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Modeling and analysis of optical interconnect systems using equivalent circuit models

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Abstract. SPICE models of optical interconnect systems that include optical devices as well as electrical circuits are implemented and their performance is analyzed using SPICE simulation. The relationships between such system parameters as bit rate and transmitter power dissipation are investigated. [S0091-3286(00)00812-6]

Subject terms: optical interconnect systems; SPICE; equivalent circuit models; laser diode bias level; bit rate; dissipated transmitter power.

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1 Introduction

The increasing requirements for high speed data transfer requires replacement of electrical interconnects with optical interconnects in many applications such as asynchronous transfer mode (ATM) and Gigabit Ethernet.[1–3] In designing such systems, it is very important to be able to estimate the system performance in the design stage. Several methods of analyzing optical interconnect systems have been reported.[4–6] However, these are based on either complicated numerical analyses or dedicated simulators that are not readily available, thus limiting their applicability. We attempt to model the optical interconnect systems including optical devices and electrical circuits using SPICE, a simulator universally used for circuit design. Our approach is motivated from the fact that optical interconnect systems can have more electrical than optical parts and its system performance can be limited by electric circuits rather than optical devices. An optical interconnect model that can be analyzed by SPICE should be very useful for interconnect system designers especially when they try to perform the system optimization for given specifications.

Various equivalent circuit models for such optical devices as laser diodes and photodetectors have been reported and their accuracy has been demonstrated.[7–10] However, the analysis of the entire optical interconnect system based on SPICE has not been reported to the best of our knowledge. In this paper, we present results of such analysis. In particular, we demonstrate the usefulness of our approach by analyzing the relationship between bit error rate (BER) and transmitter power dissipation as functions of transmitter laser diode bias levels and the transmission bit rates. Selecting the proper bias level for the transmitter laser diode is important. If the laser diode is biased below the threshold, timing jitters due to turn-on delay result in system performance degradation.[11] If the laser is biased much above the threshold, the extinction ratio of the transmitted signals decreases and the transmitter power dissipation increases. We show that the optimal bias level can be determined from the SPICE simulation results.

This paper is organized as follows. In Sec. 2, we describe the equivalent circuits for optical devices, and electrical circuits used for constructing a model optical interconnect system. In Sec. 3, we determine the relationship between the dissipated transmitter power and transmission bit rates for different bias levels. Finally, a summary is given in Sec. 4.

2 Optical Device Equivalent Circuits and Electrical Circuits

Figure 1 shows a block diagram of a board-to-board level optical interconnect system investigated in this paper. The system consists of a laser diode, laser driver circuits, fiber, a photodetector, and receiver circuits. For the laser diode equivalent circuit, the single-mode laser rate equations are transformed into the modified forms as suggested in Ref. 7. The resulting equivalent circuit is shown in Fig. 2(a). Fiber is considered as having only the coupling loss[12] of 6 dB. The fiber dispersion is not considered as its influence is negligible for fiber length usually used in short-haul optical interconnect systems. For the equivalent circuit model of

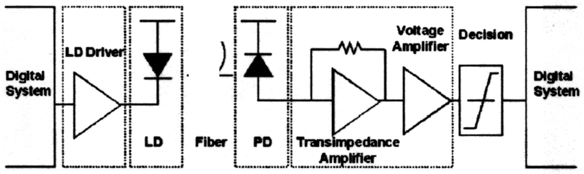

Fig. 1 Block diagram of board-to-board optical interconnection systems.

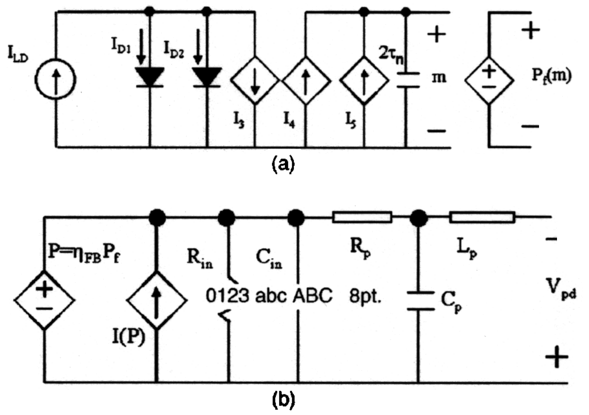

Fig. 2 Equivalent circuit model of optical devices: (a) laser diode and (b) photodetector. The equivalent circuit models of laser diode and photodetector are presented in Refs. 7 and 10, respectively.

