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A Compact Common-Mode Suppression Filter Using Modified Ground Structure for High Speed Digital Interconnects on Multi-layered PCB

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***Abstract*—A compact common-mode suppression filter is proposed by employing the modified ground structure (MGS) for high speed digital interconnects using differential signals on the multi-layered printed circuit board (PCB). It consists of two folded U-shaped slot resonators and arranged via-holes. It has compact size of $0.073\lambda_g \times 0.225\lambda_g$ when the center frequency is 5.2 GHz. A test board is fabricated on four-layered PCB through an optimizing process for verifying effects of the proposed MSG structure. The proposed MGS can suppress the common-mode noise over 10 dB from 4.34 to 6.07 GHz in the frequency domain and over 52% of amplitude in the time domain. Furthermore, the proposed filter still keeps good signal integrity characteristics with regard to the insertion loss of differential-mode signals. It is clear that the proposed filter structure can apply to the multi-layered PCB of commercial mobile devices due to its compact size and have some advantages such as wide bandwidth, gigahertz frequency range, low cost, and PCB embedded design..**

Index Terms—Common-mode filter, modified ground structure, differential signal, multi-layered PCB, defected ground plane, signal integrity.

I. Introduction

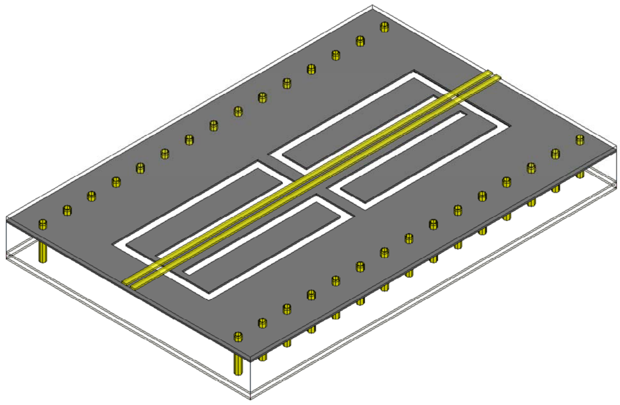
Recently, as data rate of high speed digital circuits is increased rapidly, differential signaling can be a good alternative transmitting method to single-ended signaling due to its high immunity to noise and low electromagnetic interference (EMI). However, in practical circuits, the common-mode noise is generated by imbalances of the differential line, power/ground plane resonances of a multi-layered printed circuit board (PCB), and external noises from the chip or signal lines in differential signaling. The common-mode noise reached in gigahertz frequency range causes a degradation of signal integrity and power integrity in high speed digital interconnects. Moreover, noise radiations caused by the common-mode noise are considered as significant EMI or radio frequency interference (RFI) problem.

In previous works, various researches have been conducted for suppressing common-mode noise in differential signaling. In general, a common-mode choke, that is two coils wound on a high permeability ferrite core, is easily used to suppress common-mode noise [1]. However, because it is only applicable to megahertz frequency range and has bulky in size the common-mode choke based on the multi-layered low-temperature co-fired ceramic (LTCC) was proposed [2]. It has a compact size and stop-band at gigahertz for common-mode. However, it is difficult to embed into the multi-layered PCB because of its chip type structure and the cost of LTCC fabrication is high. For wideband noise suppression up to several gigahertz, many methodologies of mounting resonator in power/ground plane such as electromagnetic bandgap (EBG) structure and localized spiral resonator have been proposed [3], [4]. Similar to these researches, methodology of etching resonator in ground plane has been proposed for wideband common-mode noise suppression. This methodology of filtering common-mode noise is employing a modified ground structure (MGS) that is also called patterned ground structure or defected ground structure (DGS) [5]. Recently, the common-mode suppression filters using periodic dumbbell-shaped DGS and composed with two U-shaped and one H-shaped patterned ground structure were proposed [6], [7]. They have the advantages such as wideband common-mode suppression over gigahertz bandwidth range and low cost whereas these filters occupy large area of ground plane in compact PCB. Also, they were designed on single-layered PCB so that their performance will be degraded on the multi-layered PCB due to the neighboring power/ground plane. The cascaded quarter-wavelength open stub resonator was proposed as the good solution for suppressing the common mode noise on the multi-layered PCB, while it is hard to apply to compact mobile applications [8].

