A Novel Common Mode Choke and Its Application for 5 Gbps USB 3.0

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***Abstract*—A novel compact common mode choke is proposed and realized without using ferrite materials. It is fabricated on LTCC substrate and possesses a small size of 1.2 mm × 2.0 mm. It provides over 10 dB common mode suppression from 1.4 GHz to 3.7 GHz and still maintains the differential signal transmission up to 8 GHz. To validate the common mode choke on USB 3.0 cable, a series of experimental tests are executed, including eye diagram for differential signal, common mode noise suppression, and elimination of common mode current on cables. The eye diagram for the filter board keeps obvious eye width and eye height and almost the same result with that for the reference board. About 57 % common mode suppression is achieved after placing the common mode filter on the board with 8 mm skew line. Moreover, the common mode current on cables related to far field radiation is also measured by current probe and eliminated over 10 dB within designed stopband by using the common mode choke.**

I. INTRODUCTION

Differential signaling predominates in high-speed digital circuits due to its high immunity to noise, crosstalk, and electromagnetic interference (EMI). Differential interfaces, such as HDMI, USB3.0, PCI-E II, and SATA III, can support differential signals transmission up to Gb/s. Ideally, it transmits balanced differential signals from transceivers to receivers. However, in practical circuits, the differential traces may meet imbalances and unwanted common mode noise will be induced [1]. These imbalances may include unbalanced digital signal output, asymmetrical routing, bends, crosstalk, and discontinuities from connectors. These will result in unwanted common mode noise coupling to radiators and cause serious electromagnetic interference (EMI) and radio frequency interference (RFI) problems [2]. Therefore, to prevent common mode noise from causing radiation becomes an essential issue for solving this kind of electromagnetic compatibility (EMC) problems.

Compensation structures and common mode filter are two main strategies to suppress common mode noise. The former employs compensation length to improve the symmetry of differential traces [3]. The compensation length depends on the level of the imbalance and only mitigates the local imbalance. That is, common mode noise resulting from other imbalances will not be eliminated by the compensation design. The latter is to use surface mounted device (SMD) or embedded structures to filter the common mode noise and still let differential signals propagate. It can reduce the common mode noise over all systems and is a good candidate to solve EMC problem.

Common mode chokes and embedded DGS filters are presented in [4]-[8]. Because of the larger size and lower flexibility of defected-ground-structure (DGS) filter, common mode chokes are preferred to be applied in today's high speed digital system. Moreover, a LTCC common mode choke is superior to the chokes using ferrite materials due to it lower cost and higher operating frequencies[2], [8]. As a result, the design of a compact LTCC common mode choke with wider band rejection for common mode noise imposes a challenge in wireless and mobile communication systems.

In this paper, a compact and wideband common mode filter is presented and fabricated on low temperature co-fired ceramic (LTCC) substrate. Different from the conventional common mode choke using the ferrite materials, it possesses the properties of high frequency operation, low mode conversion and low cost. Its good performance will be investigated on the application of the USB 3.0 cable. The differential mode insertion loss, common mode insertion loss and mode conversion loss will be seen both in the simulation and measurement. The capability of common-mode suppression will be demonstrated in the time domain measurement. In addition, the eye diagram to verify the signal integrity of this device and its test of common mode current suppression on USB 3.0 cable will be executed in this work.

II. THEORY AND CONCEPT

An equivalent circuit model is established to explain its filtering properties for the novel common-mode choke as shown in Fig. 1. The circuit model consists of two T-type circuit with a series inductor and two shunt capacitor and a parallel resonator. The T-type circuit with L_1, C_1, L_m, and C_m corresponds to the coupled line and the parallel resonator is formed by L_2 and C_2.

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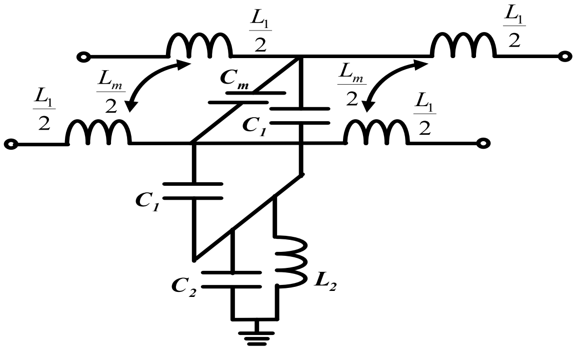


(a)

Fig. 1 Equivalent circuit model

Applying the odd and even mode analysis, the circuit model can be decomposed into two half circuit models, the odd- and even- mode. It behaves like an equivalent circuit of a transmission line when odd mode is excited whereas it introduces a stopband when even mode is excited. By designing the element values of the circuit model, broadband common mode suppression can be achieved without affecting the differential mode transmission. Due to its inherent symmetrical configuration, it experiences very low mode conversion from common mode to differential mode as opposed to the conventional common mode chokes using coil winding. Its unique properties are used to design common mode chokes [2], [8].

