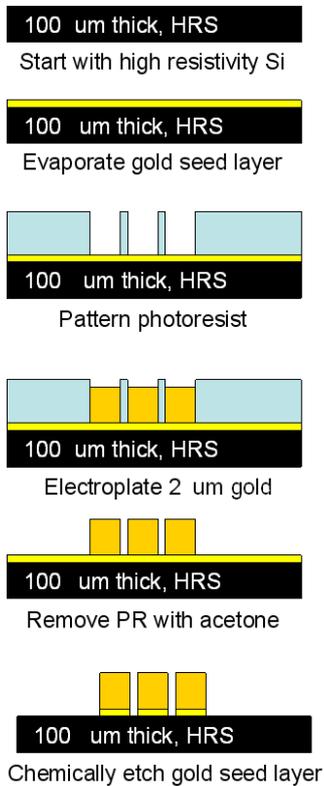
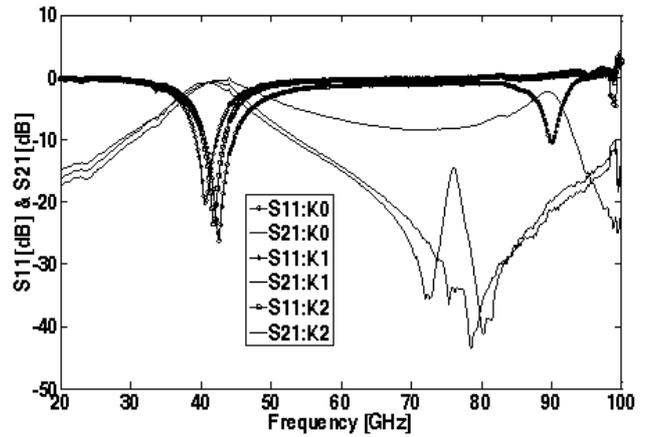
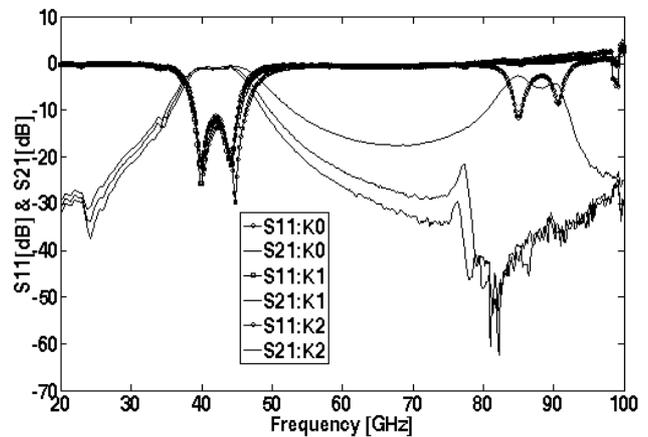


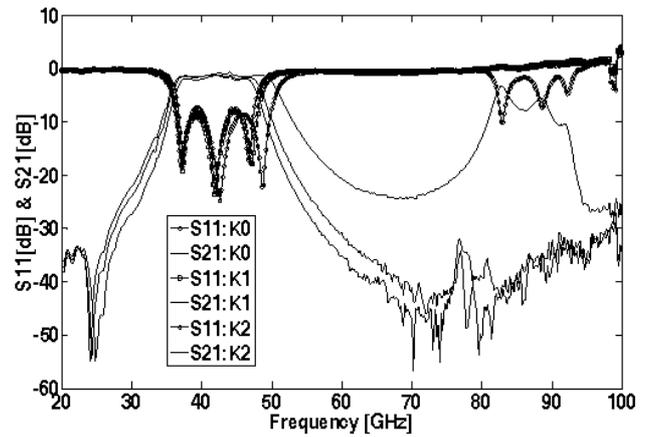
Fig. 9. Fabrication process for HRS.



(a) 1-pole



(b) 2-pole



(c) 3-pole

Fig. 10. Measured return and insertion loss.

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

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 2<sup>nd</sup> order, CF: Center Frequency [GHz], IL: Insertion Loss [dB], FB: 3 dB Fractional Bandwidth [%], 2H: 2<sup>nd</sup> Harmonics Insertion Loss [dB].

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 2<sup>nd</sup> harmonics in high permittivity substrates for suppression of the 2<sup>nd</sup> 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 2<sup>nd</sup> 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<sup>nd</sup> harmonic component. From all of numerical and fabrication results, it is found that the proposed filters can suppress the 2<sup>nd</sup> harmonic without any significant degradation; therefore, the proposed methods can be used in high dielectric constant materials.

