Letters

A Wideband Common-Mode Suppression Filter With Compact-Defected Ground Structure Pattern

Zhibin Zeng, Yindi Yao, and Yiqi Zhuang

Abstract—**A complementary-defected ground structure (DGS) common stopband filter is proposed. The filter uses two kinds of DGS patterns: a Π-shaped DGS pattern is used in both sides of the filter and a button-headed H-shaped DGS pattern is adopted at the middle of the filter. The filter utilizes the mutual inductance and mutual capacitance that exists among the DGS patterns to improve the in-band gain-flatness of the filter, which is useful to broaden the bandwidth and improve the rejection ratio in the low cutoff frequency. The simulated and measured results show that the differential signal under the DGS filter is nearly intact and the common-mode noise can be reduced by 15 dB from 3.2 to 12.4 GHz. The area of the filter is only 10 mm × 10 mm. The fractional bandwidth of the stopband can reach 118%.**

Index Terms—**Common-mode, defected ground structure, differential signaling, microwave filters.**

I. Introduction

DIFFERENTIAL signals have been widely used in high-speed board design for their high electromagnetic immunity against conducted and radiated interfering signals, and low electromagnetic interference (EMI) [1], [2]. However, in circuits that use differential routing schemes, a significant amount of common-mode (CM) noise is easily generated by the amplitude unbalance, timing skew, and crosstalk [2], [3], which have a significant impact on the EMC performance of the system.

To suppress the CM noise, microstrip lines with defected ground structure (DGS) have become a hotspot in microwave integrated circuit design [4]–[7]. The DGS is realized by etching periodic defected pattern on the backside of the metallic ground plane, which can improve the bandpass filter high-frequency performance. Generally, a single DGS filter has a small size but insufficient bandwidth. Several methods have been used to expand the bandwidth. Liu *et al.* [4] uses three periodic DGS to broaden the bandwidth, where the bandwidth range is from 3.3 to 5.6 GHz and the area is 15 mm × 24 mm. Wu *et al.* [5] uses two U-shaped and one H-shaped-coupled patterned DGS to broaden the bandwidth, where the bandwidth ranges from 3.6 to 9.1 GHz and the area is 10 mm × 10 mm. Wei-Tzong *et al.* [6] uses seven DGS to broaden the bandwidth, where each side uses three periodic dumbbell-shaped DGS, respectively, and in the middle uses one C-shaped DGS. The bandwidth range is from 3.4 to 10.9 GHz, while the area is about 42.2 mm × 11 mm. Wu *et al.* [7] uses a reduced fractal DGS to broaden the bandwidth, where the bandwidth is about 4.89 GHz and the area is about 30 mm × 12 mm. Further studies for miniaturization and bandwidth enhancement for the DGS filter are still essential.

To broaden the reject bandwidth, while keeping a small filter size, a novel approach for the design of a CM suppressed wideband filter based on complementary structures is proposed in this letter. The filter uses two kinds of DGS patterns: A Π-shaped DGS structure is used at both sides of the filter, and a button-headed H-shaped DGS is used in the middle of the filter. As the DGS patterns are complementary and compact, there exist mutual inductance and mutual capacitance, which is useful to broaden the bandwidth and the rejection ratio in the low cutoff frequency by improving the in-band gain-flatness of the filter. With a suitable design geometry of the structure, the stopband bandwidth of the proposed filter over 15 dB ranges from 3.2 to 12.7 GHz, with the fractional bandwidth of the stopband being 118%, and it still maintains good signal quality for the differential components. Furthermore, a deeper CM suppression can be achieved over 30 dB from 4.1 to 11.7 GHz if the distance between DGS patterns increases to 6 mm.

II. Analysis of the CM DGS Filter

The whole geometric structure of this filter is shown in Fig. 1. Differential-coupled microstrip lines are on the top layer. The differential lines are "w" in width, and spaced out "s" apart. Both of the identical Π-shaped patterned ground slots in the opposite direction surround the button-headed H-shaped slot. To avoid the excitation of CM noise, the defected ground slots are symmetric to the central line between the differential signal lines. A smooth transition at the junctions of DGS between the slit and the square is used to improve the depth of stopband [8].

