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On-Chip Filter for Mitigating EMI-Related Common-Mode Noise in High-Speed PAM-4 Transmitter

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Abstract

The electromagnetic interference (EMI) is generated by the common-mode (CM) noise in differential circuits and has a high risk of degrading other circuits' performance by radiating the disturbance. This paper demonstrates an on-chip filter that suppresses the CM noise while keeping the integrity of the differential-mode (DM) signal. Based on the delay equalizer, this filter provides the benefit of whole spectrum DM constant resistance, which achieves great matching between the off-chip transmission line and the on-chip circuit. The simulation results show that the filter efficiently mitigates the EMI of a 56 Gbps PAM-4 transmitter by suppressing the CM noise up to 18.85 dB at 28 GHz with core area of 207 µm × 125 µm.

1. Introduction

Differential signaling has been widely used with the increasing of the data rate owing to its inherently CM noise suppression and small crosstalk. However, the mismatch of rise and fall time caused by the imbalance in the charging and discharging paths generates CM noise in the differential circuits. That CM noise is radiated in the environment by the connectors, flex cable and electrical-to-optical interface. The interference significantly affects the weak signal of the receivers nearby, which will increase the bit error rate (BER) and caused malfunction.

The active circuit technique for automatic CM noise cancellation as one method to suppress the CM noise. However, it highly increases the complexity of the circuit and induces extra power consumption. Another method adopting off-chip filter suffers from permeability degradation over gigahertz and is hard to precisely suppress the noise at the predetermined frequency point in a high data rate communication system [1]. Benefitting from the smaller size components at high frequency and the fine accuracy of semiconductor process, the on-chip filter is a great candidate to provide suppression at specific frequencies with acceptable area consumption.

In this paper, two filters with different CM resonant frequencies are designed. A constant resistance structure is used for getting all the DM signals through without attenuation. The delay equalizer provides a wide range of constant group delay, which is critical for the high-speed communication links. In the design stage, ideal components are firstly used to determine and adjust the value of the components. The radio frequency devices based on 40 nm CMOS technique are further utilized to fine tuning the filter. To demonstrate their effects, a high-speed four-level pulse amplitude modulation (PAM-4) transmitter [2] is introduced.

This work is organized as follows. In section 2, a brief introduction of the high-speed PAM-4 transmitter is presented. Section 3 describes the design of the filters and presents the simulation results of this individual block. Then the simulation results and related discussion of the whole transmitter are shown in section 4. Finally, the conclusion of this paper is drawn in section 5.

2. High-Speed PAM-4 Transmitter

The 56 Gbps PAM-4 optical transmitter is shown in Fig. 1 [2]. Binary data are produced by a pseudo-random binary sequence (PRBS) generator, then formed the least significant bit (LSB) and the most significant bit (MSB) data. The PAM-4 signal is generated by a parallel-connected two-stage common mode logic (CML) driver combining the LSB and MSB signal. A predistortion at the output of the CML driver is produced by the feed-forward equalization (FFE) circuit through adding the pulse into data. It can reduce the inter-symbol interference (ISI) caused by the transient non-linearity and bandwidth limitation of the laser or the channel. Beads are used to block the high-frequency signals from the supply source. A non-linear laser model is connected across differential output terminals.

The CM noise generated by the rise and fall time mismatch for PAM-4 signaling is calculated in the following equation:

$$N(2F_{Nyquist})_{CML} = \frac{1}{8} R_F Amp \, \frac{|t_{rise} - t_{fall}|}{T_b} sinc^2(\frac{\pi}{2}\frac{T_{tr}}{T_b}) \qquad (1)$$

Where Amp is the amplitude, t_{rise} is the rise time, t_{fall} is the fall time, T_b is the data period and T_{tr} is the data transition period. The highest amplitude harmonic component of CM noise is at twice the Nyquist frequency, which determines the filter design to suppress CM noise at 28 GHz for 56 Gbps PAM-4 transmitter.

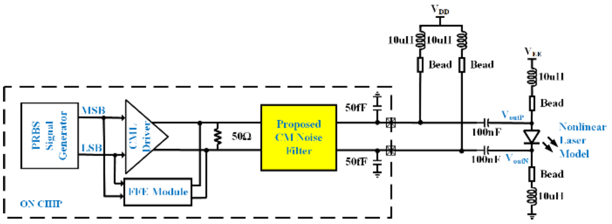

Figure 1. Schematic of 56 Gbps PAM-4 optical transmitter with FFE.

3. Filter

To keep the integrity of the DM signal while suppressing the CM noise at specific frequencies, a delay equalizer [3] is adopted as DM half circuit of the filter. An inductor is added in the CM half circuit path to provide two resonant valleys of the transmission coefficient. As the Fig. 2 shows, the filter is analyzed in CM and DM separately, which achieves CM suppression at two specified frequencies and DM constant group delay over a large frequency range.