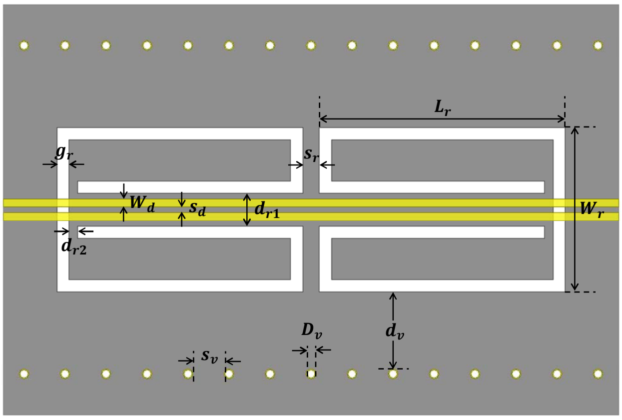
In this paper, a compact common-mode noise suppression filter was proposed by employing the MGS composed of two folded U-shaped slot resonators on the multi-layered PCB for mobile applications. There is a mutual coupling effect between two slot resonators so that the MGS acts like a mutually coupled resonator and can suppress common-mode noise over wide gigahertz range.

II. Configuration of the Proposed MGS Structure

To suppress common-mode noise in differential signaling, the MGS is designed on the ground plane beneath the coupled microstrip line. Fig. 1 and Fig. 2 show the proposed common-



(a)



(b)

Figure 1. Proposed common-mode suppression filter using the modified ground structure. (a) Three-dimensional view. (b) Top view.

mode filter on four-layered PCB which has a dielectric constant of 4.3 and a 0.02 of loss tangent. . There is the modified ground structure on the second layer, differential signal line and the ground plane acting like guard traces on the first layer, and ground planes on other layers. The MGS is composed with two folded U-shaped slot resonators in the opposite direction. For decreasing size of filter, the end of the U-shaped slot resonator is folded to the inside. Two slot resonators are separated from each other as short distance for leading mutual coupling effect. Each slot resonator is symmetric to the central line of the differential signal line. For differential-mode signal, the MGS beneath coupled microstrip line has not an important impact on signal transmission since coupled microstrip line plays a role as return current path to each other. For common-mode signal, on the other hand, return current path is built on ground plane so that the modified ground structure influences on common-mode signal transmission. As a result, only common-mode noise signal can be suppressed by different operation of the MGS as transmission mode. On the multi-layered PCB, common-mode suppression characteristics are affected by the additional ground plane beneath the MGS. It is because additional capacitance between shielding structure on layer 3 and the modified ground plane on layer 2. The arranged via-holes along the modified ground structure are applied for minimizing effect of the additional ground plane by compensating parasitic capacitance as inductance of the arranged via-holes. For investigating the performance of the proposed MGS filter, three dimensional (3D) Electromagnetic (EM) field solver and SPICE based circuit simulator is performed for the frequency and time domain, respectively.

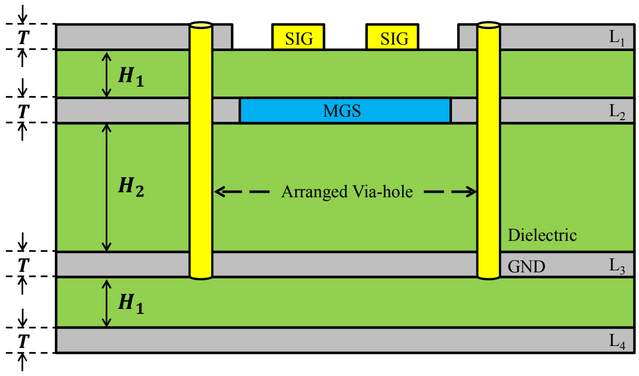


Figure 2. Side view of proposed common-mode suppression filter with multilayer stack-up information.