Since the DGS characteristics largely depend on the slot pattern, equivalent circuit models are used to predict the characteristics [4], [9]. The CM signals passing through the Π-shaped or button-headed H-shaped ground slot can be modeled as an ideal transmission line with even-mode characteristic impedance and a parallel *LC* resonator cascaded on the ground plane.

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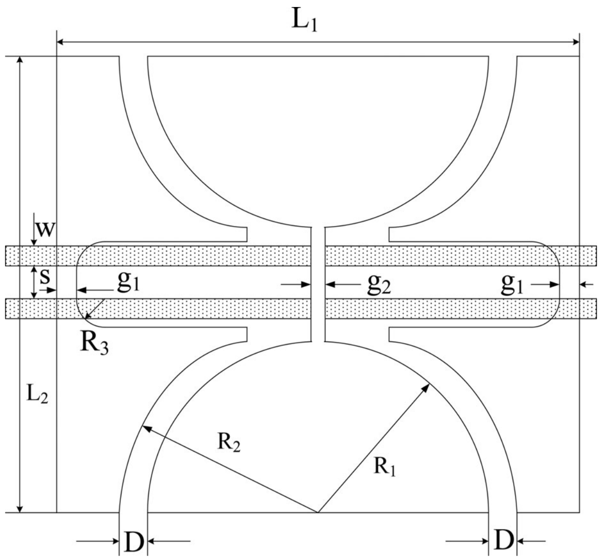

Fig. 1. Scheme of a compact three-pole DGS filter.

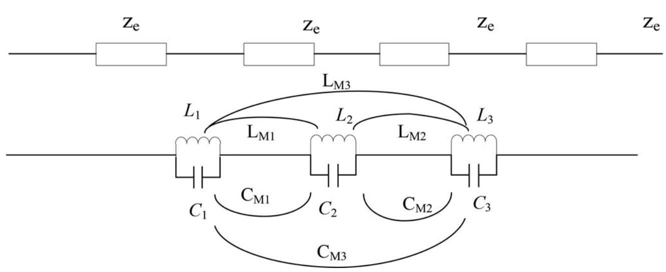

Fig. 2. Equivalent circuit of the compact three-pole DGS filter.

Therefore, the equivalent circuit model of the proposed filter can be modeled by three parallel *LC* resonance circuits, as shown in Fig. 2. The C_i and L_i $(i = 1, 2, 3)$ denote the equivalent capacitance between two sides of the slit and the equivalent inductance of the signal passing through the DGS, respectively. Note that the three resonators are closely located; thus, mutual capacitance and mutual inductance between any two resonators need to be considered. Therefore, a more detailed equivalent circuit of the proposed filter needs to be modeled, where L_{Mi} and C_{Mi} $(i = 1, 2, 3)$ are the mutual inductance and mutual capacitance, respectively. It is clearly seen that the CM noise can be significantly blocked at the frequency range close to the resonance frequency of the *LC* resonator. The cutoff frequency is mainly dependent on the dimensions of the etched pattern area in ground plane [10].

To verify the effect of mutual capacitance and mutual inductance, the CM filter unit in a PCB environment is simulated, where the geometric parameters of the filter are shown in Table I The simulation is performed using the full-wave simulator HFSS [11] based on finite-element method.

