An Embedded Common-Mode Suppression Filter for GHz Differential Signals Using Periodic Defected Ground Plane

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Abstract—A novel low-cost filter design for common-mode noise suppression in high-speed differential signals is proposed. It is realized by periodically etching the dumbbell-shape defected ground structure (DGS) to perturb the return current of the common-mode noise. A transmission-line model for the proposed structure is also developed with good agreement to the full-wave simulation and measurement result. It is found that over 20 dB suppression of common-mode noise can be achieved over a wide frequency range from 3.3 to 5.7 GHz with 3 cascaded DGS cells, while the differential signals still keep good signal integrity in eye-pattern observation. The common-mode current, which generally results in common-mode EMI, on the attached input/output cable is also proved to be efficiently suppressed (15 dB in average) within the stopband by the proposed filter.

Index Terms—Common-mode filter, defected ground plane, differential signal, electromagnetic interference (EMI), signal integrity.

I. INTRODUCTION

DIFFERENTIAL signals have played an important role in high-speed digital circuits because of their high immunity to noise, low crosstalk, and low electromagnetic interference (EMI). Several high-speed serial link formats, such as PCI Express II, Gigabit Ethernet, or OC-192, have data rates over 5 Gbps under the differential signal transmission. However, in practical circuits, the common-mode noise due to the timing skew or amplitude unbalance along the differential signal paths is unavoidable. Microwave frequency common-mode noise will degrade the signal integrity or power integrity of the high-speed circuit system. Furthermore, the EMI issue caused by the common-mode noise radiation through the input/output (I/O) cables connected to the differential signals could also be significantly serious.

Several approaches have been used for the common-mode noise suppression of differential signals. The common-mode choke using a high permeability ferrite core is one of the most general approaches [1]–[3]. This approach is valid only at MHz frequency range. Another drawback is the difficulty of reducing the size of this common-mode choke using the ferrite material. A compact device is important for high density digital circuits. A miniaturized common-mode suppression filter was proposed based on the multi-layer low-temperature co-fire ceramic (LTCC) [4]. The filtering band reaches about 1 GHz with compact device size, but the cost is high for the LTCC fabrication.

In this letter a novel broadband common-mode filter for GHz differential signals is proposed by using periodic defected-ground structures (DGSs). The unit-cell of the differential transmission line with dumbbell-shaped DGS can be considered as a parallel $LC$ circuit for the common-mode signals but as an ideal short for the differential ones. By suitable geometry design of the dumbbell-shaped structure, the proposed embedded filter has broadband and efficient suppression of the common-mode noise while still maintaining a good signal quality for the differential components. In addition, by embedding this filter at the differential I/O port where long cables are generally connected, the EMI caused by the common-mode current on the cables can be significantly reduced. Compared to previous common-mode noise suppression approaches, the proposed approach has the advantages of low cost, wideband suppression in GHz range, and good compatibility to the standard printed circuit board or packaging process.

II. DESIGN CONCEPT AND MODELING

Fig. 1(a) shows the proposed common-mode filter. It is designed by periodically etching the dumbbell-shaped structure on the ground plane underneath the differential lines. To avoid the excitation of common-mode noise, the dumbbell-shaped DGS is kept symmetrical to the central line of the two signal lines. As shown in Fig. 1(a), two dumbbells are designed as a square with side length $K_d$. An etched slit with length $W_d$ and gap width $S_d$ is used to connect two dumbbells. Because the differential signal is odd mode, relatively low current density will return through the ground plane. Thus, the degradation of the differential signals caused by the DGS will be relatively small. However, the return current of common-mode (or even-mode) will pass through the ground plane, and the DGS would have significant effect on this type of signal. As shown in Fig. 1(b), the unit-cell of the proposed filter for the common-mode can be modeled as an ideal transmission line with even-mode characteristic impedance ($Z_{even}$) and a $LC$ resonator cascaded on the ground plane. The $C_{DGS}$ and $L_{DGS}$ denote the gap capacitance between two sides of the slit and the equivalent inductance of the signal passing through the DGS, respectively. It is clearly seen that the common-mode noise can be significantly blocked.
at the frequency range close to the resonance frequency of the $LC$ resonator, i.e., $\omega_0 = 1/\sqrt{L_{DGS}C_{DGS}}$.

A common-mode filter is fabricated on a PCB with 1.6 mm FR4 substrate. The differential lines are designed with $w = 2.5$ mm and $s = 1.8$ mm to obtain 50 $\Omega$ odd-mode impedance. In order to enhance the stopband bandwidth for common-mode noise suppression, three unit-cells are cascaded with period $P_d = 10$ mm and the geometrical parameters for each DGS are $W_d = 7$ mm, $S_d = 0.4$ mm and $K_d = 4$ mm.

