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Bit error rate analysis of a silicon optical interposer using its equivalent circuit

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Abstract: We analyzed the bit error rate of optical data links in a silicon optical interposer using an equivalent-circuit model. Both optical and electrical signals can be simultaneously simulated in a circuit model where optical signals are expressed as equivalent currents. The modeled silicon optical interposer consisted of a laser diode, an optical modulator, an optical waveguide, and a photodiode. The electrical parameters of the devices were obtained from experimental results. The calculated 12.5-Gbps eye diagram and minimum sensitivity of −5.6 dBm were consistent with the experimental results.

Keywords: silicon optical interposer, silicon photonics, equivalent circuit, bit error rate analysis

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Optical interconnects with silicon photonics technology are expected to be a solution to the inter-chip bandwidth bottleneck problem [1]. We have previously proposed a photonics–electronics convergence system using a silicon optical interposer to improve the bandwidth bottleneck. We demonstrated a high bandwidth-density of more than 10 Tbps/cm^2 in a silicon optical interposer integrated with an arrayed laser diode, optical modulators, photodiodes, and optical waveguides on a single silicon substrate [2, 3]. Furthermore, our optical interposer was verified to be compatible with a high-performance field-programmable gate array (FPGA) [4]. Systematic analysis of our optical interposer and optimization of the total design are significant steps to take in order to enhance link performance.

In this study, we made an equivalent circuit of the silicon optical interposer and extracted electrical parameters from measured device characteristics. Transmission coefficients, eye-diagrams, and the bit error rate (BER) of the optical link were analyzed using an equivalent circuit. In addition, the validity of the calculations as compared with experimental results was discussed [2].

2 Equivalent circuit model of silicon optical interposer

The schematic block diagram of the optical link is shown in Fig. 1(a). The input electrical signals from the driver are pre-emphasized by the differentiator and amplified by an RF amplifier into the silicon optical interposer. The voltage

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amplitude after pre-emphasis is 3.3 V peak to peak. The silicon optical interposer consists of an arrayed laser diode [5, 6, 7], an optical modulator [8, 9], optical waveguides, and a photodiode [10, 11, 12] on a single silicon substrate. The CW light from the laser diode is input into the modulator through the spot size converter. The modulator modulates the input light and the electrical signals are converted to optical signals. The optical signals propagate through the waveguide and are subsequently input into the photodiode and converted to electrical signals. The output electrical signals from the optical interposer are obtained via the amplifier.

The equivalent-circuit model of the silicon optical interposer is shown in Fig. 1(b). In this model, an optical signal is expressed as an equivalent electrical current signal using the equation: $I_{\mathrm{ph}} = eP_{\mathrm{ph}}/\hbar\omega = eP_{\mathrm{ph}}/hf$, in which I_{ph} is equivalent current, P_{ph} is optical power, e is the elementary charge, $\hbar$ is the reduced Planck constant, and ω is the angular frequency of the photon. For example, an optical power $P_{\mathrm{LD}} = 10\,\mathrm{mW} = 10\,\mathrm{dBm}$ corresponds to $I_{\mathrm{LD}} = 12.5\,\mathrm{mA}$ at 1.55 µm wavelength. The laser diode is described using a current-controlled current source where the output current I_{LD} is a function of input current I_{source}. The dissipation current to ground represents coupling loss in the spot size converter that has a transmission efficiency $\eta_{\mathrm{SSC}} = 0.59$ (-2.3 dB) [2]. The parameters of a silicon optical modulator consisting of PIN diodes were taken from Ref. [9]. The optical phase shift is determined by the accumulated charge in the PIN diode capacitance C_{pin}. The capacitance $C_{\mathrm{pin}} = 10.7\,\mathrm{pF}$, and the charge necessary for a π phase shift $Q_\pi = 5\,\mathrm{pC}$ [13]. The series resistance and the diode resistance are expressed as R_{s} and R_{pin}, respectively. The electrical–to–optical (EO) converter in the equivalent circuit expresses the modulation of the input light from the laser diode by the electrical signal from the driver. The behavior of the EO converter depends on the characteristics of the Mach–Zehnder interferometer and its excessive loss as given by the following equation $I_{\mathrm{mod}} = \eta_{\mathrm{mod}} I_{\mathrm{SSC}}\{1 + \sin(\pi C_{\mathrm{pin}} V_{\mathrm{pin}}/Q_\pi)\}/2 \simeq$