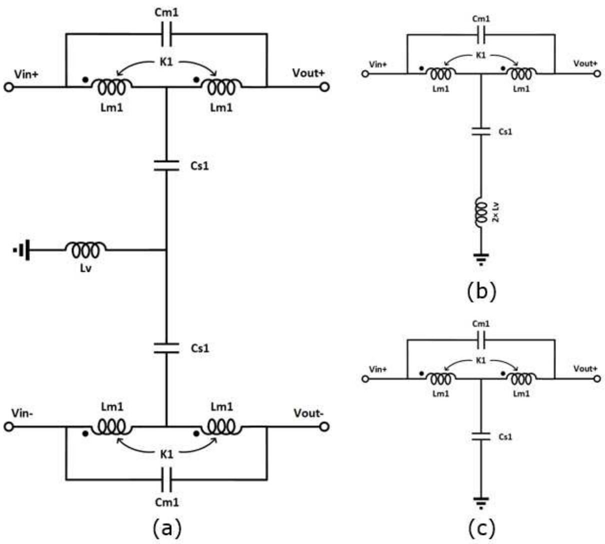

Figure 2. Schematics of CM filter. (a) Whole filter. (b) CM half circuit. (c) DM half circuit.

3.1 DM Half Circuit Design

For the DM half circuit depicted in Fig. 2(c), according to the design of 2-stage delay equalizer in [3]. The elements are calculated by

$$K_1 = \frac{1-Q^2}{1+Q^2} \tag{2}$$

$$L_{m1} = \frac{(Q^2+1)R}{2Q\omega_r} \tag{3}$$

$$C_{s1} = \frac{2}{Q\omega_r R} \tag{4}$$

$$C_{m1} = \frac{Q}{2\omega_r R} \tag{5}$$

Where ω_r is the pole resonant frequency and Q is the pole that are obtained by looking up the table in [3] to achieve the image relationship between the zeros and the poles. R is the constant input impedance over the entire frequency range.

To analyze this delay equalizer, according to the Bartlett's bisection theorem, Z_{oc} and Z_{sc} are calculated by applying the two ports with identical voltage generators and identical voltage generators with opposite polarity respectively.

$$Z_{oc} = j\omega(L_{m1}+M) - j\omega 2M + \frac{1}{j\omega C_{s1}/2} \tag{6}$$

$$Z_{sc} = j\omega(L_{m1}+M)//\frac{1}{j\omega 2C_{m1}} \tag{7}$$

$$M = K_1 \times L_{m1} \tag{8}$$

These results can be recast in terms of the resonant parameters Q, ω_r, R.

$$Z_{oc} = jQR\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right) \tag{9}$$

$$Z_{sc} = \frac{R/Q}{j\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)} \tag{10}$$

Which means $Z_{oc} \times Z_{sc} = R^2$, and the input impedance can be calculated by

$$Z_{in} = (Z_{sc}+R)//\frac{Z_{oc}-Z_{sc}}{2} + Z_{sc} = \frac{R(Z_{oc}+Z_{sc})+2Z_{oc}Z_{sc}}{Z_{oc}+Z_{sc}+2R} = R \tag{11}$$

3.2 CM Half Circuit Design

As the Fig. 2(b) demonstrates, the DM half circuit is series of the 2-stage delay equalizer and the inductor. Simply treating the delay equalizer as a section of ideal transmission line with specific group delay τ [2], the transmission zeros can be calculated by

$$Z_{21} = \frac{R}{j\sin\omega\tau} + j\omega 2L_v = 0 \tag{12}$$

After setting two specified transmission zeros ω_1 and ω_2, the group delay τ for the DM transmission line and L_v for suppressing the CM noise can be calculated.

3.3 Simulation Results

Based on the equation (2)-(12), filter I with the CM resonant at 28 GHz and 56 GHz, and filter II with the CM resonant at 26 GHz and 31 GHz are designed. The simulation results are depicted in Fig. 3-5.

As Fig. 3 shows that filter I with ideal components can achieve best suppression at 28 GHz. However, the parasitic of the nonideal components prevent the filter to precisely resonant at 28 GHz, which only provides 19.79 dB of CM noise suppression. Thus, the filter II is designed to resonant not exactly at 28 GHz, which is more tolerant of the parasitic of the components. Figure 4 demonstrates the parasitic effect on the DM transmission. Both of the two filters suffer from a severe degradation to 1 dB at around 40 GHz. The frequency range of constant group delay increases due to the parasitic but the ripple is also increased, which is shown in Fig. 5. And filter I has better performance in terms of the group delay, which is 68.65 GHz and can add less distortion on the DM signal.

