IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 28, 2017, accepted October 29, 2017, date of publication November 14, 2017, date of current version December 22, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2773577

An Ultra-Wide Stop-Band LPF Using Asymmetric Pi-Shaped Koch Fractal DGS

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This work was supported in part by Macau Science and Technology Development Fund under Grant FDCT-16-020-FI and in part by Zhejiang Natural Science Fund under Grant LY17E070004.

ABSTRACT Defected ground structure (DGS) with symmetrical geometry has been widely adopted in low-pass filter (LPF) designing, while asymmetrical geometry DGS can exhibit some specific features on transition band and stop-band. A novel asymmetrical Pi-shaped DGS with Koch fractal curve is proposed in this paper to design a low-pass filter (LPF). The designed LPF with a single resonator and two cascaded resonators are both simulated and tested. Simulation and experiment results demonstrate that the designed LPF has a very sharp transition and an ultra-wide stop-band performance compared with the existed similar symmetrical and asymmetrical DGS. The proposed LPF with two cascaded resonators is with a compact size of 36×22 mm^2, a very low insertion loss of less than 0.7 dB from 0 Hz to 1.9 GHz, and a wide stop-band from 2.1 to 12 GHz with a rejection of greater than 25 dB.

INDEX TERMS Koch fractal, defected ground structure (DGS), low-pass filter (LPF), wireless communication, wireless power transfer.

I. INTRODUCTION

With the rapid progress of wireless communication and wireless power transfer, there have been many wireless systems developed and installed all over the world. For these applications, the microwave low-pass filter (LPF)/microwave band-pass filter (BPF) is a crucial component [1]–[7]. Compared with conventional lumped LC filters, the microstrip LPF can be integrated directly on the PCB for harmonics and disturb signals suppression in these wireless systems. Microstrip LPFs have some unique advantages in terms of weight, cost, appearance, solidarity, and electromagnetic compatibility with other wireless devices in the microwave band, which are promising components for wireless communication and wireless power transfer devices.

Many techniques have been proposed for the microstrip LPF designs. The conventional microstrip LPFs with stepped-impedance resonators (SIRs) only show gradual cutoff response and narrow stop-band [2]. To get sharp cutoff characteristic, more filter units are needed to add to the SIRs, leading to increasing insertion loss and circuit size [3]. Defected ground structure (DGS) with symmetrical geometry, such as circle, rectangle, and triangle, has been widely adopted in designing a low-pass filter (LPF) to achieve good frequency response performance. For example, the photonic-band-gap (PBG)-structure-based filters with several periodic units are proposed in [4]–[7]. Recently, designing filters using the Koch fractal structure has attracted a lot of attention to achieve better performances, e.g., reducing size, sharpening transition-band (TB), and widening stop-band (SB) [8]–[10]. It is shown that the performances of an LPF with Koch fractals depend on its shape and geometry. Especially, the pass-band and stop-band performance of a filter can be achieved by changing its edges of the Koch fractal curve.

Asymmetrical geometry DGS can exhibit some specific features on sharper transition band and wider stop-band [11]–[14]. An LPF with wide stop-band using asymmetrical Pi-shaped DGS was reported in [11], as shown in Fig. 1(a). Other asymmetrical DGSs, such as U-shape, T-shape, and E-shape, were proposed in [12]–[14], as shown in Fig. 1(b), 1(c) and 1(d). However, the LPF using the asymmetrical Pi-shaped DGS with Koch fractal curve has not been discussed. In this letter, we propose a novel, compact LPF using asymmetrical Pi-shaped DGS with Koch fractal curve. The proposed Koch fractal DGS filter design was simulated, fabricated and measured. The measurement results agree well with simulation results. It presents a wider stop-band (SB), a sharper transition band (TB) compared with the