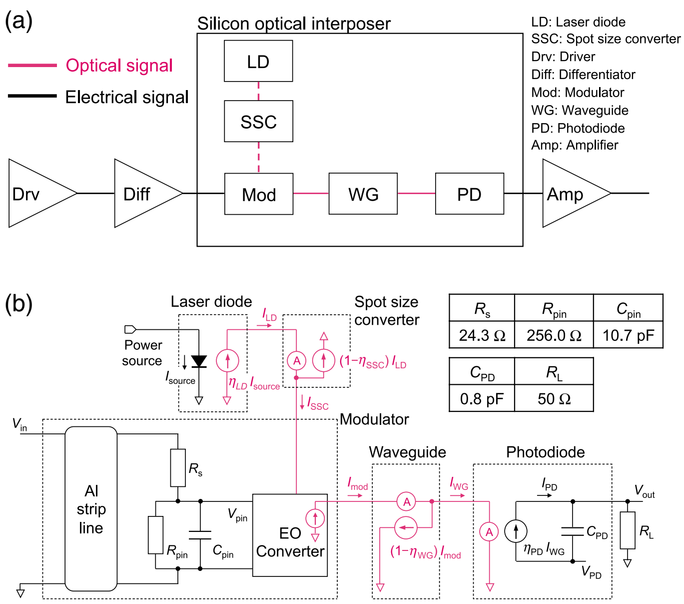

Fig. 1. (a) Schematic block diagram of optical link. (b) Equivalent circuit of silicon optical interposer.

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$\eta_{\mathrm{mod}} I_{\mathrm{SSC}}(1 + \pi C_{\mathrm{pin}} V_{\mathrm{pin}}/Q_{\pi})/2$, in which I_{mod} is modulated equivalent current, $\eta_{\mathrm{mod}} = 0.52$ (−2.8 dB) [2] is optical excessive loss, and V_{pin} is the voltage to diode capacitance C_{pin} [13]. The dissipation current to ground represents propagating loss in the optical waveguide with a transmission efficiency $\eta_{\mathrm{WG}} = 0.60$ (−2.2 dB) [2]. Optical–to–electrical (OE) conversion in the photodiode (PD) is expressed using a current-controlled current source that has a quantum efficiency η_{PD} of 80%. This quantum efficiency corresponds to a responsivity of 1.0 A/W at a wavelength of 1.55 µm. The metal-semiconductor-metal germanium photodiode [10] is expressed as an RC filter with a load resistance $R_{\mathrm{L}} = 50\,\Omega$ and capacitance $C_{\mathrm{PD}} = 0.8$ pF, which includes the carrier drift time and the parasitic capacitance of electrical pads. The photocurrent is input to the RF amplifier with the voltage gain $A_{\mathrm{amp}} = 8.9$ and the input-referred noise $\sigma_{\mathrm{noise}} = 0.33$ mV, which were obtained from measurement results. The output signals from the RF amplifier corresponded to experimentally observed waveforms.

3 Simulation of eye-diagrams and bit error rates in an optical link

We calculated frequency responses of transmission coefficients $s_{21} = V_{\mathrm{out}}/V_{\mathrm{in}}$ of the optical interposer using the equivalent circuit model as shown in Fig. 2(a). The transmission coefficient depends on the input optical power P_{LD}. Since the photocurrent I_{PD} is proportional to the received optical power and the electrical power is proportional to the square of the photocurrent, a 10-dB larger optical power results in 20-dB larger electrical power. The PIN modulator is the main limitation on the bandwidth, but this limit can be compensated by a differentiator with a slope of 20 dB/decade, as shown in Fig. 2(b) [8]. The bandwidth becomes effectively broader by this compensation and high data-rate signals are enabled to transmit.