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with School of ECE, Georgia Tech, Atlanta, GA. He has published more than 250 papers in refereed Journals and Conference Proceedings, 1 book and 8 book chapters and he is in the process of writing 2 books. Dr. Tentzeris has helped develop academic programs in Highly Integrated/Multilayer Packaging for RF and Wireless Applications using ceramic and organic flexible materials, paper-based RFID's and sensors, Microwave MEM's, SOP-integrated(UWB, multiband, conformal) antennas and Adaptive Numerical Electromagnetics (FDTD, MultiResolution Algorithms) and heads the ATHENA research group(20 researchers). He is the Georgia Electronic Design Center Associate Director for RFID/Sensors research, and he has been the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research and the RF Alliance Leader from 2003-2006. He is also the leader of the RFID Research Group of the Georgia Electronic Design Center(GEDC) of the State of Georgia. He was the recipient of the 2006 IEEE MTT Outstanding Young Engineer Award, the 2004 IEEE Transactions on Advanced Packaging Commendable Paper Award, the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award, the 2003 IBC International Educator of the Year Award, the 2003 IEEE CPMT Outstanding Young Engineer Award, the 2002 International Conference on Microwave and Millimeter-Wave Technology Best Paper Award(Beijing, CHINA), the 2002 Georgia Tech-ECE Outstanding Junior Faculty Award, the 2001 ACES Conference Best Paper Award and the 2000 NSF CAREER Award and the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society. He was also the 1999 Technical Program Co-Chair of the 54th ARFTG Conference, Atlanta, GA and the Chair of the 2005 IEEE CEM-TD Workshop and he is the Vice-Chair of the RF Technical Committee(TC16) of the IEEE CPMT Society. He has organized various sessions and workshops on RF/Wireless Packaging and Integration, RFID's, Numerical Techniques/Wavelets, in IEEE ECTC, IMS, VTC and APS Symposia in all of which he is a member of the Technical Program Committee in the area of "Components and RF". He will be the TPC Chair for IEEE IMS 2008 Symposium. He is the Associate Editor of IEEE Transactions on Advanced Packaging. Dr. Tentzeris was a Visiting Professor with the Technical University of Munich, Germany for the summer of 2002, where he introduced a course in the area of High-Frequency Packaging. He has given more than 50 invited talks in the same area to various universities and companies in Europe, Asia and America. He is a Senior Member of IEEE, a member of URSI-Commission D, a member of MTT-15 committee, an Associate Member of EuMA and a member of the Technical Chamber of Greece.

### Joy Laskar



received the B.S. degree (Computer Engineering with Math/Physics Minors, highest honors) from Clemson University in 1985. He received the M.S. and the Ph.D. degrees in Electrical Engineering from the University of Illinois at Urbana-Champaign in 1989 and 1991 respectively. Prior to joining Georgia Tech in 1995, Dr. Laskar has held faculty positions at the University of Illinois and the University of Hawaii. At Georgia Tech, he holds the Joseph M. Pettit Professorship of Electronics, is the Director of Georgia's Electronic Design Center, and heads a research group of 25 members with a focus on integration of high frequency mixed-signal electronics for next generation wireless and wired systems. He has authored or co-authored more than 390 papers, several book chapters (including three textbooks in development), numerous invited talks and has more than 25 patents pending. Most recently his work has resulted in the formation of two companies. In 1998 he co-founded an advanced WLAN IC Company: RF Solutions, which is now part of Anadigics (Nasdaq: Anad). In 2001 Dr. Laskar co-founded a next generation analog CMOS IC company: Quellan, which is developing collaborative signal processing solutions for the enterprise, video, storage and wireless markets. He is a 1995 recipient of the Army Research Office's Young Investigator Award, a 1996 recipient of the National Science Foundation's CAREER Award, the 1997 NSF Packaging Research Center Faculty of the Year, the 1999 co-recipient of the IEEE Rappaport Award (Best IEEE Electron Devices Society Journal Paper), the faculty advisor for the 2000 IEEE MTT IMS Best Student Paper award, 2001 Georgia Tech Faculty Graduate Student Mentor of the year, recipient of a 2002 IBM Faculty Award, the 2003 Clemson University College of Engineering Outstanding Young Alumni Award, the 2003 recipient of the Outstanding Young Engineer of the Microwave Theory and Techniques Society and he has been named IEEE Fellow from 2005. For the 2004-2006 term, Professor Laskar has been appointed an IEEE Distinguished Microwave Lecturer for his seminar entitled "Recent Advances in High Performance Communication Modules and Circuits". He was also named an IEEE Electron Devices Society Distinguished Lecturer in 2006.

### Jong-Gwan Yook



was born in Korea. He received the B.S. and M.S. degrees in Electronics Engineering from Yonsei University, Seoul, Korea, in 1987 and 1989, respectively, and Ph.D. degree from the University of Michigan, Ann Arbor, Michigan, in 1996. Currently he is an associate professor at Yonsei University, Seoul, Korea. His main research interests are in the areas of theoretical/numerical electromagnetic modeling and characterization of microwave/millimeter-wave circuits and components, VLSI and MMICs interconnects, and RF MEMS devices using frequency and time domain full-wave methods, signal integrity issues in high speed digital PCBs, and development of numerical techniques for analysis and design of high-speed high-frequency analog and digital circuits with emphasis on wireless communication applications.