LETTER
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Modeling and design of a compact wideband common-mode filter using internal coupling technique

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Abstract: In order to suppress the common mode (CM) noise in high-speed differential signal traces, a compact CM filter is proposed in the letter, which adopts two C-shaped defected ground structure (DGS) cells and one double-headed arrow-shaped DGS cell. An equivalent circuit model is used to explain the working principle of the CM filter. The filter has a small size of 11 mm by 10 mm. It provides a CM suppression from 3.5 GHz to 12.4 GHz over 15 dB, while the differential signals still keep good signal integrity. The experimental results are in good agreement with the simulated results.

Keywords: microwave filter, common-mode filter, defected ground structure, difference circuit

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Because of higher immunity against noise, electromagnetic coupled interference, and non-ideal return paths over single-ended signal chains, differential circuits are widely applied in modern high-speed digital system design. However, common-mode (CM) noise [1] is inevitably caused by system design in practical circuits, such as unbalanced routing and patterned ground plane [2, 3], and more, inductively or capacitively coupled from an external source. The CM noise can degrade the EMC performance of the system. Therefore, how to suppress the CM noise without influencing the differential signal integrity has become a hot issue.

To suppress the CM noise, filter adopting defected ground structure (DGS) [2, 3, 4, 5] has become a hot topic because it not only can effectively filter out CM noise over GHz but also has advantages of small size, simple structure, low cost, and easy-to-analyze. Filter adopting single DGS occupies small area, but it has limited bandwidth [6]. CM filters adopting multiple DGS patterns have been researched recently to broaden the bandwidth. Reference [7] demonstrated that a CM filter using periodic DGS can achieve a broad stopband from 3.3 GHz to 5.7 GHz, of which the size is about 15 mm by 30 mm. Reference [8] demonstrated that a filter using reduced fractal DGS can achieve a 6.558 GHz bandwidth with a transmission under the rejection level of 20 dB, of which the size is about 42 mm by 15 mm. Reference [9] demonstrated that a CM filter using complementary split-ring resonator DGS can achieve a broad stopband from 1.52 GHz to 4.07 GHz under the

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rejection level of 20 dB, of which the size is about 50 mm by 19.8 mm. Reference [10] demonstrated that a CM filter using periodic S-shaped complementary split-ring resonator DGS can achieve a common-mode suppression better than 25 dB. Reference [2] demonstrated that a CM filter using coupled DGS resonators DGS can achieve a broad stopband from 3.6 GHz to 9.1 GHz under the rejection level of 15 dB, of which the size is about 10 mm by 10 mm. However, how to expand the operating bandwidth of the filter within a small area is still a hot topic in research.

In this letter, we propose a low-cost compact CM DGS filter. It adopts two C-shaped DGS patterns and a double-headed arrow-shaped DGS pattern to construct a CM DGS filter. Because these DGSs locate adjacently, there exist mutual inductances among them, which can be utilized to broad the bandwidth. An equivalent circuit model is given to analyze the working principle of the CM filter. The characteristics of the CM filter depend not only on the equivalent LC resonators and mutual inductance parameters, but also the shunt capacitance and coupled inductance parameters. The filter can get a low cut-frequency among the DGS while can suppress wideband CM noise over 15 dB between 3.5 GHz and 12.4 GHz.

2 Design and analysis for proposed common-mode filter

As is shown in Fig. 1(a), differential coupled microstrip lines are on the top layer. The differential lines are W in width, and spaced out S apart. The DGS cells are in the bottom of ground. The two identical C-shaped DGS cells locate on both sides of the double-headed arrow-shaped DGS cell. Since the differential signal is transmitted by odd mode, the current returned by the ground plane is relatively low. Therefore, the degradation of the differential signals caused by the defected ground planes can be neglected. The even-mode equivalent circuit model is shown in Fig. 1(b). The DGS cells can be modeled as an ideal transmission line with even-mode characteristic impedance Ze and a cascaded parallel LC resonator on the ground plane. The parameters C_i and L_i $(i = 1, 2, 3)$ denote the gap capacitance between two sides of the slit and equivalent inductance of the etched lattice respectively. The shunt capacitance C_{pi} $(i = 1, 2)$ is owing to a large fringing field at the coupling plane of the discontinuity. The coupled inductance L_{pi} $(i = 1, 2)$ is owing to the existence of metal sheet among the DGS cells.