The dielectric constant and loss tangent of the structure are 4.3 and 0.02, respectively. The parameters of the differential signal of the coupled-microwave lines are 0.68 and 1 mm. The magnitudes of differential insertion losses ($|S_{dd}21|$), return loss ($|S_{dd}11|$), and common ($|S_{cc}21|$) insertion losses obtained for

TABLE I
GEOMETRIC PARAMETERS USED IN THE TEST BOARD FABRICATION

Parameter	R_1	R_2	R_3	g_1	g_2	D	L_1	L_2	h
Value(mm)	3.3	3.5	1.1	0.3	0.2	0.5	10	10	0.4

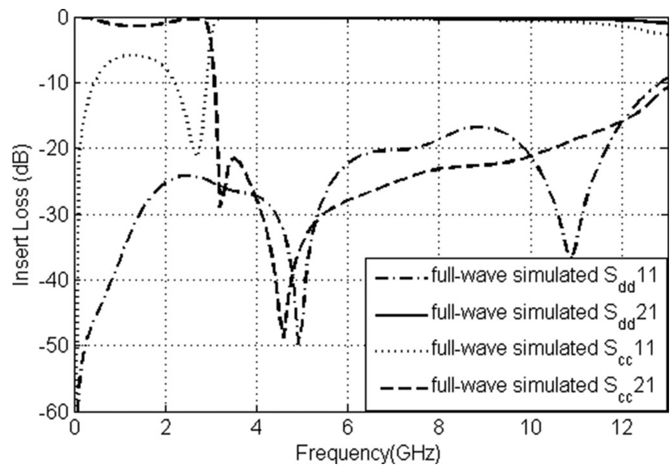

Fig. 3. Simulated return and insertion loss of the proposed DGS filter.

the CMF unit by full-wave simulator (HFSS), are given in Fig. 3. The bandwidth of the wide stopband CMF is from 3.3 to 11.2 GHz for −20-dB suppression, and from 3.2 to 12.4 GHz for −15-dB suppression, and the return loss $S_{dd}11$ is less than −10 dB in the rejection band of CMF, which meet the design requirements of $S_{dd}11$ in industry. Furthermore, it is clear that the parameter value $S_{cc}11$ is almost close to 0 dB, which means the CM noises are reflected back toward the source nearly.

Two compared CM filters are also considered, which keep the same DGS patterns but increase distance D to 3 and 6 mm, respectively. The bandwidth of the filter A over 15-dB suppression is from 3.6 to 14 GHz. However, a stub over –15 dB exists in filter A, which needs to be further suppressed. One method is to adopt the proposed filter structure, which can improve the in-band gain-flatness of the filter by utilizing the existed mutual capacitance and mutual inductance. Another method is to further increase the distance D. As shown in Fig. 4, when the distance D is 6 mm, the bandwidth of the filter B over 15-dB suppression is from 3.5 to 14.4 GHz. Furthermore, the CM noise can be reduced by 30 dB from 4.1 to 12.3 GHz. Generally, the cutoff level is defined by −15 dB, which is sufficient for solving the signal integrity and EMI issues in high-speed digital circuit applications. Obviously, filter B has the widest rejection bandwidth over 15 dB, which is about 18% more than that of the proposed filter. But the area of filter B is 22 mm × 10 mm, which is about twice that of the proposed filter. Therefore, the proposed filter has a more effect than that of filter B. The main reason is that the effect of the mutual inductance and mutual capacitance in the proposed filter play an important role in the ground plane electric fields.

Figs. 5– 7 show the diagram of simulated current distributions at 5 GHz for the bottom view. It can be clearly seen that