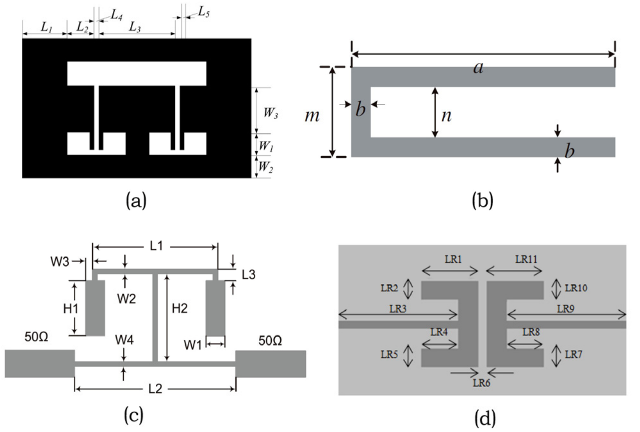


FIGURE 1. Asymmetric LPF with (a) Pi-shaped, (b) U-shaped, (c) T-shaped, and (d) E-shaped DGS.

conventional microstrip DGS LPF and reported Koch fractal DGS LPF.

II. PROPOSED KOCH FRACTAL DGS DESIGN

Generally, in a microwave circuit, the basic harmonic can be suppressed by a single resonant unit of a filter, while the higher order of harmonic can be suppressed by multiple resonant units. However, this leads to a higher insertion loss and a bigger size of an LPF. To miniaturize the size of an LPF and to improve the quality factor of a DGS LPF, fractal geometry is introduced [8], [15], [16]. The recursive constructions of a triadic Koch fractal curve up to five fractal iterations are shown in Fig. 2.

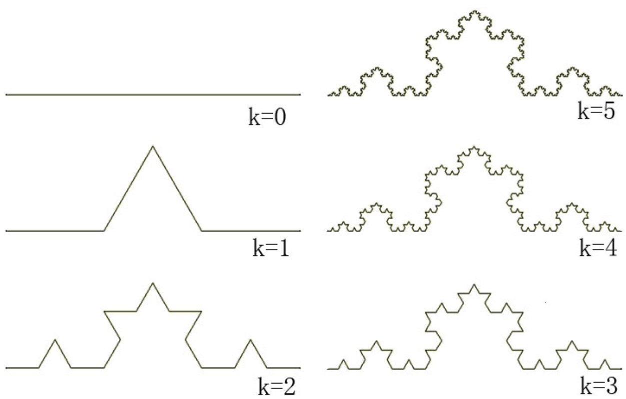


FIGURE 2. Koch fractal curve with different fractal iterations.

After each iteration, the number of sides of the Koch fractal increases by a factor of 4, so the number of sides N after k iterations is given by

$$\mathrm{N}_k = \mathrm{N}_{k-1} \times 4 = 3 \times 4^k$$

If the original equilateral triangle has its sides of length s, the length of each side of the Koch fractal after k iteration is

$$S_k = \frac{\mathrm{S}_{k-1}}{3} = \frac{\mathrm{S}}{3^k}$$

The perimeter of the Koch fractal P after k iterations is

$$\mathrm{P}_k = \mathrm{N}_k \times S_k = 3 \times S \times \left(\frac{4}{3}\right)^k$$

The Koch curve has an infinite total length as k tends to infinity because the length of the curve has a (4/3)k times relation related to the original equilateral triangle length s.

Koch fractal configurations can achieve much wider passband resonant features. Changing the edges of the asymmetric rectangle Pi-shaped DGS LPF [11] into Koch fractal curve shape with two iterations, the proposed DGS LPF using asymmetric Pi-shaped Koch fractal is described in Fig. 3. Next, the designs of asymmetric Pi-shaped Koch fractal DGS filters with one and two resonators are presented.

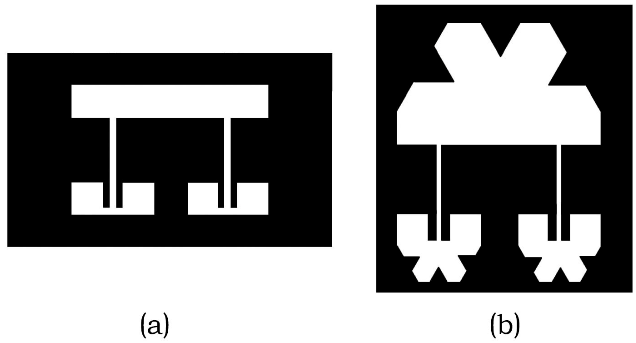


FIGURE 3. Asymmetric Pi-shaped DGS configuration with (a) rectangle curve, (b) Koch fractal curve.