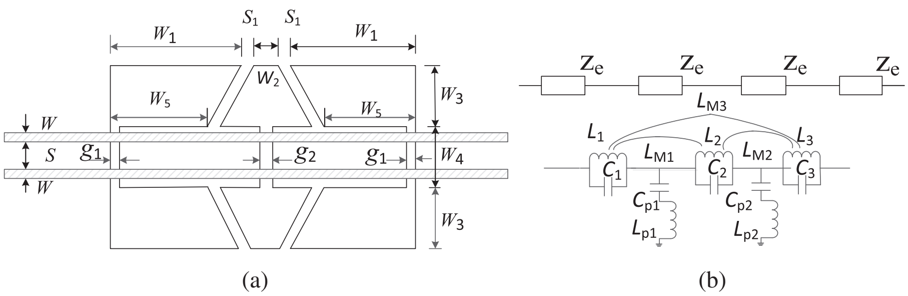

Fig. 1. (a) Schematic diagram of the proposed filter (b) Equivalent LC resonant circuit model of the proposed filter

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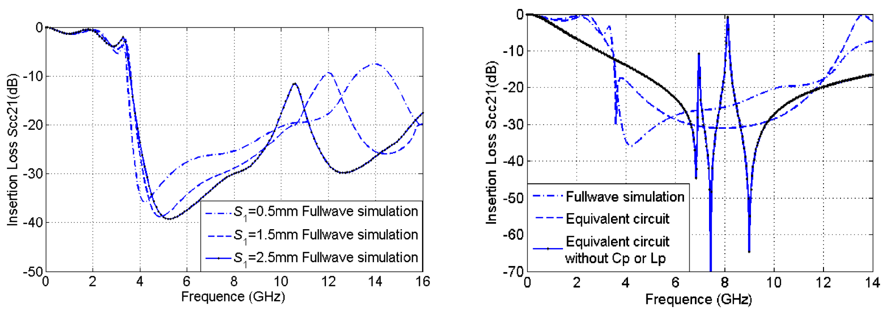
In order to verify effect of the filter and the correctness of equivalent circuit, dimensional parameters of the filter are shown in Table I. It is built in commonly PCB whose relative permittivity is 4.4, loss tangent is 0.02, and thickness is 0.4 mm, the area of the filter is limited to 11 mm by 10 mm, which aims at design of miniaturization and low-cost.

Table I. Simulation parameters used in common-mode filter

parameter	W	W_1	W_2	W_3	W_4
value (mm)	0.68	4.8	0.4	0.2	0.3
parameter	W_5	g_1	g_2	S	S_1
value (mm)	2.3	0.4	0.3	1	0.5

The simulation results of Scc21 with different space distance S_1 are given in Fig. 2a. The lower-cutoff frequency is defined by 15 dB, which is sufficient for solving the signal integrity and EMI issues in high-speed digital circuit applications [2, 7, 11]. It is found that the smaller the space distance S_1, the lower the cutoff frequency point. The reason is that there exist coupled inductances among adjacent DGS cells, and the closer the distance between DGS cells, the greater the absolute values of mutual inductances. Fig. 2b compares the simulation results between full-wave simulation and the equivalent circuit model. The insertion loss Scc21 of the proposed equivalent circuit model is basically in agreement with that of the full wave simulation [2, 12, 13, 14]. There exist differences between the equivalent circuit model and the full-wave simulation because minor influencing factors aren't considered here. The values of lumped elements are followed as $(L_1, L_2, L_3) = (6.09\,\text{nH}, 5.41\,\text{nH}, 6.09\,\text{nH})$, $(C_1, C_2, C_3) = (0.076\,\text{pF}, 0.0706\,\text{pF}, 0.076\,\text{pF})$, $(L_{M1}, L_{M2}, L_{M3}) = (-0.688\,\text{nH}, 0.426\,\text{nH}, -0.688\,\text{nH})$, $(L_{p1}, L_{p2}) = (1.2\,\text{nH}, 1.2\,\text{nH})$, and $(C_{p1}, C_{p2}) = (0.5\,\text{pF}, 0.5\,\text{pF})$. If the shunt capacitance C_{pi} $(i = 1, 2)$ and coupled inductance L_{pi} $(i = 1, 2)$ are not considered, the exist two distinct spikes at 6.8 GHz and 8.1 GHz respectively, and the bandwidth is compressed. As is shown in Fig. 3, If only considering the shunt capacitance C_{pi} $(i = 1, 2)$ or coupled inductance L_{pi} $(i = 1, 2)$ are not considered, the exists obvious difference between the equivalent circuit and the full-wave simulation. Therefore, the factors of shunt capacitance C_{pi}



(a) (b)

Fig. 2. (a) Comparisons of the simulated results of $Scc21$ with different distance S_1 (b) Comparisons of the simulated results of $Scc21$ between full-wave simulation and equivalent circuit model