TABLE I. OPTIMIZED VALUES OF DESIGN PARAMETERS

Parameter	D_v	d_{r1}	d_{r2}	d_v	g_r	H_1	H_2
Value [mm]	0.1	0.4	0.1	0.95	0.15	0.07	0.53
Parameter	L_r	s_d	s_r	s_v	T	W_d	W_r
Value [mm]	3	0.07	0.2	0.38	0.03	0.1	2

The important parameters of the filter are indicated in Fig. 1(b) and Fig. 2. A width of microstrip line and a space between two signal lines expressed as W_d and s_d are related to the impedance of differential-mode and common-mode, respectively. A resonance frequency of the single slot resonator is determined by slot width $g_r$and length of resonator that is expressed as L_r, W_r, d_{r1}, d_{r2}. Mutual coupling coefficient of two slot resonators is decided by s_r which means space between two resonators. For wide common-mode suppression bandwidth from 4 to 6 GHz, design parameters are optimized and shown in Table I.

III. INVESTIGATION OF THE PROPOSED MGS STRUCTURE

A. Frequency domian

Fig. 3 shows the simulated transmission coefficients results for common-mode and differential-mode with and without via-holes. The differential-mode transmission coefficient (S_{dd21}) is not changed by existence of the via-holes since return current path is conducted on differential line. However, the common-mode transmission coefficient (S_{cc21}) is influenced by the arranged via-holes along the MGS. In the multi-layered structure, the parasitic capacitance can be made between the modified ground plane and the ground plane in layer 3. Because resonance characteristic of the coupled slot *LC*-

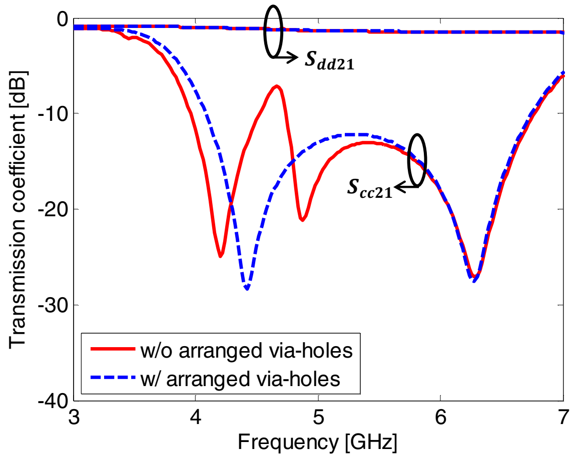


Figure 3. Common-mode and differential-mode transmission coefficients according to the usauge of arranged via-holes.

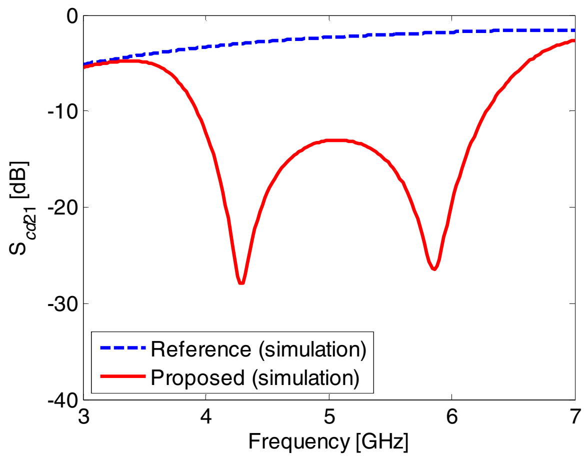


Figure 4. Transmission coefficient of differential-to-common mode conversion.

resonator is changed by the additional parasitic capacitance, common-mode suppression characteristic is changed. It is represented as the solid red line as depicted in Fig. 3. The via-holes between the MGS and the ground plane in layer 3 can produce additional inductance in parallel to parasitic capacitance. This inductance produces another resonance with parasitic capacitance. So, it is found that the effect of parasitic capacitance can be minimized by optimizing the resonance due to the arranged via-holes. In other words, common-mode suppression characteristic of the proposed filter is optimized in case of using the via-holes.

