166 Gb/s PDM-NRZ-DPSK modulation using thin-$LiNbO_3$-substrate modulator

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Abstract: The modulation of a 166-Gb/s PDM-NRZ-DPSK signal is demonstrated using a thin-$LiNbO_3$-substrate modulator. The use of a 0.1-mm-thick substrate and a ridge-type waveguide improves the optical response and brings about a reduction in Vπ.

OCIS codes: (060.5060) Phase modulation; (230.4110) Modulators

1. Introduction

For high-speed transmission link, optical communication uses a combination of time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) technologies to optimize the transmission capacity. In particular, optical TDM- (OTDM-) transmission experiments were performed with a high-speed data signal of greater than Tb/s [1, 2]. This multiplexing technique is, however, complicated due to a usage of a large number of optical multiplexers with slower modulators. Moreover, because a bandwidth of an optical spectrum of the OTDM signal is much broader than that of the WDM signal, dense WDM (DWDM) technique was not applicable for huge-capacity transmission. On the other hand, WDM transmission experiments were performed with phaseshift-keying (PSK)-based multilevel modulation such as differential quadrature phase-shift keying and quadrature amplitude modulation [3, 4]. This modulation technique was also complicated, but the narrower optical bandwidth helped realize the DWDM transmission. A higher-speed modulation based on the WDM technology with a simple modulation scheme, such as a binary coding, was strongly desired. However, in a conventional lithium niobate ($LiNbO_3$, LN) modulator, there are some problems pertaining to the optical frequency response and the half-wave voltage Vπ. In particular, at frequencies above 40 GHz, propagation loss in the modulator electrodes causes the degradation of the optical signal quality. This problem can be solved by using a thin-LN-substrate modulator. The use of such a substrate facilitates the generation of a high-sumbol-rate non-return-to-zero- (NRZ-) on-off keying (OOK) and differential PSK (DPSK) signal [5, 6].

In this study, we demonstrated high-speed NRZ-DPSK modulation using an electrical TDM (ETDM) technique and an LN modulator with a thin LN substrate having a thickness of 0.1 mm. The electrooptic (E/O) frequency response of this modulator was better than that of the conventional modulator. In addition, a low Vπ resulting from the use of a ridge-type optical waveguide allowed high-speed drivers, which had a low output power, to be employed. The generation of a 166 Gb/s polarization division multiplexing- (PDM-) NRZ-DPSK signal, which symbol rate was achieved to be 83 Gbaud, with a bit error rate of the order of 10^{-9} was demonstrated.

2. High-speed modulator with low Vπ

The use of a modulator with a high optical bandwidth and a low operation voltage are desirable for achieving modulation at a high symbol-rate. For increasing the 3 dB bandwidth of the modulator, we propose the use of a thin LN substrate. At operation frequencies greater than 10 GHz, an increase in the propagation loss, especially the radiative loss due to substrate-mode coupling, in the electrodes plays a significant role in the degradation of the electric signal quality. The mode coupling between the signal propagating in the electrodes and the substrate drastically increases the propagation loss at the resonant frequency. This frequency is inversely proportional to the substrate thickness [7]. Thus, using a thin LN substrate can help improve the optical frequency response. Figure 1 (a) shows the E/O frequency response for various substrate thicknesses. The response of the 0.1-mm-thick substrate is flatter than that of a 1.0-mm-thick substrate, which is used in conventional modulators. Thus, the use of the thin LN substrate improved the optical