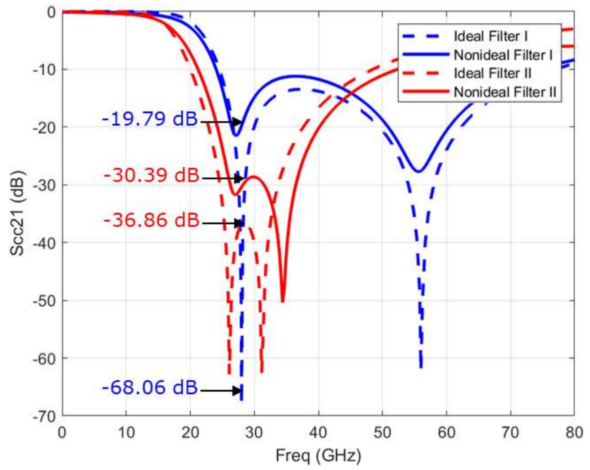

Figure 3. The CM transmission coefficient simulation results of filter I and filter II with ideal components and nonideal components.

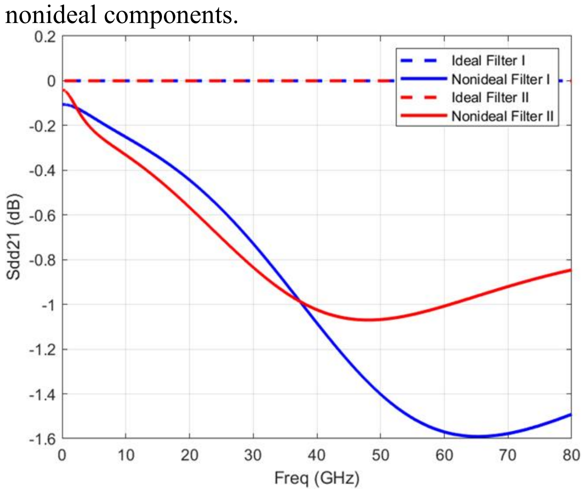

Figure 4. The DM transmission coefficient simulation results of filter I and filter II with ideal components and nonideal components.

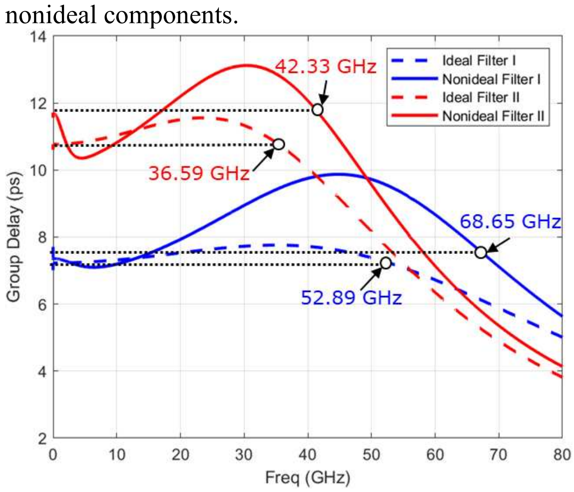

Figure 5. The DM group delay response of filter I and filter II with ideal components and nonideal components.

4. Whole System Simulation

The filter is proposed between the pads and the driver output to suppress the CM noise and achieve impedance matching of the on-chip circuit and off-chip transmission line simultaneously. Eye diagram is used to evaluate the integrity of the DM signal. The spectrum of CM output presents the suppression effect of the CM noise by the filter.

Simulation results of the transmitter with or without FFE and with different filters are shown in Fig. 6-11. Table 1 summarizes the performance of transmitter under different configuration. For the transmitter without FFE, both filter I and filter II can well preserve the DM signal. While for the transmitter with FFE, filter II distorts the DM signal due to the limited frequency range of the constant group delay. However, this situation can be compensated by adjusting the FFE circuit based on the different filters.

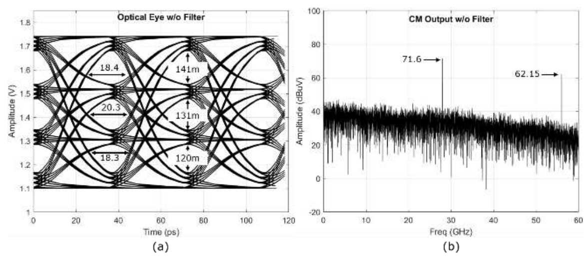

Figure 6. The PAM-4 optical transmitter w/o FFE and filter. (a) Optical output eye diagram. (b) CM noise spectrum.

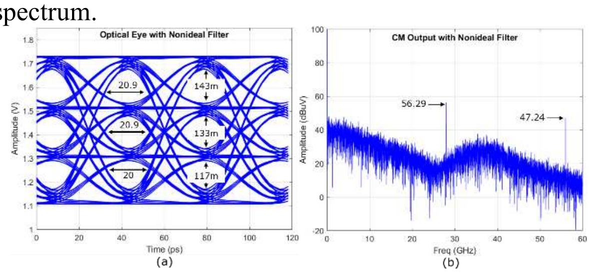

Figure 7. The PAM-4 optical transmitter w/o FFE. (a) Optical output eye diagram with nonideal filter I. (b) CM noise spectrum with nonideal filter I.