In the contrast, the dashed blue line in Fig. 3 shows the wide common-mode suppression bandwidth from 4.10 to 6.75 GHz based on -10 dB as well as differential-mode transmission coefficient is less than -1.5 dB on the whole simulated frequency range which is reasonable insertion loss in differential signals. It is clear that the proposed filter suppress the common-mode noise while maintaining good signal integrity of differential-mode signals.

In order to verify the effects of MGS for the common-mode noise, the common-mode noise is intentionally generated by employing the delay line on one of two signal lines. T It leads to signal skew so that differential-mode signals are not transmitted properly and common-mode signals are generated. In differential signaling, a phenomenon that differential-mode signals are converted to common-mode signals is called as differential-to-common mode conversion which means EMI radiation for a differential application. To prevent from generating differential-to-common mode conversion, isolation between differential-mode and common-mode should be secured. Fig. 4 shows the differential-to-common mode transmission coefficient (S_{cd21}) for the reference and the proposed filter. The reference indicates the ground plane without the proposed MGS. The differential-to-common mode transmission of proposed filter satisfies isolation margin level by -10 dB from 4 to 6.3 GHz unlike a reference. Therefore, the common-mode noise by differential-to-common mode conversion is suppressed on target bandwidth by the proposed filter.

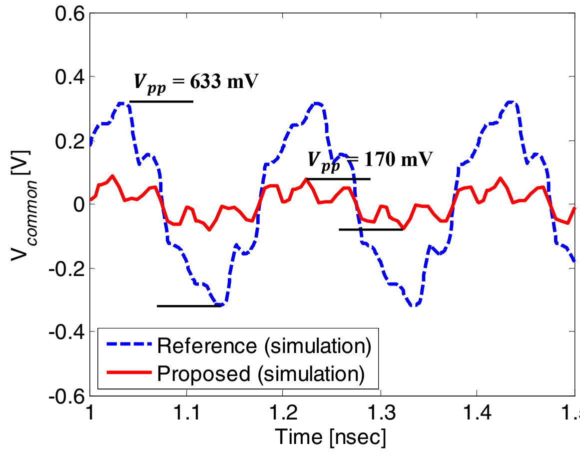


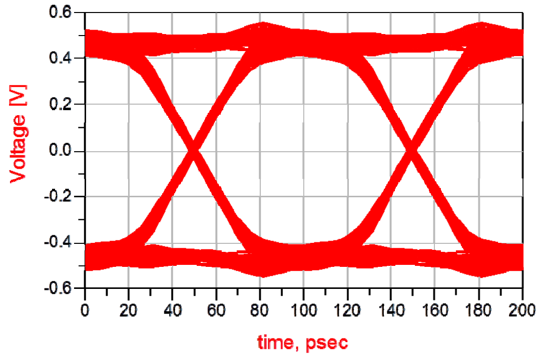
Figure 5. Common-mode noise voltage swing level of the proposed filter (simulation) and reference (simulation).

TABLE II. PEAK-TO-PEAK COMMON-MODE NOISE VOLTAGES

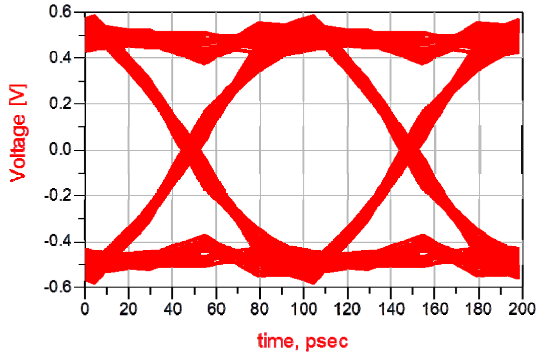
	The peak to peak noise level
Filter board	170 mV (-0.082 ~ 0.088 V)
Reference board	633 mV (-0.314 ~ 0.312 V)