photodetector, a model made up of a current source and parasitic elements[10] is used and it is shown in Fig. 2(b). Parameters for the laser diode and the photodetector used for our analysis are obtained from Refs. 7 and 10, respectively, and are shown in Table 1. Note that the equivalent circuits are valid for various types of laser diodes and photodetectors as long as accurate parameter values are supplied.

Electrical circuits required in the optical interconnect systems include a laser driver for the transmitter and transimpedance and voltage amplifiers for the receiver. These circuits are designed with 0.6 μm complementary metal oxide semiconductor (CMOS) technology parameters. Their schematics are shown in Fig. 3. The laser driver is made up of a current mirror and a differential pair input stage[13] and it converts the voltage input (V_{in}) to the current (I_{LD}) passing through the laser diode (LD). The transimpedance amplifier converts the photogenerated currents into voltages, which are further amplified by the voltage amplifier. We use a common-gate type transimpedance amplifier, which improves the 3 dB bandwidth by isolating the input capacitance from the feedback resistor.[14] The voltage amplifier consists of a conventional differential amplifier and a level shifting source follower. The differential input stage of the receiver reduces the noise induced from power supply fluctuations and process-dependent deviations. For simplicity in analysis, we did not include automatic offset control and automatic gain control circuits. To achieve the optimal performance, the receiver circuits are optimized for a given transmission bit rate. For 1 Gbps operation, the transimpedance amplifier is designed so that its 3 dB bandwidth is 775 MHz and transimpedance gain is about 60 dBΩs. Figures 4(a), 4(b) and 4(c) show the frequency responses of laser driver current output (I_{LD}), laser output power (P_f), and receiver output voltage (V_{outp}) for 1 Gbps operation, respectively. It is evident that the designed circuits are sufficient for 1 Gbps operation. Figure 5 shows an example of SPICE simulation results for pseudorandom NRZ input signal of 2^7-1 at 1 Gbps. Figure 5(a) is the output of the laser driver, Fig. 5(b) is the optical output power (P_f), Fig. 5(c) is the photogenerated currents at the photodetector (I_{pd}) and Fig. 5(d) the receiver output voltage (V_{outp}). For our analysis, the total receiver input capacitance is assumed[15] to be 0.5 pF.

Table 1 The major parameters of laser diode and photodetector used in this paper are extracted from Refs. 7 and 10, respectively.

Devices	Parameters	Description	Value	Units
Laser diode	λ_0	Lasing wavelength		cm
	Γ	Optical confinement factor		—
	β	Spontaneous emission coupling factor		—
	g_0	Optical gain coefficient		$s^{-1}\,cm^3$
	N_0	Carrier density at material transparency		cm^{-3}
	τ_n	Carrier lifetime		s
	τ_p	Photon lifetime		s
	η	Differential quantum efficiency		—
	N_e	The zero bias, thermal equilibrium concentration of carriers		cm^{-3}
Photo detector	R	Responsivity	0.264	A/W
	V_{FB}	Flatband voltage	0.68	V
	A	Fitting factor used in Eqs. (9) and (10) of Ref. 10	0.534	A
	B	Fitting factor used in Eqs. (9) and (10) of Ref. 10	3.19	V