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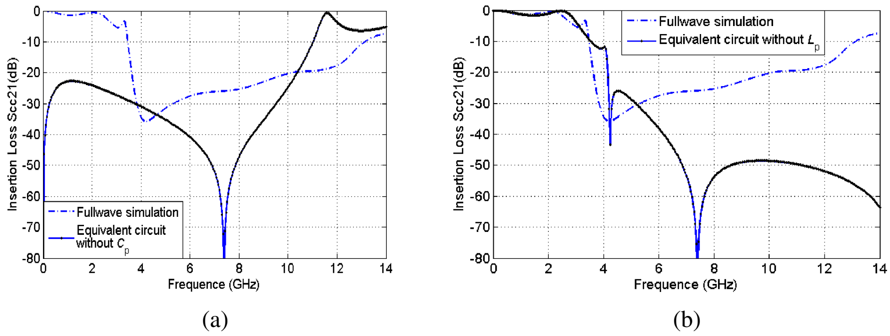

Fig. 3. (a) Comparisons of the simulated results of *S*cc21 between full-wave simulation and equivalent circuit model without C_p (b) Comparisons of the simulated results of *S*cc21 between full-wave simulation and equivalent circuit model without L_p

and coupled inductance L_{pi} need to be considered where filter adopting multiple adjacent DGS cells.

3 Evaluation of common-mode noise suppression

To verify the results of the simulated and measured results concerning the coupled DGS cells CM filter, a testing board is fabricated on a FR4 substrate material with a relative dielectric constant of 4.4, and loss tangent 0.02. The area and the total thickness of it are 68 mm by 60 mm, and 0.4 mm respectively. The geometrical sizes of the differential signaling and the proposed filter are shown in Table I.

Fig. 4(a) shows the photograph of the fabricated CM filter. Fig. 4(b) shows the measured results and the simulated results. The simulated results show that the filter has a wide stopband for the CM between 3.5 and 12.4 GHz for −15 dB suppression. The fractional bandwidth of the filter is 120%. For the differential mode, the insertion loss $S_{dd}21$ is less than 3 dB below 12.4 GHz, of which the loss is mainly caused by the transmission on the microstrip line. The measured results show that the filter has a wide stopband for the CM between 3.6 and 12.3 GHz for −15 dB suppression, of which the insertion loss $S_{dd}21$ is less than 4 dB below 12.4 GHz. Comparing the results of simulation with that of measurement, good agreement between the results of equivalent full-wave simulation (HFSS) and measurement is observed. The discrepancy between the full-wave simulation and measurement may be caused by the dispersive effect of the FR4 material, manufacture tolerance, and measurement error.

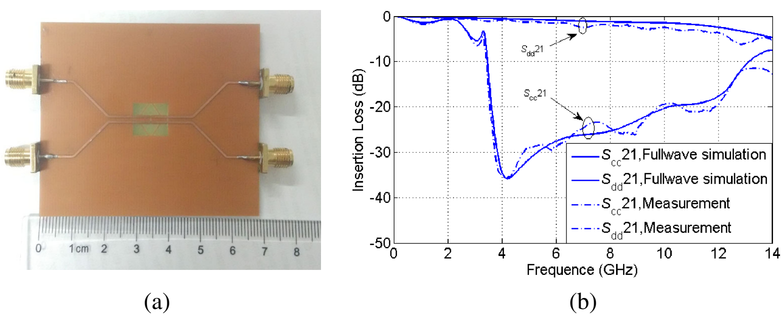

Fig. 4. (a) Photograph of fabricated filter (b) Simulated and measured Insertion Loss of Sdd21 and Scc21

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Table II shows the comparisons of different DGS filter designs in terms of dimensions and stopband performance. As is shown in Table II, this filter has a comparable size while it has the widest stopband.

Table II. Comparison of various DGS filter

Ref.	Sizes (mm^2)	Frequency range (GHz)	Bandwidth (GHz)
[2]	10 × 10	3.6–9.1	5.5
[7]	15 × 30	3.3–5.7	2.4
[8]	42 × 15	3.5–10.06	6.56
[9]	50 × 19.8	1.52–4.07	2.55
Proposed filter	11 × 10	3.5–12.4	8.9

4 Conclusion

A novel common-mode noise suppression filter using two C-shaped DGS cells and one double-headed arrow-shaped DGS cell is proposed in this letter. It analyzes the relationship between the coupling inductance and the spacing of DGS cells. An equivalent circuit model is used to clarify the principle of the filter. It is proved that the filter can significantly suppress the common-mode noise over 15 dB from 3.5 to 12.4 GHz without degrading the signal integrity of the differential signals, of which the size is only 11 mm by 10 mm. Both simulations and measurement on the optimized CM filter have demonstrated the optimum performances in the stopband.

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