A. Koch fractal DGS Filter with a Single Resonator

The layout of proposed Koch fractal DGS LPF is composed of a Koch fractal defected ground structure and a microstrip transmission line, which are shown in Fig. 4(a) and Fig. 4(b) respectively. The DGS is designed on an FR4 PCB (ε_r = 4.4, $\tan\delta$ = 0.025) substrate with a size of $L_{sub} \times W_{sub} \times h_{sub}$ = 19.8 × 22 × 0.8 mm^3. An L_{sub} = 19.8 mm and W_{tran} = 4 mm microstrip feed line with 50 Ω characteristic impedance is fixed on the top of the PCB substrate. At the bottom side of the substrate, the DGS resonator is designed as a Pi-shaped pattern with Koch fractal curve.

The DGS resonator can be described as a parallel resonant LC tank, creating an ultra-wide stop-band. The equivalent circuit is shown in Fig. 4(c). The inductance L, capacitance C, and the stop-band resonant frequency f_s are determined by the dimensions of the Koch fractal DGS. By adjusting the design parameters, the LPFs can achieve different stop-bands.

According to the layout described in Fig. 4, the compact Koch fractal DGS LPF is fabricated. The photograph of the LPF is shown in Fig. 5. The microstrip feed line is connected using SMA connectors. In multi-layer PCB design, the microstrip feed line can be printed on the top layer, while the Koch fractal DGS is printed on the bottom layer, and the other layers should be empty.

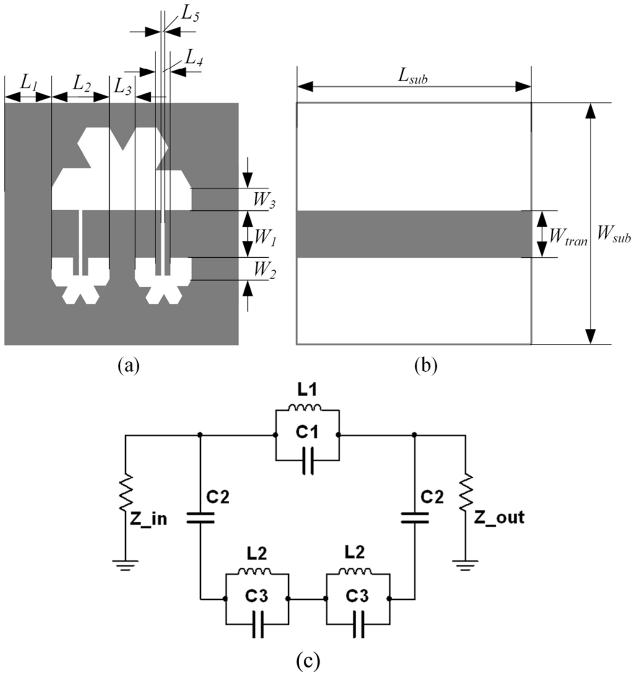


FIGURE 4. Layout of the proposed Koch fractal DGS. (a) Bottom side. (b) Top side. $\varepsilon_r = 4.4$, $\tan\delta = 0.025$. $W_{sub} = 22$, $L_{sub} = 19.8$, $h_{sub} = 0.8$, $W_{tran} = 4$, $L_1 = 4$, $L_2 = 5.2$, $L_3 = 2$, $L_4 = 1.2$, $L5 = 1.0$, $W_1 = 2$, $W_2 = 2$, $W_3 = 2$ (Unit: mm). (c) Extracted equivalent circuit.