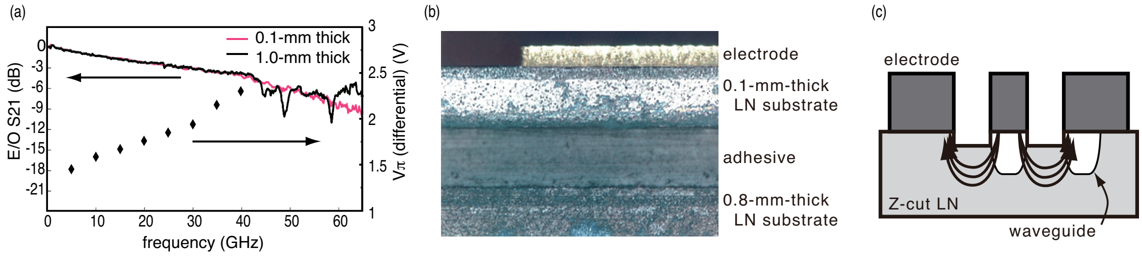

Fig. 1. (a) Electrooptical frequency response of the modulator for substrate thickness of 0.1 mm and 1.0mm, and the frequency dependence of Vπ for the substrate thickness of 0.1 mm. (b) Cross-sectional image of the modulator and (c) a schematic of the ridge-type waveguide with a Z-cut LN substrate.

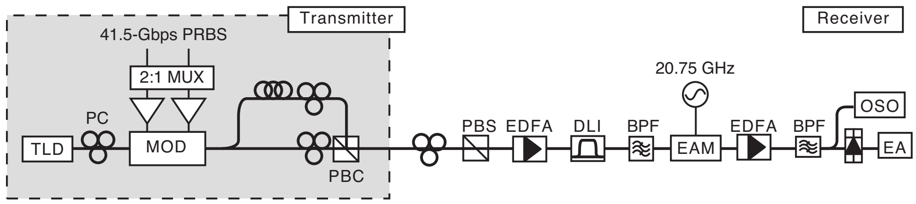

Fig. 2. Experimental setup.

frequency response of the modulator. Handling the thin LN substrate is, however, difficult due to its thickness. We fabricated a modulator with a reinforced structure (Fig. 1 (b)). The 0.1-mm-thick substrate was bonded to a 0.8-mm-thick LN substrate using a low-dielectric-constant adhesive. The total thickness of the substrates was close to 1 mm, i.e., almost equal to that for conventional modulators.

On the other hand, the reduction in Vπ was accomplished by the fabrication of a ridge-type waveguide with a Z-cut LN substrate. The use of the Z-cut LN substrate resulted in the deposition of the electrodes onto the waveguide (Fig. 1 (c)). The electric field of an incident electric signal is confined to the interior to the waveguide because of the ridge structure. Therefore, the effective applied voltage is lower than that for conventional modulators, that is, Vπ is decreased. The measured Vπ of the modulator was 1.9 V at a frequency of 25 GHz (Fig. 1). This value was about 70 % of the conventional value (2.5 V). The optical insertion loss increased due to the ridge structure and was minimized by optimizing the width and height of the ridge structure.

3. Experimental setup and demonstration

Figure 2 shows an experimental setup; the experiment involves the use of optical demultiplexing technique with an electro-absorption modulator (EAM) for demultiplexing. The setup is based on a well-known conventional configuration for NRZ-DPSK modulation. A 41.5 Gb/s pseudo-random bit stream (PRBS) with a length of 2^7-1 bits was generated by a pulse pattern generator (PPG). The output signals were fed to a two-to-one multiplexer (2:1 MUX) to generate signals at twice the frequency of the incident signal. The multiplexed signals with a length of 2^8-2 bits were fed to the thin-LN-substrate modulator through broadband power amplifiers.

A tunable laser diode (TLD) operated at a wavelength of 1550 nm was used as the light source. The polarization controller (PC) maintained the polarization of the lightwave fed to the modulator. The output optical signal from the modulator was split into two components by an optical splitter. The polarization of these components was controlled to be along the x and y axes, and the components were then fed to a polarization beam combiner (PBC) for PDM. The difference in the distance traveled by the x and y components was 20 m. At the receiver end, an incident optical signal was fed to the PC and to a polarization beam splitter (PBS) functioning as a polarizer for polarization division demultiplexing. The demultiplexed signal was boosted by an Er-doped fiber amplifier (EDFA) with an output power of 15 dBm. A variable delay line interferometer (DLI) was introduced to perform demodulation. The EAM was used for OTDM demultiplexing and was operated at a frequency of 20.75 GHz, which was a quarter of the modulation frequency. Thus, the output signal from the EAM was a 20.75 Gb/s return-to-zero (RZ) OOK signal. The optical signal that passed through a bandpass filter (BPF) for reduction of the amplified spontaneous emission was boosted again and was detected by the photodiode. The bit error rate (BER) was analyzed by an error analyzer (EA). The optical sampling oscilloscope (OSO) with a temporal resolution of 1 ps was used to plot eye diagrams.