Based on this concept mentioned above, a more compact common mode choke is realized on LTCC substrate with the dielectric constant of 3.9. The properties of the multilayer structure of LTCC are applied to miniaturize the structure and a small size of 1.2 mm × 2.0 mm is achieved. The device photo is shown in Fig. 2. To verify the suppression capability and performance of the common mode choke, some simulations are executed and a series of tests are experimented as follow.

III. Performance of Common Mode Choke

A. Differential Signal Quality

To understand the performance of the proposed choke, two test samples are presented and manufactured as shown in Fig. 3. They are individually composed of four microstrip lines radially locating on FR4 substrate with the thickness of 0.8 mm. One is reference board and with a short coupled line. The other is experimental board and with the common mode choke. The four microstrip lines are mutually uncoupled so as to directly investigate the properties of the common mode choke without extra effects.

Fig. 4 shows the *S*-parameter simulation and measurement results. It is simulated by the full wave tool and measured by four-port VNA system. The acquired four-port *S*-parameter results are transformed into mixed mode *S* parameter by the simple matrix manipulation. The mixed-mode *S* parameter

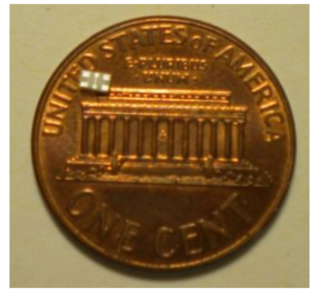
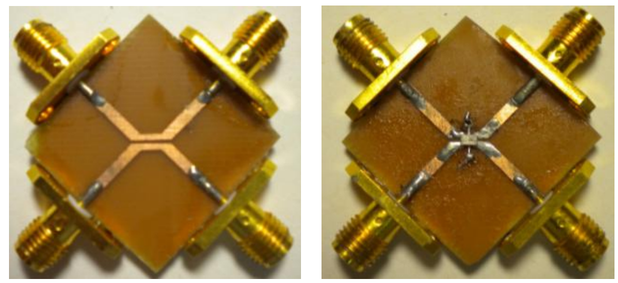


Fig. 2. The device photo of the proposed common mode choke



(a) (b)

Fig. 3. Two test samples for (a) reference board and (b) filter board.

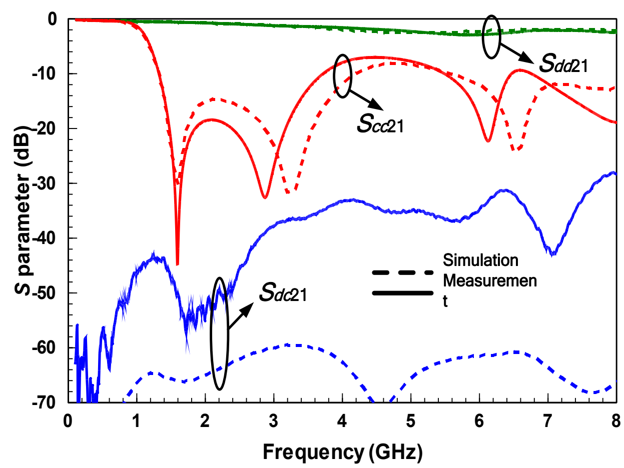
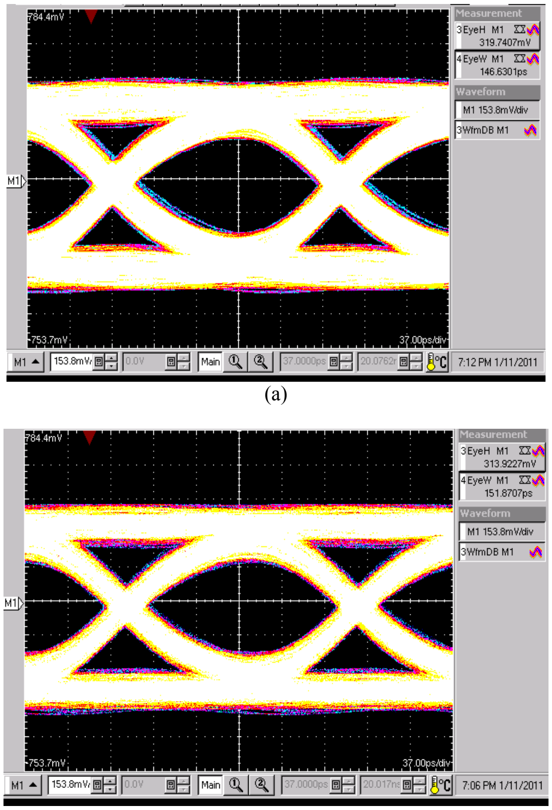


