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Electrical and Optical Characteristic Modeling of Silicon Modulator

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1. Introduction

Optical interconnection with Si photonics is a promising candidate for dealing with bandwidth bottleneck in LSI chips because of the intrinsic properties of optical signals, including wide bandwidth, low latency, low power consumption, and low mutual interference. We previously proposed a photonics-electronics convergence system in which light sources, optical modulators, and photodetectors are linked by optical waveguides on a Si substrate [1]. We aim for high density transmission of over 10 Tbps/cm^2.

To operate at over 10 Tbps/cm^2, high speed operation faster than 10 Gbps per 1 ch. is required, and advanced features for the Si optical modulator and driver circuit are indispensable. Moreover, to maximize the link performance of the convergence system, simulating transceiver characteristics is significant. In this paper, we modeled the phase shifter in the p-i-n diode by making an equivalent circuit for the Si optical modulator and formulizing optical characteristics.

2. Modeling of Phase Shifter

Figure 1 shows a schematic view and an equivalent circuit of the Mach-Zehnder modulator (MZM)[2] which is formed of silicon based waveguides on a silicon on insulator substrate. Each of the two arms of the MZM has a 250-μm-long phase shifter which consists of a p-i-n diode and Al stripe lines.

We deal with a distributed constant model for the p-i-n diode with Al stripe lines. From S-parameter measurements, we estimated 43 (72) pF/mm as the value of the capacitance of the phase shifter C_{pin} in Fig. 1 at a bias voltage of 0.85 (0.90) V.

Figure 2(a) shows measured and calculated optical frequency responses with a forward bias voltage of 0.90 V. Calculated optical frequency responses could be estimated from the voltage applied to the capacitance C_{pin} in the p-i-n diode. High coincidence was checked up to 10 GHz between the measured and the calculated values, and then the usefulness of the equivalent circuit model had been proved also in the frequency domain. Fig. 2(a) also shows a frequency response for a finite impulse response (FIR) digital filter which consists of a broadband divider, half-bit delay, and multiplier and combiner (see Fig. 2(b)). A pre-emphasis signal through the FIR filter was used to obtain a flat response in the entire frequency domain [3, 4].

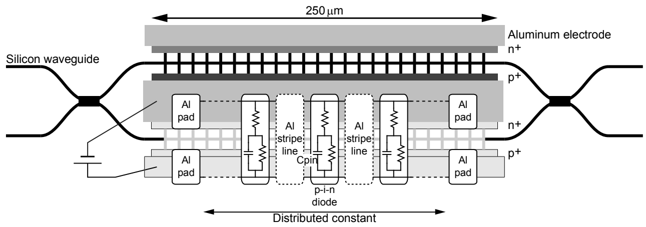

Fig. 1 Schematic top view of fabricated silicon MZM.

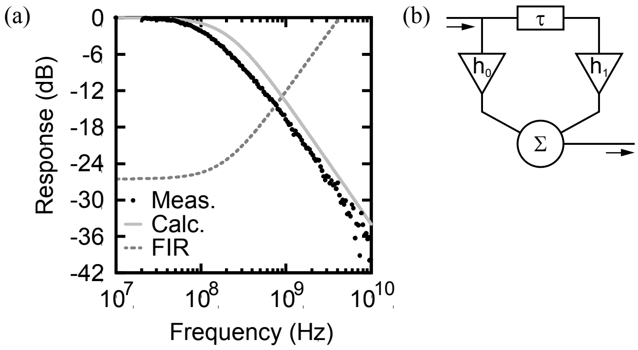

Fig. 2 (a) Measured and calculated optical frequency responses with a forward bias voltage of 0.90 V. The black dots are the measured response of the modulator. The gray solid line is the calculated response of the modulator. We also show a calculated response of a FIR digital filter as the gray dased line. (b) Block diagram of the filter.