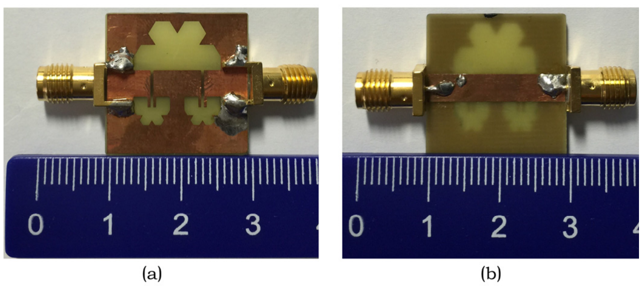


FIGURE 5. Photograph of fabricated Koch fractal DGS with a single resonator. (a) Bottom side (DGS). (b) Top side (microstrip transmission line).

B. Koch Fractal DGS Filter with Two Cascaded Resonators

The layout of the Koch fractal DGS LPF with two cascaded resonators and a microstrip feed line is shown in Fig. 6. This DGS is designed on FR4 PCB ($\varepsilon_r = 4.4$, $\tan\delta = 0.025$) substrate with a size of $L_{sub} \times W_{sub} \times h_{sub} = 36 \times 22 \times 0.8$ mm^3. As similar as the LPF with one resonator in last subsection, the 50 Ω microstrip feed line ($L_{sub} = 36$ mm and $W_{tran} = 7.28$ mm) is fixed on the top of the PCB substrate. The bottom side of the PCB consists of two cascaded, Pi-shaped Koch fractal DGS. A photograph of the miniaturized LPF with two cascaded Koch fractal DGS is shown in Fig. 7.

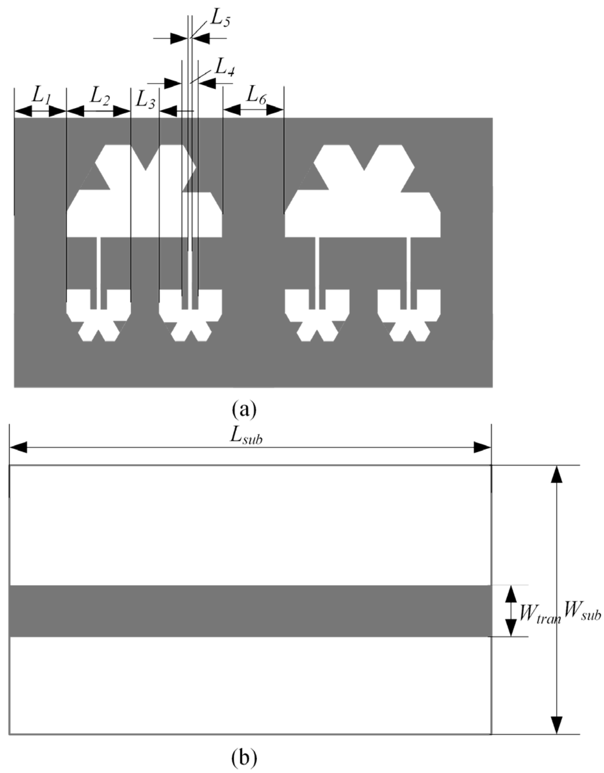


FIGURE 6. Layout of the proposed Koch fractal DGS with 2 cascaded resonators. (a) Bottom side (DGS). (b) Top side (microstrip transmission line). $\varepsilon_r = 4.4$, $\tan\delta = 0.025$. $W_{sub} = 22$, $L_{sub} = 36$, $h_{sub} = 0.8$, $W_{tran} = 7.28$, $L_1 = 4$, $L_2 = 5.2$, $L_3 = 0.4$, $L_4 = 1.2$, $L5 = 1.0$, $L_6 = 4$, $W_1 = 2$, $W_2 = 2$, $W_3 = 4$ (Unit: mm).

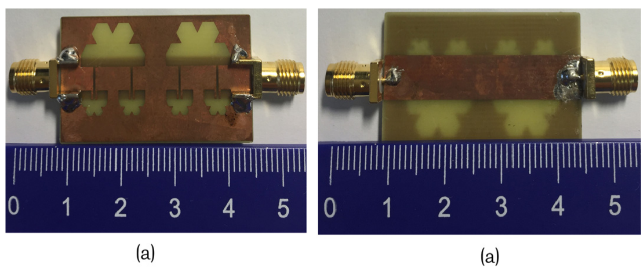


FIGURE 7. Photograph of fabricated Koch fractal DGS with 2 cascaded resonators. (a) Bottom side (DGS). (b) Top side (microstrip transmission line).