Fig. 4. *S*-parameter results for the simulation and measurement

results for simulation have a good agreement with that for measurement. The differential mode insertion loss maintains below 3 dB up to 8 GHz. The mode conversion from common mode to differential mode related to the differential signal integrity is also shown in this figure. The simulated mode conversion loss is below 50 dB, but the measured is about 30 dB . The discrepancy between the simulation and measurement is from the fabrication tolerance. However, compared to conventional common mode choke, which is inherently asymmetrical structure due to coil winding or the spiral routing, the proposed common mode choke largely eliminate the mode conversion



(a)

(b)

Fig. 5. Measured Eye diagrams on USB 3.0 cable for (a) reference board and (b) filter board.

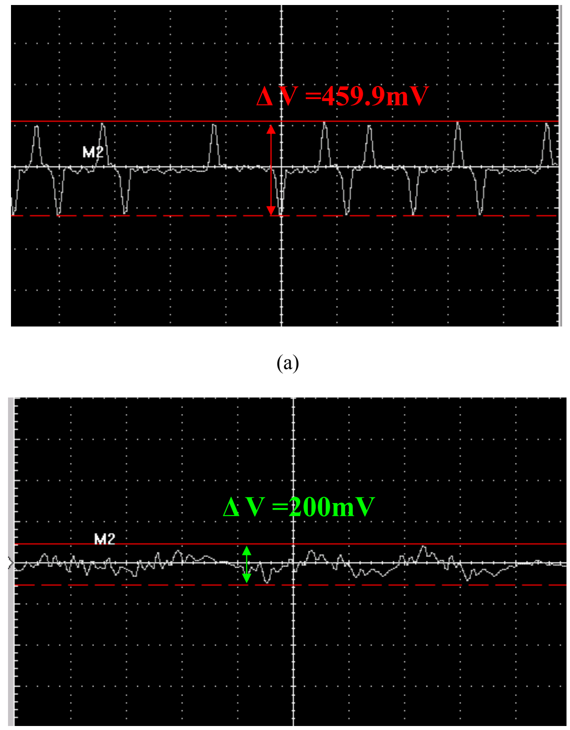
The eye diagram to evaluate the differential signal quality is also measured in this work. The input source is a pseudo random bit sequences (PRBSs) with the bit rate of the 5Gb/s, which is the nominal transmission bit rate of USB 3.0 cable. The sequence with 2048 - 1 bits is launched into the device through the USB 3.0 cable and the eye diagram is observed by the digital oscilloscope. Two sample devices are manufactured for comparison. One is the reference case and the other is the experimental case. The reference case is the test vehicle without a choke but allow the differential signal pass through. The experimental case is the test vehicle with the choke mounted on it. Fig. 6(a) and Fig. 6(b) shows the measured results for the reference case and common mode choke, respectively. The corresponding eye width and the eye height are tabulated on Table I. The eye widths for two cases are almost the same, but the difference of eye height between the two cases is 6 mV. This is because the extra loss of the common mode choke. In practice, the eye diagram, including USB 3.0 cable and common mode choke, proves the proposed common mode choke still can support differential signal transmission up to 5 Gb/s.

B. *Common mode Suppression*

The capability of common-mode noise suppression is also investigated both in frequency domain and time domain. The common mode suppression in frequency domain, in terms of the common mode insertion loss, is demonstrated in Fig. 4. Common mode noise is reduced over 10 dB from 1.4 to 3.7 GHz. A stopband for common mode with FBW of 90 % is accomplished.