B. Time domain

Fig. 5 shows simulated results of common-mode noise voltage swing level at differential output port. These results are obtained by circuit simulation with simulated *S*-parameters of the proposed filter by 3-D EM field solver. The common-mode noise is generated by signal skew. Two pulse trains of 10 Gb/s, which is data rate of Thunderbolt with 0.5 V peak-to-peak voltage, are applied on coupled microstrip line differentially. Note that Thunderbolt is the cutting-edge high speed digital interconnect which has bit rate of 10 Gb/s. A fundamental frequency of the input signal is 5 GHz, which is included in common-mode stop-band of the proposed filter. It is found from Fig. 5 and Table II that peak-to-peak output common-mode noise voltage of the reference is 633 mV although it is



(a)



(b)

Figure 6. Eye-diagram comparison at 10 Gb/s. (a) Reference (simulation). (b) Proposed filter (simulation).

TABLE III. EYE PARAMETERS

	Reference board (simulation)	Filter board (simulation)
Max. eye width	96.2 ps	92.2 ps
Max. eye open	784 mV	774 mV
Jitter	3.99 ps	9.31 ps

decreased to 170 mV using the proposed filter. As a result, a common-mode noise voltage is suppressed over 73%.

Fig. 6 shows the simulated eye-diagrams of differential line for the reference and the proposed filter. The input signal is a pseudorandom bit sequence (PRBS) of 10 Gb/s with 1-V amplitude. The eye-diagram qualities such as maximum eye width, maximum eye height, and jitter are indicated in Table III. It is found that the eye-diagram qualities of the proposed filter are approximately equal to the eye-diagram qualities of the reference. The signal integrity degradation is only about 4.16% and 1.27% for the eye width and eye height. So, it is determined that the proposed common-mode filter maintains good signal integrity by comparing the eye-diagrams.

IV. FABRICATION AND MEASUREMENT RESULTS

The proposed filter is fabricated based on optimized value of design parameters in Table I on the four-layered PCB.

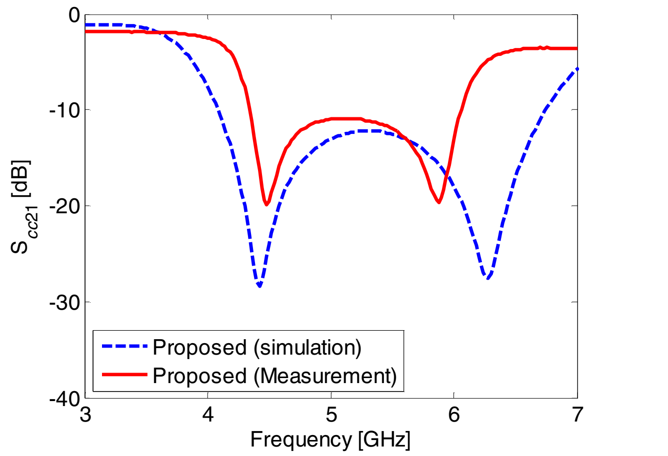


Figure 7. Transmission coefficients of the proposed filter for the common-mode (simulation and measurement).

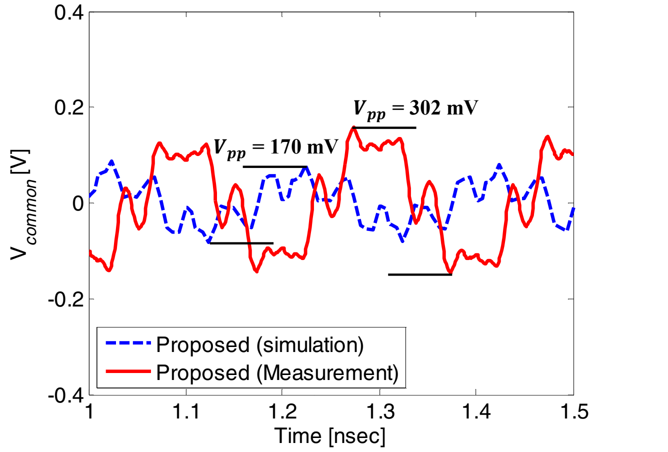


Figure 8. Common-mode noise voltage swing level of the proposed filter (simulation and measurement).