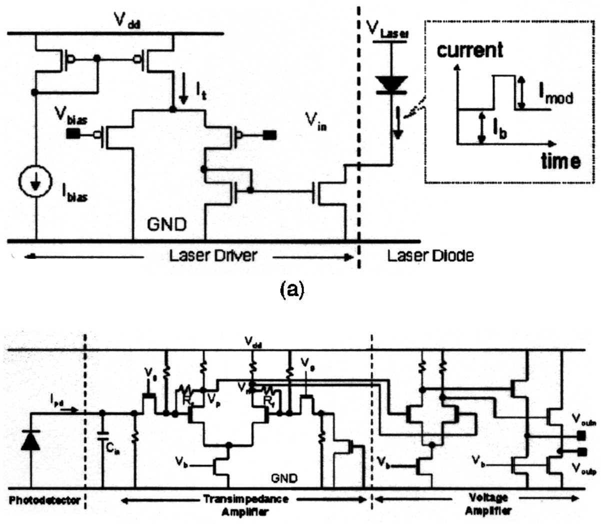

Fig. 3 Circuit schematic diagrams of (a) laser driver for transmitter and (b) transimpedance amplifier and voltage amplifier for receiver. The laser driver circuit is presented in Ref. 13.

3 BER Analysis

For the optical interconnection system performance evaluation, the BER analysis are performed. SPICE simulations are first carried out for the entire optical interconnection systems. From the simulation results, the eye diagrams are obtained for the receiver output. For the BER calculation, the receiver noise is assumed dominated by the thermal noises at the feedback and load resistors of the receiver circuit. The decision point is set for the point where the variance of crossover time is minimal, and the decision time is set at half a bit period away from the average crossover time.[6] With this, the BER can be expressed as[16]

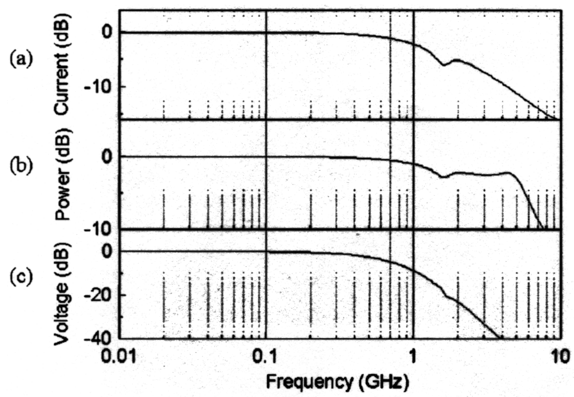

Fig. 4 Simulation result of frequency response for (a) laser driver output current (I_{mod},I_b), (b) laser output power (P_f), and (c) receiver output voltage (V_{outp}).

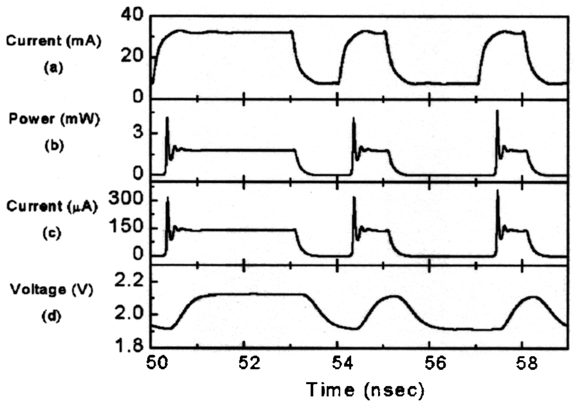

Fig. 5 SPICE simulation results when biased below threshold current.

$$P_e(t_0,y_0)=\frac{1}{N}\sum_{j=1}^{N/2}\left\{V\left[\frac{v_{1j}(t_0)-y_0V_0-V_{\mathrm{sen}}}{\sigma_{1j}}\right]+V\left[\frac{y_0V_0-v_{0j}(t_0)-V_{\mathrm{sen}}}{\sigma_{0j}}\right]\right\} \tag{1}$$

where V_0 is the nominal peak voltage, y_0V_0 is the threshold voltage, and

$$V(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp(-z^2/2)\,dz. \tag{2}$$

The total noise current value and decision sensitivity V_{sen} are obtained from Ref. 17. In the preceding equations, σ_{1j} and σ_{0j} are the noise voltages made by the total noise current multiplied by the receiver's transimpedance gain. BER is numerically calculated using SPICE simulated output voltages of the receiver and the noise voltages.

