Fast Dynamic-Response Measurement Technique for Electrooptic Devices Based on Modified Optical Sampling

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Abstract—**A fast dynamic-response measurement technique for electrooptic modulators is proposed that employs modified optical sampling. Using a gain-switched laser-diode pulse as a strobe, random modulation characteristics including eye-diagrams of wide-band $LiNbO_3$ modulators were clearly measured with a resolution of about 20 ps. The developed method is proven to have high temporal-resolution, and the limitation of signal-to-noise ratio experienced by the conventional direct detection method is not encountered.**

Introduction

Electrooptic (EO) devices such as optical modulators are one of the key devices for developing high-speed optical transmission systems. Although wide-band $LiNbO_3$ modulators (20 GHz bandwidth) have been reported [1], their dynamic properties relative to error-rate performance are not always satisfactory owing to the pattern effects that frequently occur in random modulation signals. This implies that frequency-domain (FD) measurement itself is insufficient in evaluating the fluctuations in modulated waveforms or eye-diagrams when the optical modulators are applied in actual use. To correctly evaluate such EO devices, time-domain (TD) measurement is essential because it can analyze the real-time waveforms and also can optimize the electrical drive conditions.

So far, the conventional TD method, using a fast optical-to-electrical (O/E) converter such as a p-i-n detector followed by a wide-band preamplifier, suffers from bandwidth limitations and nonuniformity of frequency response characteristics. This prevents wideband modulators from being measured in the time domain. Moreover, both thermal and shot-noises place an upper limit on the signal-to-noise-ratio (S/N) even if sufficiently fast O/E converters could be applied. In this letter, we propose a new measurement technique for EO devices based on modified optical sampling [2], [3], which solves the above problems.

Principle of Measurement

In the conventional TD method, CW light is modulated by an optical modulator. After converting the modulated optical signals into electrical signals with a fast O/E converter, the electrical signal waveforms are measured by a sampling oscilloscope. The bandwidth limitations and S/N degradation caused by the O/E conversion are inevitable.

On the other hand, in the proposed optical sampling method, an ultrashort optical pulse train with a low repetition frequency

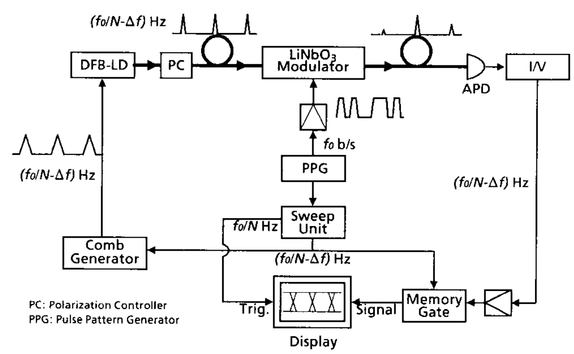

Fig. 1. Proposed dynamic response measurement system.

is used as a probe signal. When the pulse train is coupled to the modulator, output amplitude of each optical pulse from the modulator is varied according to the instantaneous transmittance of the modulator. Therefore, the optical output pulse energy corresponds to the sampled signal of the temporal waveform of the modulator with the resolution of the optical pulse width used. Because the sampling process is executed only within the optical domain and a relatively slow O/E converter can be applied, the proposed method is inherently free from the bandwidth limitation and the S/N degradation.

Fig. 1 shows the proposed experimental setup for measuring the temporal response of external modulators. A $LiNbO_3$ intensity modulator with a Mach–Zehnder interferometer structure was used. Its bandwidth and half-wave switching voltage are 10 GHz and 4 V, respectively. The modulator is driven by a f_0-b/s (= 5–7 Gb/s) pseudorandom pulse pattern generated from a pulse pattern generator (PPG) followed by a power amplifier. An electrical f_0-Hz clock signal from the PPG is connected to a commercial sweep unit, Tektronix 7T11, used in a sampling oscilloscope, which generates a count-down signal of (f_0/N)-Hz for synchronization and a strobe pulse train of $(f_0/N - \Delta f)$-Hz for a sampling signal. Here, N is a large integer and the sampling frequency of $(f_0/N - \Delta f)$-Hz can be as low as 30 kHz. The electrical strobe pulse train is fed to a distributed-feedback laser diode (DFB-LD) through a comb generator to obtain short, intense optical strobe pulses with a 20 ps duration and a 14 mW peak output.