III. COMMON-MODE NOISE SUPPRESSION

A. Frequency Domain

Fig. 2 shows the simulated (HFSS) and measured insertion loss $|S_{dd}|$ and $|S_{cc}|$ for the differential transmission line. The corresponding results predicted by the equivalent circuit model are also shown in this figure. The equivalent inductance $L_{DGS} = 2.5$ nH is extracted from the TDR measurement and the gap capacitance $C_{DGS} = 0.47$ pF is approximated by the equation [5]

$$C_{DGS} = \frac{\varepsilon_0 \varepsilon_r}{\pi} \ln \left( \cosh \left( \frac{\pi S_d}{4 \ h} \right) \right) + \frac{\varepsilon_0}{\pi} \ln \left( 2 + \frac{1}{1 - \sqrt{k'}} \right)$$  \hspace{1cm} (1)\

where $k' = \sqrt{1 - k^2}$ and $k = S_d/K_d$. Good agreement between modeling and full-wave simulation is observed, but the discrepancy between the measurement and simulation at frequencies above 5.5 GHz could be resulted from frequency-dependent loss of the metal and the dispersive effect of the substrate. These two effects are not considered in the modeling. It is observed that the stopband is from 3.3 to 5.7 GHz with about 2.4 GHz bandwidth, where the stopband is defined as the frequency ranges at which $|S_{cc}| > 20$ dB. However, within the stopband the insertion loss of the differential-mode signals is less than 2 dB in average. It implies that the embedded common-mode filter can efficiently suppress the common-mode noise with broad stopband in the GHz range, but still keep good signal integrity performance for the differential signals. In addition, the simulated transmission of mode-converson from differential mode to common mode, $|S_{dd}|$, is also shown in Fig. 2. It is clearly seen that the cross-mode transmission is less than $-50$ dB from 2 to 8 GHz. The proposed filter will not increase the common-mode noise due to mode conversion.

B. Time Domain

The common-mode noise suppression capability is also verified in time domain. The differential lines with the solid ground plane (reference board) and with the DGS filter (filter board) are both measured for comparison. To excite the common-mode noise, a signal skew is created by designing a delay line (10 mm) on one of the differential lines as shown in the inset of Fig. 3. Two pulse trains of 800 mV peak-to-peak voltage and 8 Gbps are
differentially launched into port 1 and port 2 by the pattern generator (Agilent N49001A). The output waveforms are measured at port 3 and port 4 using digital oscilloscope (Agilent DAJ86100C), respectively. The common-mode noise ($V_{\text{COMMON}}$) is defined as half of the sum of the measured voltage at these two output ports. It is observed from Fig. 3 that the peak-to-peak output common-mode voltage for the reference board is 412 mV, but it is reduced to 64 mV employing the proposed DGS filter. Over 80% improvement is achieved. Fig. 4 shows the measured differential eye-pattern with 1 V amplitude in 8 Gbps. The maximum eye opening is 830 mV for the reference board and 746 mV for the filter board. The maximum eye width and jitter is almost the same for both boards. It is proved in time-domain that the proposed embedded filter behaves excellent performance in common-mode noise suppression while good differential signal quality is preserved.

C. Reduction of Common-Mode Radiation

To investigate the suppression ability for the radiation caused by the common-mode noise, 4 cm cables of twisted wires are attached at port 3 and 4 of the differential lines for the aforementioned test boards. It is well known that the common-mode radiation through the attached cable is proportional to the amplitude of the common-mode current on the cable [3]. Current probe (FCC F-2000) and spectrum analyzer (R&S FSP40) are used to measure the common-mode current on the cables when differential signals are launched into the test boards from port 1 and 2. It is observed from Fig. 5 that the common-mode current is significantly suppressed for the proposed structure in the frequency range from 2.8 to 5.6 GHz. About 15 dB reduction in average for the common-mode current is achieved in the designed stopband.

IV. CONCLUSION

This letter proposes a novel common-mode noise suppression filter for GHz differential signals by employing the periodic DGS. A LC resonator for the common-mode noise is simply realized by periodically embedding the dumbbell-shape defected structures on the ground plane. As demonstrated in the example design, it is proved both in time and frequency domain that the proposed filter with 3 DGS cells can significantly reduce the common-mode noise, over 20 dB within 2.4 GHz bandwidth and over 80% in time-domain, without degrading the signal integrity of the differential signals. The radiation caused by the common-mode current on the attached I/O cables is also efficiently suppressed by 15 dB in average within the designed stopband. To our best knowledge, it is the first low-cost common-mode filter designed for the GHz high-speed signals using the defected ground concept.

REFERENCES