3. Simulation of Optical Waveform

First, we tried to simulate a large signal modulation. From the DC bias dependence of the optical power, we derived 8 rad/V as the phase change at a bias voltage of 0.85 V. By using an equivalent circuit, the relation between injected electric charges ΔQ and phase change $\Delta\phi$ is expressed as:

$$\frac{\Delta\phi}{\Delta Q} = 0.8[\mathrm{rad/pC}]. \qquad (1)$$

Here we note that injected 4 pC charge can induce π-phase shift. Fig. 3(a) shows optical eye pattern from the MZM at 12.5 Gbps. Two driving signals with 2.37 V_{pp} were used to operate in a push-pull configuration. A forward DC bias voltage of 0.85 V was applied to the diode of the two arms of the MZM. The equivalent circuit and eq. (1) can well simulate the eye pattern under the same condition (see Fig. 3(b)).

Next, we estimated code dependence of the output signal by using our simulation scheme as shown in Fig. 4. The optical waveforms were simulated by using the values of the FIR filter for a pseudorandom binary sequence (PRBS) of 2^7-1 and 2^{31}-1 with and without the 8B10B code [5]. We chose a bit-by-bit simulation for a PRBS of 2^7-1 and a statistical mode for a PRBS of 2^{31}-1. As the number of bits increased to infinity, the two channel simulation modes gave identical results [6, 7]. As a result, for a PRBS of 2^{31}-1, the optical waveform was sensitive to a pre-emphasis signal amplitude ratio. In particular, the optical waveform for h_1 = -0.98 was used to observe the difference between the cases with and without the 8B10B code for a PRBS of 2^{31}-1. In this way, we could obtain a clear eye opening by using the 8B10B code.

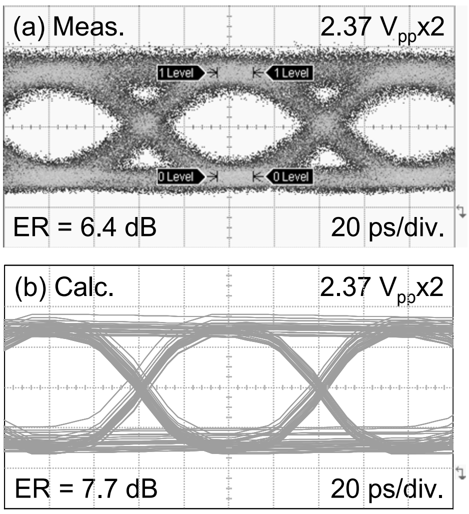

Fig. 3 Optical eye-patterns at 12.5 Gbps with a forward bias voltage of 0.85 V (h_0 = 1, h_1 = -0.98, τ = 40ps, PRBS of 2^7-1). (a) a measured result. (b) a simulation result.

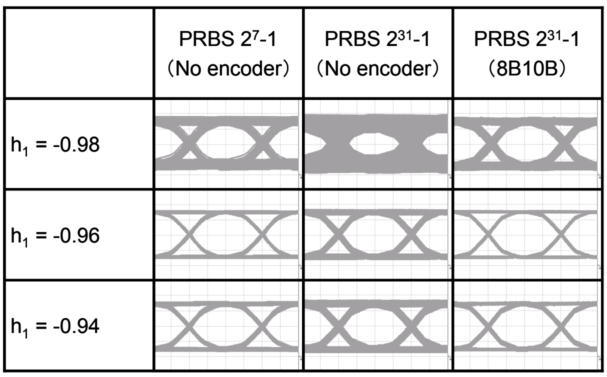

Fig. 4 Optical waveforms of the values of the FIR filter for PRBSs of 2^7-1 and 2^{31}-1, which were simulated to observe the difference between cases with and without the 8B10B code.

4. Conclusions

We investigated the optical modulation characteristic in the silicon MZM. We modeled the phase shifter from S-parameter measurements and the DC bias dependence of the optical power. It became clear that the calculation result of the model reproduced comparatively well the optical modulation characteristic actual to the high frequency domain of 10 GHz. We also demonstrated a large signal modulation simulation by using pre-emphasis processing and obtained a correlation between the measured and calculated optical waveforms in this equivalent circuit model.

It also became possible to carry out a simulation of the quantitative difference of the optical waveforms with a FIR filter for a PRBS of 2^{31}-1 simulated with and without the 8B10B code. As a result, for a PRBS of 2^{31}-1, it turned out that the optical waveform was sensitive to a pre-emphasis signal amplitude ratio. However, it became clear that a clear eye opening was obtained by using the 8B10B code currently used widely.

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