These optical strobe pulses are then coupled to a polarization controller (PC) so that polarization direction can be optimized. The optical pulses output by the EO device being tested are converted into electrical signals by an O/E converter consisting

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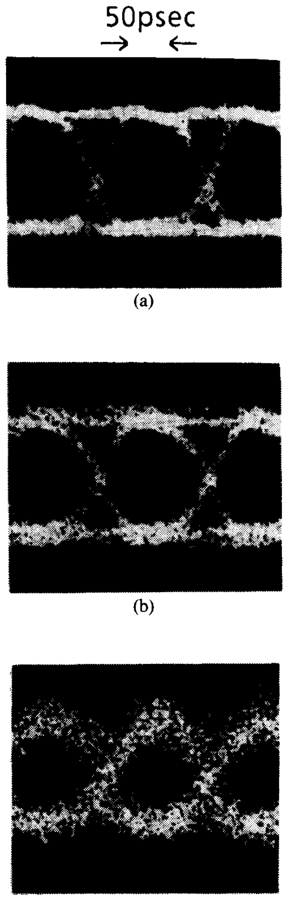

Fig. 2. Measured eye-diagram at 7 Gb/s modulation. (a) Electrical driving signals. (b) The proposed optical sampling method. (c) The conventional method.

of an InGaAs APD, a current/voltage converter and a voltage amplifier. Bandwidth of the converter is selected to be 200 kHz wider then the sampling frequency of $(f_0/N - \Delta f)$-Hz. After gating, holding, and memorizing the electrical signals with a memory-gate circuit, the signals are fed into a display triggered with the count-down signal of f_0/N Hz. The frequency difference Δf between the trigger and sampling frequencies makes it possible to automatically scan the sampling timing with respect to the measured waveform.

It is noted that averaging techniques, widely used for improving the measured S/N, cannot be applied for the measurement of randomly modulated signals, but only for the measurement of the repetitive pulse signals. Therefore, each sampled signal itself must have a sufficiently large S/N to allow the clear analysis of its eye-diagram as discussed later.

Result and Discussions

Fig. 2(a)-(c) show the experimental results. Fig. 2(a) is the 7 Gb/s electrical driving signal with a peak-to-peak output voltage of 6 V. Fig. 2(b) and (c) compare the measured 7 Gb/s eye-diagrams using the proposed optical sampling method and the conventional method using 0.2 mW averaged output light detected with the fastest commercially available O/E converter with a 10 GHz bandwidth and an equivalent input noise current of 30 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$. As you can see, the conventional method [Fig. 2(c)] fails to resolve the pattern effects in the modulated signal due to poor S/N which mainly originates from the thermal noise and bandwidth limitations of the O/E converter used. On the other hand, the proposed method successfully reveals the fine structure of the eye-diagram with high resolution and high S/N. Line broadening of "1" and "0" traces is attributed to the pattern effect of the modulated signal. Also, rise and fall time and waveform distortion are clearly seen from the eye-diagram.

Here, let us consider the relationship between temporal resolution and S/N value for the proposed TD measurement technique. For the conventional method using a fast O/E converter, S/N value is determined by the following equation:

$$S/N = i_{\mathrm{sig}}^2/(2ei_{\mathrm{sig}} + i_{\mathrm{th}}^2)B. \qquad (1)$$

Here, i_{sig} is the signal photocurrent proportional to optical output power, e is a unit charge, i_{th} is the equivalent input noise current density of the preamplifier, and B is the bandwidth which is inversely proportional to temporal resolution. The first and second terms in parenthesis represent the optical shot noise ($\propto i_{\mathrm{sig}}$) and the thermal noise ($\propto i_{\mathrm{th}}^2$), respectively, and both are proportional to bandwidth B. For high-speed O/E converters, the thermal noise is dominant since i_{th} is as large as 15 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$ and i_{sig} is limited to less than 1 mA. Consequently, the S/N value obtainable from the conventional method is mainly limited by the thermal noise and proportionally degrades as temporal resolution is improved. This limits the resolution to around 100 ps at most.

On the other hand, in the proposed sampling method, temporal resolution does not depend on the bandwidth of the O/E converter, but is determined by the duration of the optical sampling pulse used. By reducing the bandwidth down to the sampling frequency, S/N can be improved without degrading temporal resolution. Assuming that the pulse energy of the optical pulse is large enough relative to the thermal noise, the maximum obtainable S/N value approaches the optical shot noise limit expressed by the number of photons (n) within one optical pulse. Therefore the S/N value is determined by one optical pulse energy, independent of the temporal resolution.

In order to make the eye-diagram measurement, large S/N values are necessary by the following reason. Required S/N for ordinal binary digital signal transmissions is as low as 10 dB for the error rate of 5×10^{-2}. But this is the case for decision of only two levels of "1" and "0." To correctly measure the pulse waveform, analog values, in other words, multilevels corresponding to each sampled level must be determined. For example, assuming that 100 different levels are measured, the signal amplitude required is 100 times higher than that of the binary digital signal. Consequently the required S/N is increased to (10 + 40) dB. In the present experiment, an optical pulse with an energy of 0.3 pJ corresponding to 2×10^6 photons is obtained. Therefore the S/N value of more than 50 dB, sufficient for the eye-diagram evaluation, has been achieved in the present measurement technique.

Conclusion

A dynamic-response measurement technique with high temporal-resolution and good S/N characteristics has been developed for the evaluation of EO modulators using modified optical sampling. By applying gain-switched DFB-LD pulses as optical strobe signals, random modulation characteristics including eye-diagrams of high-speed $LiNbO_3$ modulators have been successfully measured with a resolution of about 20 ps. This technique can be applied to the evaluation of other optical devices controlled by electrical signals such as $LiNbO_3$ matrix switches, and semiconductor laser amplifier switches.

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