LETTER

A common mode filter using DGS-based coupled multiple resonance points for all-pass differential circuit

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Abstract

An ultra wideband common-mode filter based on coupling multiple resonance points is proposed in the letter. The coupling multiple resonant points are realized by four compact defected ground structure (DGS) cells, of which both the ends are C-type DGS cells and the middle are H-type DGS cells. The structure and size of these DGS units are different, which leads to their different resonance points. Because of the close distance between DGS cells, coupling inductors are generated between them, which can be used for smoothing filtering. A coupled LC resonator equivalent circuit model is built to explain the filter's working principle. The DGS-based filter with an area of 20 mm x 12 mm are implemented under the differential microstrip line. The simulated results shows the filter can achieves a wide 15-dB common-mode suppression of frequency range from 2.9 to 12.6 GHz. Good agreement between full-wave simulation and measured results is observed.

key words: wideband filter; all-pass differential signal; defected ground structure; common-mode; equivalent circuit.

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

1. Introduction

Due to the nature of strong immunity to noise, low crosstalk, and good electromagnetic interference (EMI) cancellation, differential signals have played an important role in high-speed digital circuits. However, in practical circuits, the common mode (CM) noise is unavoidable because of the asymmetries, amplitude unbalance or timing skew in the differential pair. Therefore, how to alleviate the CM noise problem has attracted extensive attention in the design of high-speed differential digital circuits.

At present, the requirements on all-pass differential circuits [1, 2, 3, 4, 5, 6, 7, 8] is critical in high-speed digital circuit application, where transmitted digital signals are random. it is difficult to design a full-band CM filter because the size of a full-band CM filter is very large, which needs a number of band filtering cells to achieve. However, it is still meaningful to design a compact ultra wideband CM filter, which can filter out wideband CM noise as much as possible

and further expand the application scope of the high-speed digital circuit system.

Several approaches have been used to suppress the CM noise in differential signals. CM filter adopting high permeability material [9, 10] is used in the past years. However, its operate range is seldom larger than 100 MHz and its size is still large. CM filter adopting LTCC technique [11, 12] is compact and can easily provide efficient common-mode rejection over GHz frequency range, but they need complex technical to implement, and increase the cost of the circuit. CM filter using periodically corrugated reference plane to achieve a stepped impedance performance is proposed in [13], which has a wide CM suppression frequency range from 5.3 to 10.4 GHz. Since the band-gap characteristic of electromagnetic bandgap (EBG) structure can restrain the propagation of electromagnetic wave, CM filter adopting EBG [14, 15, 16, 17, 18] can achieve CM suppression in the gigahertz range with low-cost. However, it often adopts periodic structure and then takes up large space. Since DGS [19, 20, 22, 23, 24, 25] has advantages of band gap, high impedance and slow wave characteristics, attention has been paid to the filter adopting DGS. Liu et al. [19] uses three periodic dumbbell-shape DGS to suppress CM noise, achieving a wide working frequency range from 3.3 to 5.6 GHz. Wu et al. [20] adopts a compact multiple DGS cells, which can broaden bandwidth by utilizing mutual coupling between DGS patterns and then realize a working frequency between 3.6 and 9.1 GHz.

Recently, tunable CM filters [26, 27, 28, 29] have attracted increasing attention for they have advantages of large tuning range, a broad stopband, compact size and a sharp cutoff frequency response. However, it needs to predict the stopband for the CM noise according to the operational condition.

In this letter, an ultra-wideband DGS-based CM filter is proposed. The filter is composed of four DGS cells, which uses four different resonance points to expand the filtering range on the basis of miniaturization. The structure pattern of the filter adopts two C-type patterns on both sides and H-type patterns in the middle, so as to reduce the influence of coupling capacitance as much as possible on the premise of utilizing coupling inductance, and then simplify the design. An equivalent circuit model for it is also analyzed, which explains that the working principle of the CM filter. As a demonstration, a wideband CM filter based on cou-

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Fig. 1. schematic diagram of the proposed reconfigurable DGS filter, (a) Top view of original ultra-wideband CM filter, (b) Bottom view of original ultra-wideband filter. Dimensions (mm): $W_1=5.20$, $W_2=5.70$, $W_3=4.10$, $W_4=2.50$, $S_1 = S_3 = 0.80$, $S_2 = 0.90$, $g_1=0.25$, $g_2=0.30$, $D_s = 0.80$, $D_w=0.90$, $b_1=1.40$, $b_2=4.60$, $d_1=2.7$, $d_2=1.8$.

pling multiple resonance points is designed, fabricated and measured. The proposed filter exhibits a wide CM suppression range from 2.9 to 12.6 GHz. The proposed design has been experimentally validated and a detailed comparisons between simulations and measurements show good agreement.