III. SIMULATION AND MEASUREMENT RESULTS

The commercial simulator HFSS is used to design and optimize the Koch fractal DGS LPFs. The Agilent N5245A PNA network analyzer is used to measure the S-parameters of the proposed LPFs.

As mentioned in Section I, the SB and TB performance of proposed Koch fractal DGS filter are affected by the geometry of the Koch fractal curve. The affections of different values of parameters L5 and W1 of the proposed filter are shown in Tables 1 and 2, respectively.

The equivalent current distributions of proposed asymmetric Koch fractal DGS and tradition asymmetric DGS [11],

TABLE 1. The affection of parameter L5 on SB and TB.

L5 (mm)	SB maximum rejection (dB)	SB minimum rejection (dB)	TB (GHz)
0.2	-54	-6.5	0.2
0.4	-56	-10	0.2
0.6	-55	-14	0.25
0.8	-57.5	-19	0.25
1.0	-57	-22	0.3
1.2	-53	-35	0.3
1.4	-67	-32	0.3

TABLE 2. The affection of parameter W1 on SB and TB.

W1 (mm)	SB maximum rejection (dB)	SB minimum rejection (dB)	TB (GHz)
0.5	-51	-25	0.7
1.0	-53	-27	0.6
1.5	-52	-28	0.4
2.0	-60	-30	0.2
2.5	-57	-29	0.3
3.0	-60	-28	0.4
3.5	-71	-26	0.5

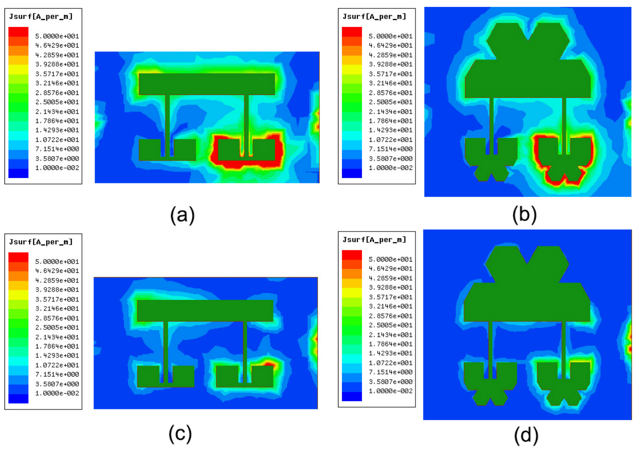


FIGURE 8. Equivalent surface current distribution of traditional asymmetric DGS at (a) 1.2 GHz and (c) 7 GHz. Equivalent surface current distribution of asymmetric Koch fractal DGS at (b) 1.2 GHz and (d) 7 GHz.

by simulation, at 1.2 GHz and 7 GHz are shown in Fig. 8, respectively. The current flow around the edges of Koch fractal DGS can be equivalent by capacitance and inductance. Therefore, the corresponding S parameter can have a better passband rejection, and a larger stopband extension.

Firstly, the optimized Koch fractal DGS LPF with a single resonator is measured. The measured and simulated S-parameters are shown in Fig. 9(a). The etched DGS structure interferes with the shield current distribution in the ground plane which affects the characteristics of the asymmetric Pi-shaped Koch fractal resonator. It can be found that the measurement results agree very well with simulation ones on the transition of sharp pass-band to stop-band and the