Fig. 3(a) shows a 12.5-Gbps simulated eye-diagram for 2^7–1 pseudo-random bit sequence (PRBS) signals using the equivalent circuit model. The eye-diagram is similar to the experimental result shown in Fig. 3(b) and the eye openings degrade owing to intersymbol interference (ISI) caused by the RC constants of the modulator and the photodiode. Furthermore, we calculated the BER of the optical links for 12.5-Gbps PRBS 2^7–1 signals, as shown in Fig. 3(c), using the following equation:

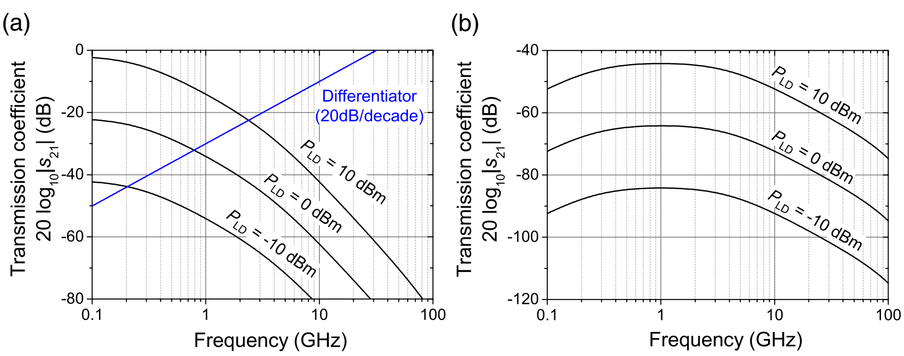

Fig. 2. (a) Simulated transmission coefficients of the silicon optical interposer and differentiator. (b) Compensated transmission coefficients of the optical interposer by a differentiator.

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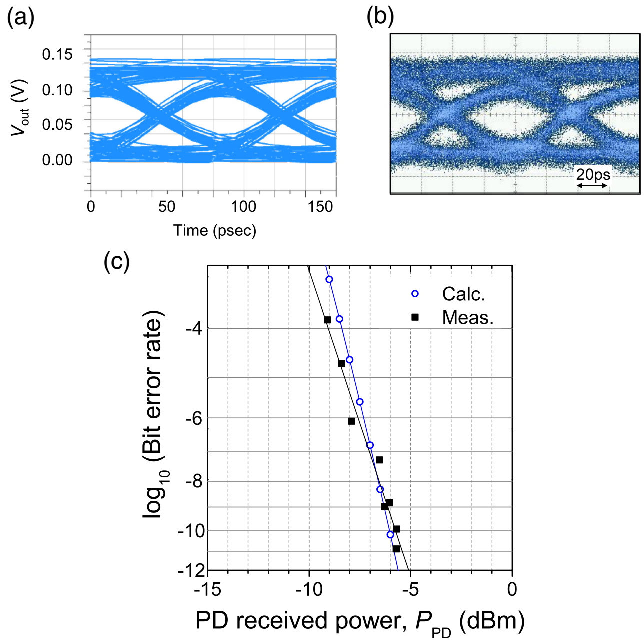

Fig. 3. (a) and (b) Calculated and measured eye-diagrams for the 12.5-Gbps PRBS 2^7–1 signals, respectively. (c) Calculated BER at 12.5 Gbps compared with measurement results.

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{1}{2\sqrt{2}}\frac{V_{eye}}{A_{amp}\sigma_{noise}}\right),$$

where V_{eye} is the simulated eye-height. The simulated BER showed a similar dependency on the PD received optical power to that of the measurement results. The calculated minimum sensitivity of -5.6 dBm was consistent with the measured sensitivity of -5.0 dBm, in which the sensitivity is defined by the BER $= 10^{-12}$. The parameters of the proposed equivalent circuit model were obtained from the experimental results of the discrete devices. These calculations indicated that we could describe the quantitative characteristics of the optical link using an equivalent circuit without any fitting parameters.