2. ultra wideband common-mode Filter

2.1 Design of ultra wideband common-mode filter

Figure 1 shows the configuration and dimensions of proposed CM filter, where four DGS cells are located in the ground plane, and kept symmetrical to the differential line. The four DGS cells adopt C-type DGS cells on both sides and H-type DGS cells in the middle. The size parameters of all DGS cells are different, which are used to get different resonant frequencies and then achieve an ultra wideband.

The DGS patterns are kept symmetrical to the differential line, which are used to avoid the excitation of common-mode noise. And more, due to the symmetrical DGS patterns, a two-port equivalent-circuit model can be used to analyze the even-mode equivalent circuit model analysis of the proposed filter for simplification[19].

As we known, each of the DGS cells can be treated as one pair parallel LC resonator circuit since they alter the path of return currents. The equivalent inductance comes from the increased path that a portion of the return currents go around the DGS cells pattern, and the equivalent capacitance comes from displacement current propagation of which a part of the return currents propagates through the narrow slot in the middle of DGS structures in the form of current path.

Fig. 2. Simulation comparison results of common mode suppression, where the gap of DGS cell adopts dotted line column or solid line column.

And more, when the two sides of two adjacent DGS units are close, there will appear obvious equivalent inductance, while the equivalent inductance can be ignored when the two DGS units are far apart since the coupling between them becomes small. Similarly, when the slots of two DGS are close, there exists coupling capacitance. However, the coupling capacitance will increase the complexity of design and the difficulty of equivalent circuit modeling. The simulation comparison results of filter slots at different positions are shown in Fig. 2. As shown in Fig. 1, when $d_1 = d_2 = 0$ mm, the position between the two slots is closest, the coupling capacitance between the two DGS units is the largest, so a low cut-off frequency can be obtained, as shown in Fig. 2. However, the coupling capacitance has an impact on common mode noise suppression. And the suppression ability of common mode noise is poor at 4-5 GHz, so its $|S_{cc21}|$ curve is not flat, as is shown in Fig. 2, that is, the filtering characteristics are unstable. When the gaps of the two filters are far apart, for example, when $d_1 = 2.7$ mm, $d_2 = 1.8$ mm, its $|S_{cc21}|$ curve is flat and the broadband common mode suppression is good. To simplify the design, the DGS cells adopt H-type pattern to avoid of the distance between adjacent slot is small, which is useful to suppress the mutual capacitance. Therefore, the mutual capacitance can also be omitted.

As shown in Fig. 3, the DGS cells can be treated as four pairs parallel LC resonator circuits in cascade, where the equivalent inductance L_{Di} ($i = 1, 2, 3, 4$) comes from the increased path that a portion of the return currents go around the DGS cells pattern, And there exists mutual inductance L_{Mij} ($i = 1, 2, 3; j = i + 1$) between adjacent DGS cells since edges of them are close, while the mutual inductance between nonadjacent cells can be omitted since the distance is far.

2.2 Analysis of ultra wideband common-mode filter

During design of CM filter, equivalent circuit modeling has the following advantages:

- 1) The equivalent circuit model is helpful to master the working principle of the CM filter;
- 2) By adjusting and optimizing the parameters of the estab-

Fig. 3. Equivalent LC resonant circuit model of the proposed CM structure.

Fig. 4. Comparison of full-wave simulation and equivalent circuit simulation results of the proposed filter.

lished equivalent circuit model, the required filtering effect can be achieved, thus greatly reducing the simulation time of full wave simulation software and enhancing the elasticity and efficiency of the design of CM filter;

As shown in Fig. 3, each DGS cell can be modelled as a parallel LC circuit. According to equation 1 and 2, the equivalent parameters of each DGS cell can be determined from the 3 dB lower angular cutoff frequency ω_{ci} and resonant angular frequency ω_{oi} , obtained from full-wave simulation HFSS-15 [21].

$$L_i = \frac{2Z}{\omega_{ci}} \frac{\omega_{oi}^2 - \omega_{ci}^2}{\omega_{oi}^2}, \quad (1)$$

$$C_i = \frac{1}{2Z} \frac{\omega_{ci}}{\omega_{oi}^2 - \omega_{ci}^2}. \quad (2)$$

where ω_{ci} ($i = 1, 2, 3, 4$) denotes the 3 dB lower cutoff angular frequency, and resonance angular frequency $\omega_{oi} = \frac{1}{\sqrt{L_i C_i}}$ ($i = 1, 2, 3, 4$).