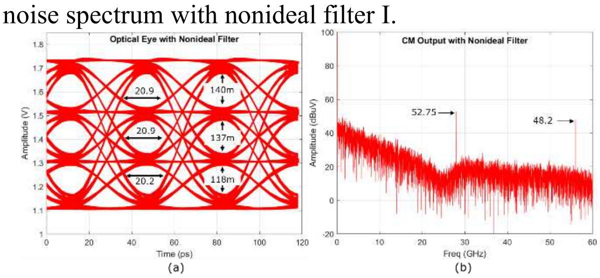

Figure 8. The PAM-4 optical transmitter w/o FFE. (a) Optical output eye diagram with nonideal filter II. (b) CM noise spectrum with nonideal filter II.

Table 1. Summary table of the transmitter under different configuration.

		Without FFE					With FFE				
		w/o Filter	With Filter I		With Filter II		w/o Filter	With Filter I		With Filter II	
			Ideal	40 nm	Ideal	40 nm		Ideal	40 nm	Ideal	40 nm
Optical Output	Eye Width (ps)	19	21.4 (+12.81%)	20.6 (+8.42%)	21.3 (+12.28%)	20.7 (+8.77%)	25.7	25.9 (+0.78%)	25.9 (+0.78%)	25.2 (-2.07%)	25.0 (-2.72%)
	Eye Height (mV)	131	149 (+14.29%)	131 (+0.26%)	156 (+19.13%)	132 (+0.77%)	191	190 (-0.7%)	180 (-5.93%)	168 (-12.04%)	148 (-22.51%)
CM Noise Output	@ 28 GHz (dBuV)	71.6	50.42	59.29	43.34	52.75	72.37	52.04	60.69	50.36	58.35
	@ 56 GHz (dBuV)	62.15	49.24	47.24	54.18	48.2	59.05	54.17	51.68	59.43	52.33

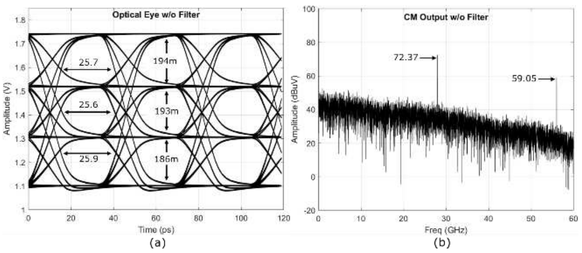

Figure 9. PAM-4 optical transmitter with FFE and filter. (a) Optical output eye diagram. (b) CM noise spectrum.

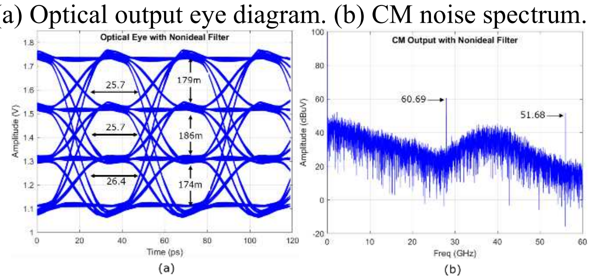

Figure 10. The PAM-4 optical transmitter with FFE. (a) Optical output eye diagram with nonideal filter I. (b) CM noise spectrum with nonideal filter I.

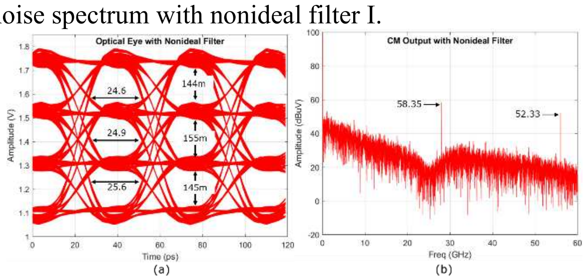

Figure 11. The PAM-4 optical transmitter with FFE. (a) Optical output eye diagram with nonideal filter II. (b) CM noise spectrum with nonideal filter II.

Filter II achieves better CM noise suppression because of the relatively wide suppression frequency range around 28 GHz. Due to the high-frequency port impedance mismatch, the suppression effect at 56 GHz shows less matching with the simulation results of the filter, which makes designing CM resonant around 28 GHz practical.

5. Conclusion

The proposed on-chip filter in this paper can effectively suppresses the CM noise up to 18.85 dB while slightly increase the quality of the DM signal with core area of 207 μm × 125 μm. From the comparison among different filters, filter that provides CM suppression over a frequency range has better performance.

Acknowledgments

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