Copper is used as a conductor and the FR-4 substrate ($\varepsilon_r = 4.4$) is used. The *S*-parameter of the fabricated common-mode filter is obtained by 4-port vector network analyzer (VNA). A circuit simulation is performed with the measured results.

Fig. 7 shows the simulated and measured results of the proposed filter for common-mode transmission coefficients. The common-mode suppression bandwidth that based on -10 dB for the measurement is from 4.34 to 6.07 GHz. The stop-band of the measurement result is reduced as compared with that of the simulation result. It is because process error of the fabricated PCB or impedance mismatch on the port. However, the fabricated filter still keeps wide common-mode suppression bandwidth over 1.6 GHz. As common-mode suppression characteristic on the frequency domain is weakened a little, the common-mode noise voltage swing level which is common-mode suppression characteristic on the time domain is also diminished. The peak-to-peak output common-mode noise voltage of the fabricated filter is 302 mV (-0.124 ~ 0.138 V) as shown in Fig. 8, which means that a ratio of the common-mode noise suppression is over 52%.

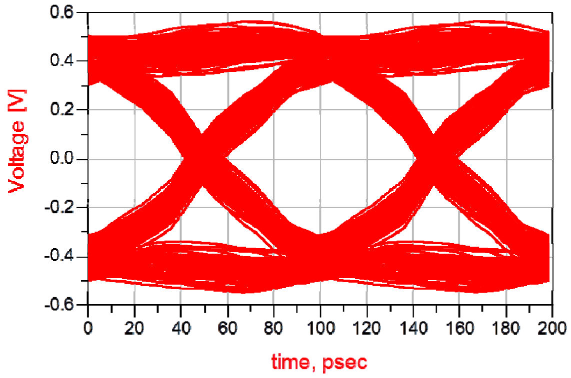


Figure 9. Eye-diagram of the proposed filter (measurement) at 10 Gb/s.

TABLE IV. EYE PARAMETERS

	Reference board (simulation)	Filter board (measurement)
Max. eye width	96.2 ps	86 ps
Max. eye open	784 mV	546 mV
Jitter	3.99 ps	14.63 ps

Fig. 9 shows the measured eye-diagram of the proposed filter. Because of some errors as mentioned before, eye-diagram qualities are degraded slightly. The eye width, eye height, and jitter are 86 ps, 546 mV, and 14.63 ps respectively for the proposed filter as shown in Table IV. Although eye-diagram qualities are reduced for measurement, the proposed filter still maintains good signal integrity by eye-opening.

V. CONCLUSION

In this paper, the common mode noise suppression filter is proposed by using the MGS on the multi-layered PCB for high speed differential signaling system. The MGS is composed of two folded U-shaped slots operated *LC* resonator on the ground plane. It is designed on the multi-layered PCB by the via-holes on the both side of the MGS. The test sample of the proposed filter is fabricated on four-layered PCB and the filter sized is about $0.073\lambda_g \times 0.225\lambda_g$, where λ_g is the wavelength in the substrate at center frequency of 5.2 GHz. Using the proposed filter, the common-mode noise signal is reduced over 10 dB from 4.34 to 6.07 GHz in frequency domain and common-mode noise voltage is suppressed over 52 % in time domain. Also, it is found that signal integrity of differential signals is not deteriorated. Compared with the previous research, the proposed filter in this paper has small size from electrically and physically point of view and can be applied on the multi-layered PCB with the via-holes.

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