The transmitter power dissipation is assumed to be dominated by currents passing through the laser diode and is estimated with $0.5\times V_{\mathrm{laser}}(2I_m+I_b)$, where V_{laser} is the supply voltage directly connected to the laser diode, I_m is the modulation current and I_b is the bias current. Figure 6 shows the eye diagrams for the receiver output voltages for two schemes of biasing the transmitter laser diode: Fig. 6(a) below and Fig. 6(b) above the threshold. It is clear that timing jitter occurs more seriously when the laser diode is biased below the threshold. The reason is that data-dependent effects of laser turn-on delay occur when biased below the threshold. The turn-on delay is influenced by the stochastic nature of spontaneous emission,[18] but this effect is not considered in our analysis.

The relationship between BER and transmitter power dissipation is determined for bit rates of 1.0, 0.5, and 0.25 Gbps at three different bias levels as shown in Figs. 7(a), 7(b) and 7(c). For this calculation, the 3 dB bandwidth of the transimpedance amplifier is designed to have about 75% of each bit rate. Figure 8 shows the transmitter power required to achieve BER of 10^{-17} as function of transmission bit rates for three different transmitter laser bias levels; above the threshold ($I_{\mathrm{bias}}=1.1I_{\mathrm{th}}$), slightly below the

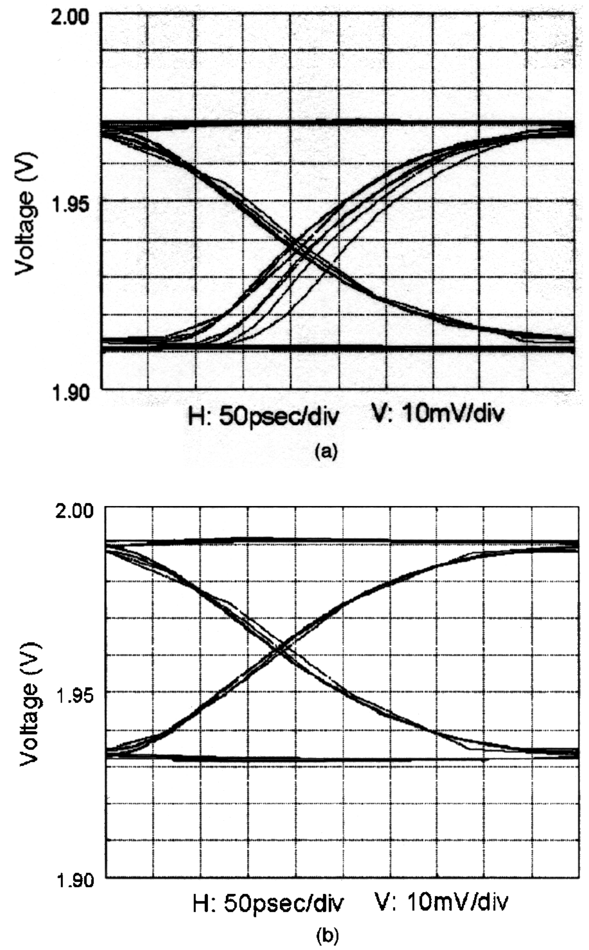

Fig. 6 Eye diagrams of output voltage of receiver (a) when biased below threshold current and (b) when biased above threshold current.