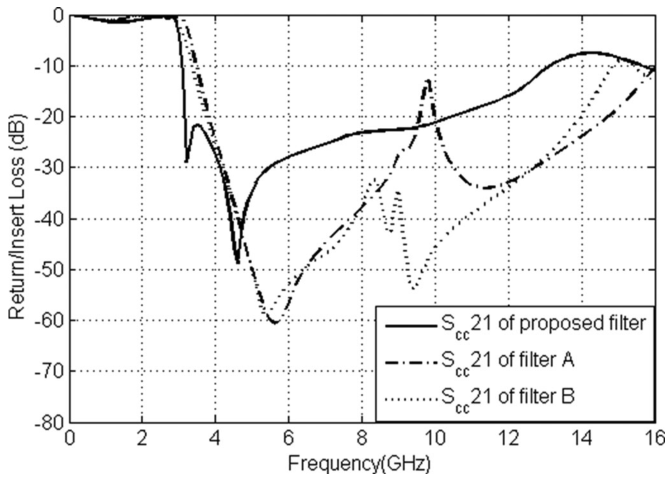

Fig. 4. Simulated results of the proposed DGS filter, filter A which has the same DGS pattern, but a 3-mm longer spacing among DGS patterns, and filter B which has the same DGS pattern, but a 6-mm longer spacing among DGS patterns.

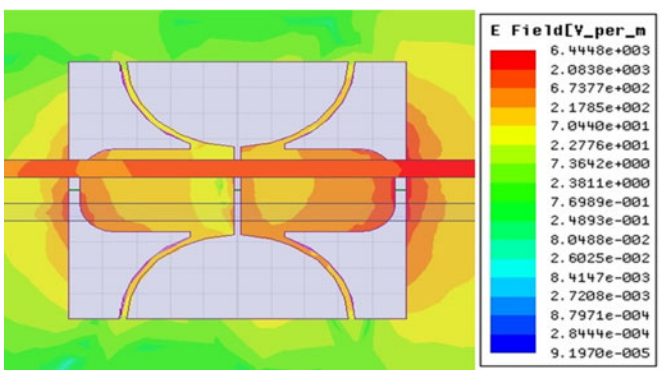

Fig. 5. Simulated ground plane electric field of the proposed DGS filter.

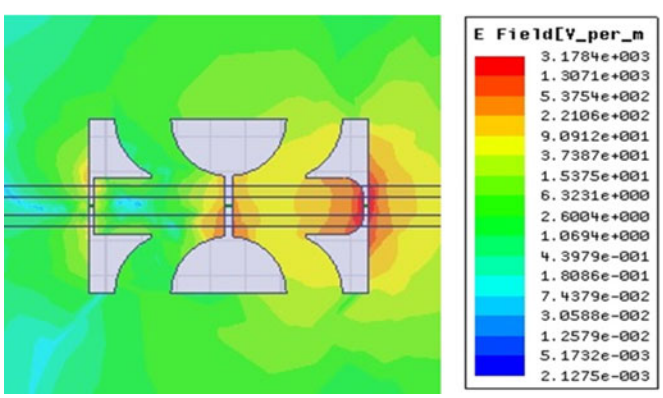

Fig. 6. Simulated ground plane electric field of filter A, which has the same DGS patterns but a 3-mm longer spacing among DGS patterns.

there is a coupling between the DGS slots. The maximum electric field density value is fixed at 6.4448 × 10^3, 3.1784 × 10^3, and 4.7142 × 10^3 V/m in Fig. 5, 6, and 7, respectively. The maximum electric field density of them is at the same density level. However, the electric field density distributed among the DGS patterns of the proposed filter is obviously stronger than that of the other filters. As we know, this effective capacitance and inductance depend on the narrow- and wide-etched areas in backside metallic ground plane, respectively. In Fig. 5, the value of electric-field density is high among the whole DGS structure, which plays an effective role in the mutual inductance and mutual capacitance of the proposed filter. With the distance D between the DGS patterns increase, the value of electric field density between the DGS patterns decrease, which means the values of the mutual inductance and mutual capacitance are decreased. The existed mutual inductance and mutual capacitance among the DGS patterns of the proposed filter lowers the low cutoff frequency. Furthermore, though the characteristics of the compact pattern are changed compared to a longer space pattern, the degradation is not significant whereas the size is substantially reduced. It is determined by the geometry of the problem and the materials involved, of which the existing mutual capacitance and mutual inductance enhance the distribution of electric field.