TABLE I
EYE PARAMETERS SUMMARY

	Reference	Filter board
Max. Eye Width	146.6 ps	151.8 ps
Max. Eye Open	319.7 mV	313.9 mV



(a)

(b)

Fig. 6. Measurement setup for the common mode current on USB 3.0 cables

To demonstrate the suppression degree of the common mode choke in time domain. The differential lines with a short coupled line (reference board) and with the common mode choke (filter board) are both measured for comparison. To excite the common-mode noise, a signal skew is created by designing a delay line (8 mm) on one of the differential lines. Two 5 Gbps PRBSs with 1 V peak-to-peak voltage are differentially launched into port 1 and port 2 by the pattern generator (Anritsu MP1763C). The output waveforms are measured at port 3 and port 4 using digital oscilloscope. The common-mode noise (V_{common}) in terms of the half of the sum of the two output signals is observed in Fig. 6. It shows that the peak-to-peak output common-mode voltage for the reference board is 460 mV, but it is reduced to 200 mV employing the proposed common mode choke. Over 57 % improvement is achieved. It proves that the proposed common

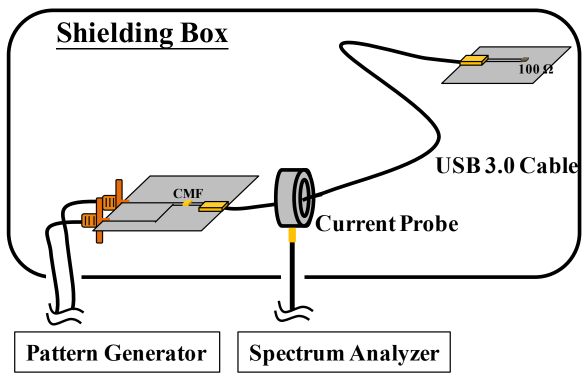


Fig. 7. Measurement setup for the common-mode current on a USB3.0 cable

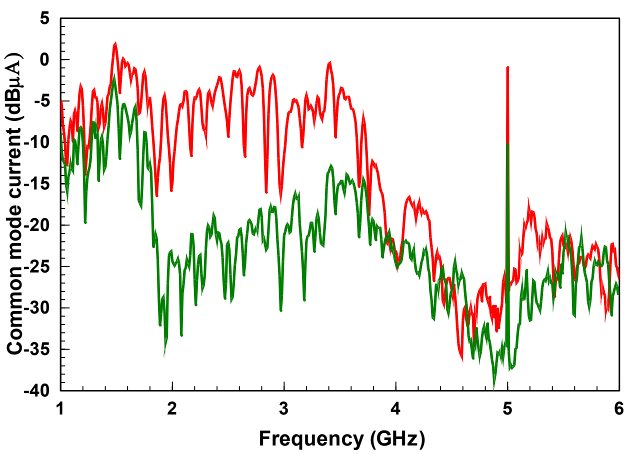


Fig. 8. Measured common mode current on USB 3.0 cable.

mode chokes behaves excellent performance of common-mode noise suppression not only in frequency domain but also in time domain.

C. Reduction of EMI source

To evaluate suppression of the far field emission for the common mode choke, the level of common mode current is an important index and is proportional to the amplitude of the radiation [9]. The lower the common mode current on cables is, the less the far field radiation is. The measurement environment is set as shown in Fig. 7. The test is for USB 3.0 cable, so the differential PRBSs with 5 Gb/s, is used, launched into the USB 3.0 cable, and terminated with a matching impedance at the other end of the cable.

The current probe (F 2000) is applied here to detect the common mode current and its result is observed on the spectrum analyzer. Fig. 8 shows the experimental results. The curve for the reference case has a larger noise level around 2.5 GHz corresponding to the fundamental frequency of the 5 Gb/s differential signal. But for the case with the choke, common mode current is largely eliminated from 1.4 to 3.7 GHz . This proves that the proposed common mode choke has a good capability of suppressing the common mode current. Note the current probe rated at 3 GHz can still work up to 5 GHz because it is used to compare the relative level between reference case and the case with the choke.

IV. CONCLUSION

A novel common mode choke is proposed on LTCC substrate. It is realized with the size of 1.2 mm × 2.0 mm and has a low cost. It can support differential mode transmission up to 8 GHz whereas it has a stopband for common mode from 1.4 to 3.7 GHz. Meanwhile, it introduces mode conversion loss less than 30 dB. It is validated for the application of the USB 3.0 by examining the eye diagram, common mode suppression, reduction of emission source. The proposed common mode choke shows good differential signal integrity, strong suppression on common mode noise, and large reduction of common mode current on USB 3.0 cable.

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