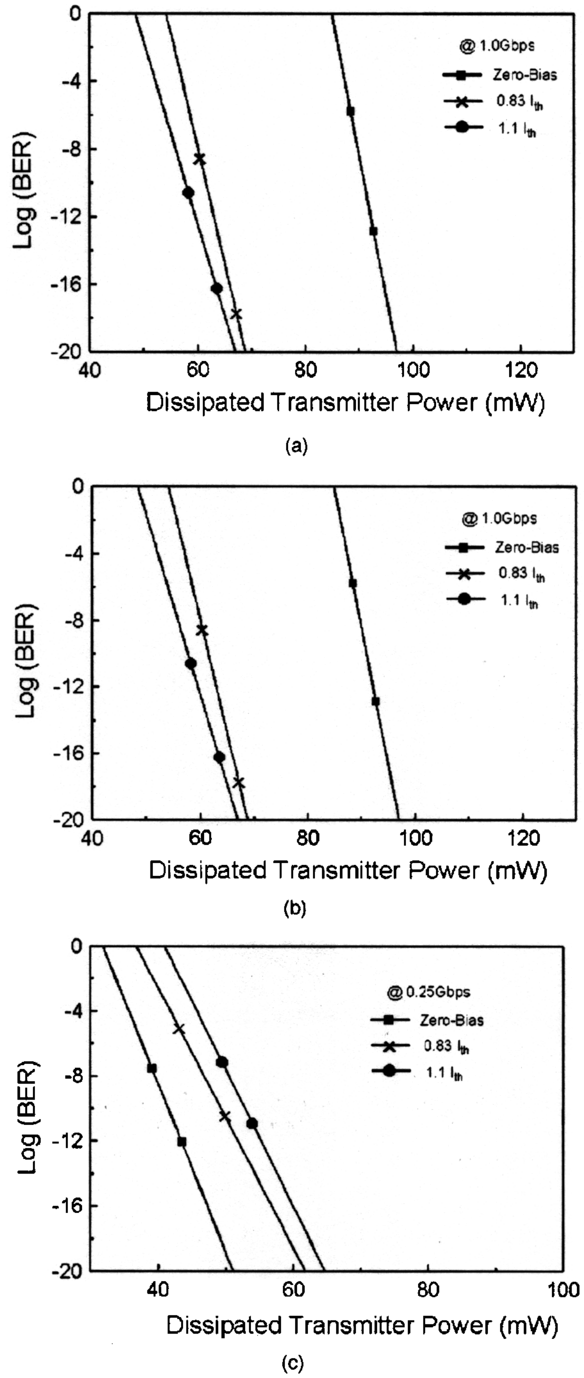

Fig. 7 Relationship between BER and minimum dissipated transmitter power for (a) 1 Gbps, (b) 0.5 Gbps and (c) 0.25 Gbps.

threshold ($I_{bias}=0.83I_{th}$), and zero bias. At 0.25 Gbps, lowering the bias level results in reduced transmitter power dissipation as expected. This is not the case, however, for higher speed operation. At 1 Gbps, the zero-bias scheme requires much more transmitter power than other bias schemes. This is because the timing-jitter due to laser turn-on delay becomes very pronounced at the high-speed operation and, consequently, the eye diagram has smaller opening. In short, lowering the bias level below the laser threshold has an advantage in power consumption only if the bit rate is not too high. Although our investigation was done for a particular set of optical devices and electric circuits, a similar analysis can be done for any optical interconnect systems with the identical configuration so that the optical transmitter bias level can be determined.

4 Summary

With equivalent circuit models of optical devices and SPICE simulation based on them, we attempted to model and optimize the optical interconnection systems including optical devices and electrical circuits. As an example for usefulness of our approach, we determined the relationship between transmitter power dissipation and the transmission bit rates for different bias levels and identified the optimal bias condition. We believe our approach can be useful in modeling and optimizing optical interconnect systems, especially when they contains many complex electrical circuits.

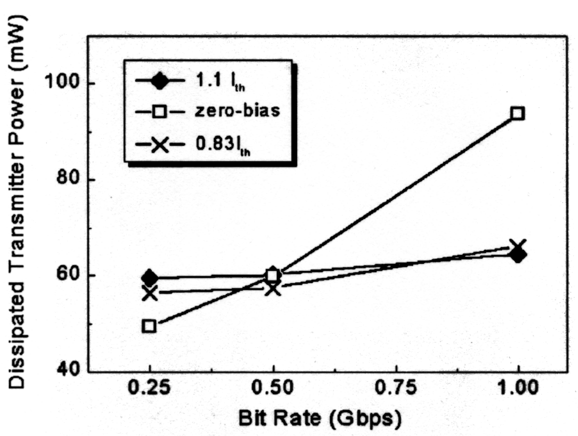

Fig. 8 Relationship between bit rate and minimum dissipated transmitter power for BER$=10^{-17}$.

Acknowledgment

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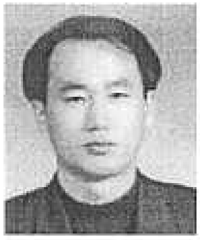

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