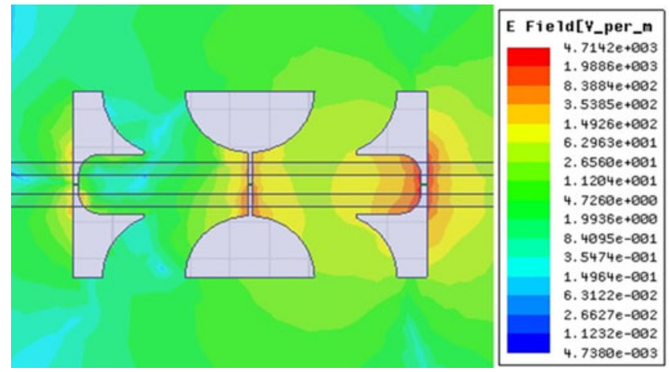

Fig. 7. Simulated ground plane electric field of filter B which has the same DGS patterns but a 6-mm longer spacing among DGS patterns.

III. Simulation and Verification

To confirm the above analysis, a test sample using the proposed DGS structure was designed and fabricated on a FR4 substrate of dielectric constant 4.3. Its external dimensions are 60 mm × 60 mm, and the total thickness is 0.4 mm. The parameters of the differential signal of coupled microwave lines are $w = 0.68$ mm and $s = 1$ mm, the odd- and even-mode impedance of the coupled microstrip line above perfect ground plane is 50 and 54 Ω, respectively. The parameters of the DGS are shown in Table I.

The fabricated filter was measured using an Agilent E8363C vector network analyzer. A comparison between the simulated and measured results is shown in Fig. 8, where the dash dot line indicates the measured results and the solid line indicates the simulated results using HFSS software. The simulation results show that the rejection band ranges of the CM filter are from 3.2 to 12.4 GHz for –15-dB suppression, and the differential-mode signals are almost intact. It proves that the filter can efficiently suppress the CM noise and still keep good signal integrity for the differential signals. The measured rejection band ranges of the CM filter are from 3.2 to 12.5 GHz for –15-dB suppression. The simulated and measured return loss $|S_{cc}11|$ of the CM filter is nearly 0 dB in the range of 3.2 to 13 GHz. The measured

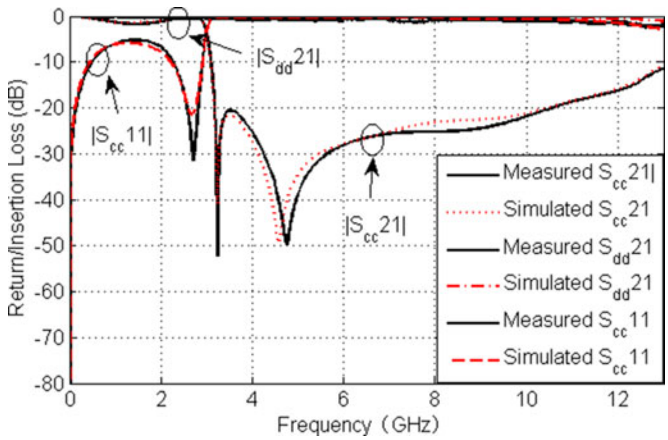

Fig. 8. Simulated and measured result of the proposed DGS filter with comparison with periodic DGS filter

results basically agree with the simulation data. The discrepancy between the full-wave simulation and measurement may be caused by the length of transmission line, the usual connectors, manufacture tolerances, the dispersive nature of the FR4 material, and measurement error.

IV. Conclusion

A low-cost CM noise suppression filter for GHz differential signals is proposed in this letter. The miniaturized filters using complementary DGS have been designed, fabricated, and measured. Because complementary DGS patterns make the structure of the filter compact, the equivalent circuit includes mutual inductance and mutual capacitance, which improves the gain flatness of the proposed filter, and can be utilized to broaden the rejection bandwidth. From the simulated and experimental results, the CM noise is reduced by 15 dB from 3.2 to 12.4 GHz, whereas the differential signal is nearly intact. This structure can be widely used in high-speed digital circuit system and integrated system design.

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