We can now discuss ways to improve the link performance of the silicon optical interposer based on the calculation results. The compensation by the differentiator was insufficient at the frequency range lower than 0.5 GHz, but a finite-impulse response filter can broaden the bandwidth to the lower frequency [8]. Faster PDs that have lower capacitance C_{PD} can enhance the transmission coefficients at the high frequency range as shown in Fig. 4(a). A clearer eye-opening can be obtained with lower capacitance $C_{PD} = 0.2$ pF, resulting in a 2.5-dB sensitivity improvement compared with $C_{PD} = 0.8$ pF, as shown in Figs. 4(b) and 4(c). Actually, optical links with more than 20-Gbps [3, 4] were demonstrated using PIN-type germanium PDs with bandwidths of 45 GHz [11]. As discussed above, we can predict and optimize the total performance of the optical link from discrete device characteristics using this simulation technique.

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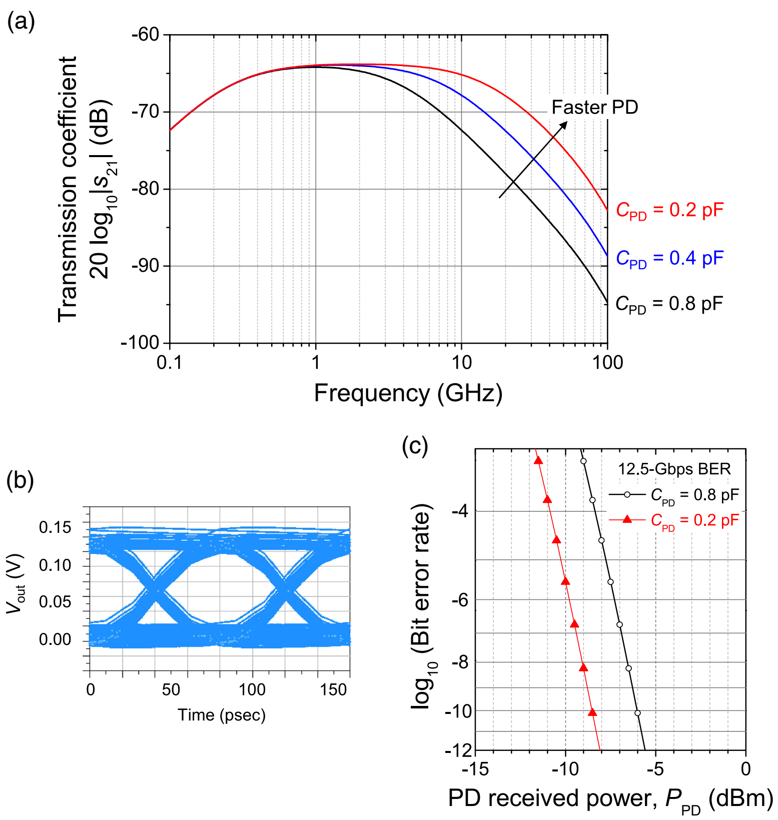

Fig. 4. (a) Calculated transmission coefficients of silicon optical interposer with $C_{PD} = 0.2$ pF, 0.4 pF, and 0.8 pF. (b) Improved 12.5-Gbps eye-diagram with $C_{PD} = 0.2$ pF. (c) Calculated BER at 12.5 Gbps with $C_{PD} = 0.2$ pF and 0.8 pF.

4 Conclusion

We analyzed transmission coefficients, eye-diagrams, and the BER of the optical link using the proposed equivalent-circuit model of the silicon optical interposer. The calculated 12.5-Gbps eye diagram and minimum sensitivity of −5.6 dBm were consistent with the experimental results. The simulation results indicate that a finite-impulse response filter and an improvement of the photodiode, resulting in a decrease in the ISI, can enhance the bandwidth. This analysis method can be applied to other optical-interconnect configurations such as intra/inter-chip interconnects and active optical cables.

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