Figure 3 (a,b) show the demodulated eye diagrams of the 166-Gb/s PDM-NRZ-DPSK modulation signal. The cross

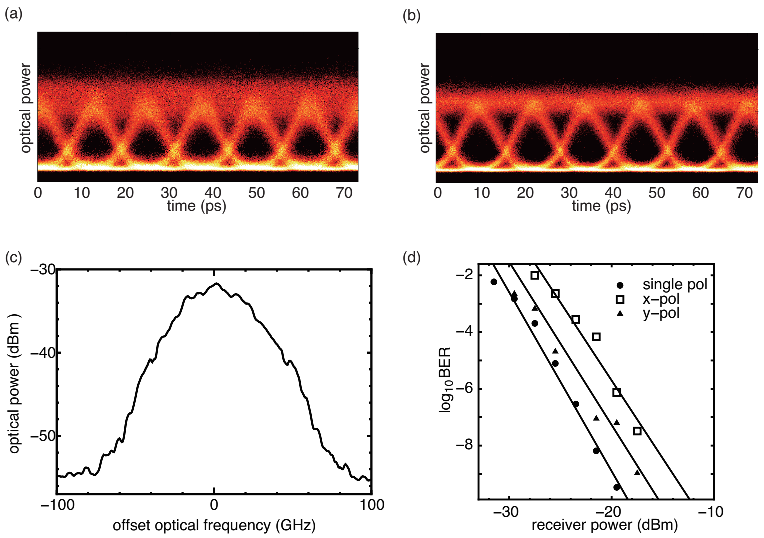

Fig. 3. Demodulated eye diagrams of (a) x- and (b) y-polarization component. (c) The optical spectrum of the PDM-NRZ-DPSK signal. (d) Bit error rate versus optical receiver power for a singly polarized NRZ-DPSK signal and x- and y-polarized components of the PDM-NRZ-DPSK signal.

point of the eye diagrams was not located at the center of the diagrams. The optimization of the receiver is not enough. Moreover, the bandwidth of the power amplifier was 65 GHz. This limitation may cause the degradation of the optical signals. The optical power spectrum is shown in Fig. 3 (c). This shows a suppression of a carrier component and an optical signal-to-noise ratio was higher than 20 dB.

The dependence of the BER on the receiver power is shown in Fig. 3 (d). Error-free transmission was successfully demonstrated under all conditions. The power penalty between the NRZ-DPSK and the PDM-NRZ-DPSK signals was estimated to be 4 dB. The BER of the x-polarization component was worse than that of the other two components. It is considered that some indifference problems may occur in the transmitter section. The eye diagrams of these components show the degradation of the signal quality of the x-polarization components. The polarization of the signals incident on the PDM section may be unstable. Thus, the transmitter optical powers of the x- and y-polarization components were not the same.

4. Conclusion

We demonstrated the modulation of a 166-Gb/s PDM-NRZ-DPSK signal using a thin-LN-substrate modulator. The 0.1-mm-thick substrate helped decrease the propagation loss of incident electric signals, and the frequency response of the electric signals improved drastically. The ridge structure of the LN waveguide enhanced the effective electric field applied to the waveguide. Thus, $V\pi$ of the modulator was reduced. We conclude that the generation of a signal greater than 200 Gb/s would be possible by using an optical vector modulator, such as a dual-parallel Mach-Zhender interferometric (MZI) modulator and a quad-parallel MZI modulator [8], with a high-speed modulator structure with a thin LN substrate and a ridge-type optical waveguide.

Acknowledgement

The authors wish to thank Dr. Thomas Lee and Mr. Tomonori Okitsu of SHF Communication Technologies AG for their encouragement.

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