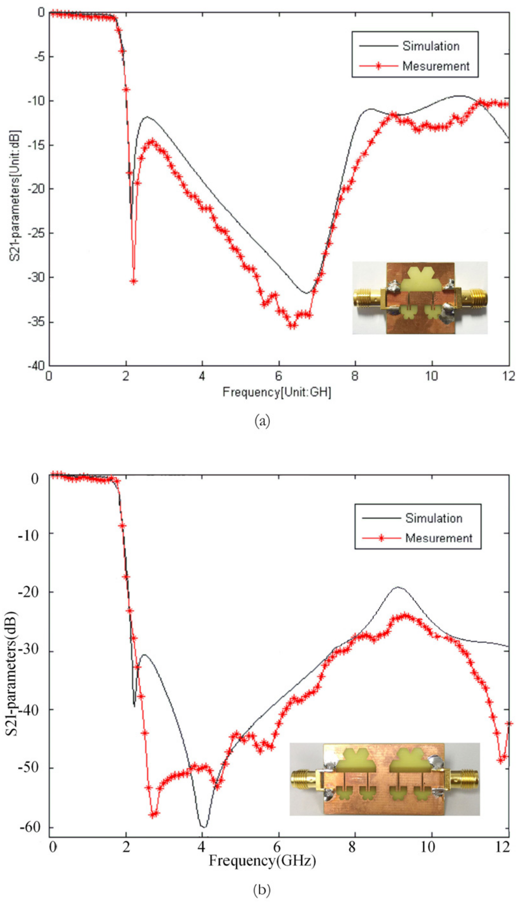


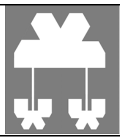
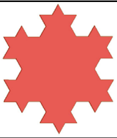
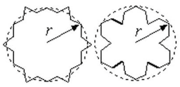
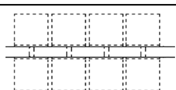
FIGURE 9. Measured and simulated S21 parameters of Koch fractal DGS. (a) A single resonator and (b) two cascaded resonators.

bandwidth of ultra-wide stop-band. Specifically, this LPF can achieve a pass-band from 0 Hz to 1.9 GHz with an insertion loss of less than 0.5 dB, and a wide stop-band from 2 GHz to 8 GHz with a rejection of greater than 12 dB.

Then, the measured and simulated S21-parameters of Koch fractal DGS LPF with 2 cascaded resonators is plotted in Fig. 9(b), agreeing very well with each other. Compared with the LPF with a single resonator, the LPF with two resonators shows much better performance as expected. It can achieve a pass-band from 0 Hz to 1.9 GHz with an insertion loss of less than 0.7 dB, and a wide stop-band from 2.1 GHz to 12 GHz with a greater rejection of more than 25 dB. Also, it achieves a maximum rejection of more than 60 dB in the point of 4 GHz and a very sharp transition band from 1.9 to 2.1 GHz (with −0.7 dB and −25 dB, respectively), showing that the LPF has excellent skirt performance.

The performance comparison of some referenced LPFs is shown in Table 3. Our proposed asymmetrical Pi-shaped DGS LPF with Koch fractal curve has the widest SB (10 GHz) and the sharpest TB (0.2 GHz) even it is fabricated with FR4 substrate, a very common and cheap material. The different performance of pass-band, SB and TB can be designed by changing key parameters, such as W3, W1 and L3. The LPF

TABLE 3. Performance comparisons among the reported filters (SB: stop-band, TB: transition band).

Ref.	Size / λ	Structure and shape	SB (GHz)	TB (GHz)	Substrate
this work	0.13*0.23		10	0.2	FR4
[11]	0.08*0.23		3.8	0.8	RF4
[10]	0.1*0.16		7	0.3	Rogers
[9]	0.32*1.17		3.5	0.9	Rogers
[6]	0.2*0.39		3	1.3	Rogers

size is only $0.13 * 0.23\ \lambda$, and is more compact, compared with the work in [9] and [6].

IV. CONCLUSION

The asymmetric Koch fractal Pi-shaped DGS LPFs with a single and two cascaded resonators are designed, simulated and fabricated with the cheap FR4 substrate. Compared with the existed similar asymmetric and symmetric DGS, the proposed LPFs has a wider stop-band and a sharper transition band. The measured S21-parameters agree very well with simulation results. The LPF with a single unit cell provides a pass-band from 0 Hz to 1.9 GHz with an insertion loss less than 0.5 dB, and stop-band from 2 GHz to 8 GHz with an attenuation greater than 12 dB. With two cascaded resonate units, the LPF demonstrates a more sharp transition band of only 0.2 GHz and a better rejection performance with a wider stop-band of larger than 10 GHz.

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