For the mutual inductance, they can be estimated according to [20, 30]

$$M_{ij} = -0.5 \left(\frac{f_{oi}}{f_{oj}} + \frac{f_{oj}}{f_{oi}} \right) \times \sqrt{\left(\frac{f_i^2 - f_j^2}{f_i^2 + f_j^2} \right)^2 - \left(\frac{f_{oi}^2 - f_{oj}^2}{f_{oi}^2 + f_{oj}^2} \right)^2} \quad (3)$$

where f_{oi} and f_{oj} ($f_{oi} > f_{oj}$) denotes the self resonance frequency of DGS cells by themselves while f_i and f_j ($f_i > f_j$) stand for their two split resonance frequencies because of the coupling.

Table I. LC equivalent circuit values of each DGS cell and mutual inductance

Parameters	L_1	L_2	L_3	L_4
Value	4.57 nH	4.62 nH	7.36 nH	7.69 nH
Parameters	C_1	C_2	C_3	C_4
Value	0.0858 pF	0.0862 pF	0.115 pF	0.127 pF
Parameters	M_{12}	M_{23}	M_{34}	
Value	-0.159	-0.171	-0.157

Fig. 5. Comparison of equivalent circuit simulation results of the proposed filter with or without considering mutual inductances.

Figure 4 shows the comparison of simulated results of HFSS and equivalent circuit model. The LC equivalent parameters are shown in Table I, which are obtained from equations 1, 2 and 3.

The suppression of CM noise over 15 dB ($|S_{cc21}| < -15$ dB) is from 2.9 to 12.6 GHz in HFSS simulation whereas the values range from 3.1 to 13.0 GHz in equivalent circuit model. The results of full wave simulation are consistent with those of equivalent circuit modeling, which is helpful to verify the feasibility of filter design.

2.3 Effect of mutual inductance in the proposed filter

When DGS structures are close to each other, there will be mutual coupling effect between them and then a third resonant frequency is generated. The multi-resonant circuit caused by mutual coupling is helpful to smooth the filter and expand its bandwidth. As is shown in Fig. 5, without considering the coupling effect between DGS units, the filter has strong ability to suppress common mode noise, and its depth can reach more than 100 dB, while the working frequency ranger from 3.8 GHz to 13 GHz under the condition of 15 dB common mode noise suppression. Considering the mutual coupling effect between DGS cells, the filter has a wide range of common mode noise suppression, which is from 3.1 GHz to 13.0 GHz under the condition of 15 dB common mode noise suppression.

2.4 Filter Design and Experimental verification

A practical CM rejection filter for all-pass differential trans-

Fig. 6. Photograph of the fabricated CM filter prototype. (a) top view, and (b) bottom view.

Fig. 7. Comparison of simulated and measured results of $|S_{dd21}|$ and $|S_{cc21}|$.

mission line is designed and fabricated, which use Rogers 4350B with the relative dielectric constant of 3.48 and the thickness of 0.508 mm. The overall dimensions of the PCB for the filter are $80 \times 60 \text{ mm}^2$, as is shown in Fig. 6. The parameters for differential transmission line and DGS cells are shown in Fig. 1. The filter prototype is measured using a vector network analyzer 5071C.

The simulation and measurement results of $|S_{dd21}|$ and $|S_{cc21}|$ of the wideband CM filter are shown in Fig. 7. The simulated and measured 15-dB rejection bandwidths range from 2.9 to 12.6 GHz, and from 2.9 to 12.1 GHz, respectively. Additionally, the simulated DM transmission coefficient $|S_{dd21}|$ is less than -1 dB in the frequency range of 0 to 12 GHz, and less than -1.2 dB in the frequency range of 12 to 12.6 GHz. It offers an excellent DM performance, which is an essential requirement for CM suppression filters. A good agreement has been observed between simulation and measurement results. The discrepancy between them can be mainly explained by the following two main reasons. One reason is the parasitic capacitances formed between the soldered SMA components and the ground are not considered in the simulations. The other is the imperfect materials and fabrication tolerances also introduce the discrepancies.

3. Conclusion

A wideband CM filter for all-pass differential signals has been presented. By applying complementary DGS patterns, the structure of the filter is compact and miniaturized, which improves the gain flatness of the proposed filter, and can be

utilized to broaden the rejection bandwidth. The equivalent circuit model includes mutual inductance for the proposed CM filter has been developed and analyzed. From the simulated results, the CM noise is reduced by 15 dB from 2.9 to 12.6 GHz, whereas the differential signal is nearly intact. The fabricated sample board has proved that the proposed filter has wide and deep stop-band characteristics. This structure can be widely used in high-speed digital circuit system and integrated system design.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of Shaanxi Province under Grant no. 2019KW-057.

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