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120-Gb/s NRZ-DQPSK signal generation by a thin-lithium-niobate-substrate modulator

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Abstract: A high-speed DQPSK optical modulator is fabricated with a thin lithium niobate substrate. Decrease in the propagation loss of electrodes and a low half-wave voltage, which can be realized by fabrication of a ridge-type optical waveguide structure, can help achieve 120-Gb/s (60-Gbaud) NRZ-DQPSK modulation with full electrical-time-division-multiplexing technique.

Keywords: optical modulator, phase-shift-keying, quadrature-phase-shift-keying, $LiNbO_3$

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

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1 Introduction

Quadrature phase-shift keying (QPSK) can be used to make high-capacity transmission links tolerant to chromatic and polarization-mode dispersion [1, 2]. These multilevel modulation schemes help achieve high spectral efficiency. Thus, transmission technologies using advanced modulation formats with full electrical-time-division-multiplexing (ETDM) technique have been developed rapidly [3, 4]. However, a baud rate of these modulation techniques used in above reports is much slower than the data rate because of the bandwidth limitation of the modulation. In the case of optical modulation with full-ETDM technique at a symbol rate greater than 50 Gbaud, frequency response of the optical modulator is one of the most important issues. This is because the modulator response is limited by the response of the electrodes, as the electro-optic response in lithium niobate (LN) is sufficiently fast even for generation of signals at frequencies greater than 100 GHz. On the other hand, the velocity mismatch between the incident electric and lightwave signals can be mitigated by using traveling-wave coplanar waveguide (CPW) electrodes. Hence, the bandwidth is dominantly limited by the electric losses that depend on the electrode structure and the electrode material and the substrate. The preliminary result of a high-baud rate modulation was performed by a phase-shift-keying (PSK) technique with a high-speed modulator [5]; however, the QPSK modulation have not been performed yet.

In this study, we fabricated a high-speed differential QPSK (DQPSK) modulator with traveling-wave CPW electrodes and a thin LN substrate

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(thickness: ∼0.1 mm). The thin substrate helps reduce the loss resulting from substrate-mode coupling at frequencies greater than 50 GHz. In addition, fabrication of a ridge waveguide structure with a z-cut LN substrate helps realize a decrease in the half-wave voltage Vπ. The value of Vπ is achieved to be 1.9 V under a differential drive condition, that is, push-pull operation condition, at a frequency of 25 GHz. We successfully demonstrated 120-Gb/s (60-Gbaud) non-return-to-zero (NRZ)-DQPSK modulation by conventional technique and by using equipments required to fabricate high-speed microwave and millimeter-wave components.

2 Frequency response for thin LN substrate

It is important to increase the bandwidth of the LN modulator to achieve high symbol-rate modulation. In the LN modulator, mismatches in the traveling velocity between the incident microwave electric signal and a lightwave can be mitigated by optimizing the traveling-wave CPW electrodes. Bandwidth limitation is caused by the propagation characteristics of the traveling microwave signals in the electrode. The propagation loss is pronounced in case of signals with frequencies greater than 10 GHz. Moreover, in a vector modulator such as a dual-parallel Mach-Zhender modulator (DPMZM) [6], the use of long electrodes has a pronounced effect on the loss and gives rise to cross-talk effects. This effect is caused by the large number of complicated structures present in the DPMZM with long electrodes. The loss in the electrode is described by the summation of the conductor loss, dielectric loss, and radiative loss. At frequencies greater than 10 GHz, the radiative loss resulting from substrate-mode coupling is significant in 1-mm-thick LN substrates [7]. The electric-electric (E/E) frequency response and the quality of optically modulated signals are degraded at the resonant frequency of the substrate-mode coupling. This frequency is inversely proportional to the substrate thickness [8]. Hence, thinning of the LN substrate helps reduce the propagation loss effectively.

Figure 1 shows the dependence of the E/E response on the substrate thickness. From the figure, it is clearly seen that thinning of the substrate helps improve the frequency response. The dip in the E/E response at 58.6 GHz for a substrate thickness of 0.2 mm is caused by mode coupling. No such dip

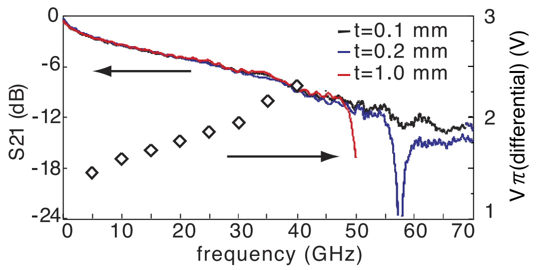

Fig. 1. Electric-electric response of traveling-wave CPW electrode and frequency dependence of half-wave voltage Vπ

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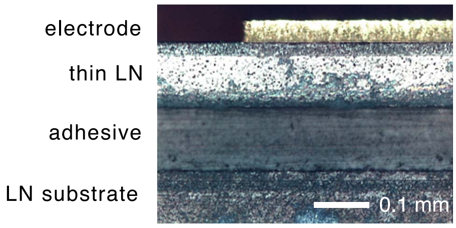

Fig. 2. Cross-sectional image of the modulator with thin LN substrate

is observed in the E/E response for a substrate thickness of 0.1 mm, and the effective frequency is increased to 70 GHz in this case. In the conclusions, you have stated that the resonant frequency of the substrate-mode coupling could be increased to more than 100 GHz by using a 0.1-mm substrate. Hence, the 0.1-mm-thick substrate is suitable for high-speed operations at symbol rates greater than 50 Gbaud. The thin LN substrate was bonded to a thick LN substrate using a low-dielectric-constant adhesive for easy handling (Fig. 2). A DPMZM with this reinforced structure is fabricated for DQPSK modulation.

The frequency dependence of Vπ of the fabricated modulator is shown in Fig. 1. At a frequency of 25 GHz, Vπ is 1.9 V under a differential-drive condition, which is considerably smaller than that of about 2.5 to 3 V in the case of conventional modulators. This low value of Vπ is realized by a ridge structure modulator with Z-cut LN substrate [9, 10]. The effective electric field applied to the waveguide of the Z-cut substrate is enhanced, and thus, the value of Vπ is decreased drastically. By extrapolating the observed values, we estimated the value of Vπ at 60 GHz to be 3 V.

3 Experimental configuration and demonstration

The experimental setup is shown in Fig. 3. The data streams are pseudorandom bit-sequences with a length of $2^{31} - 1$ bits generated by a pulse pattern generator (PPG). The output data and complementary data are fed to the input ports of a two-to-one multiplexer (2 : 1 MUX) in order to generate signals at a symbol rate twice that of the incident signal. The multiplexed signals are transmitted to suitable ports of the DQPSK modulator through power dividers and ultra-broadband amplifiers; the 3-dB bandwidth of the power dividers is 65 GHz. The gain, saturated power, and 3-dB bandwidth

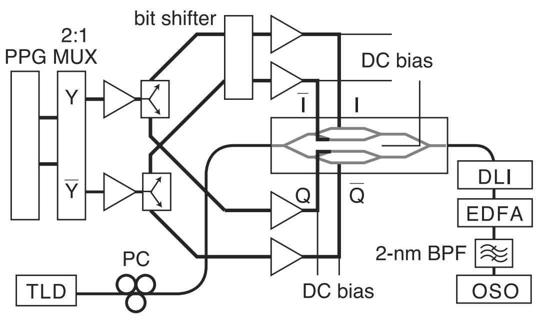

Fig. 3. Experimental setup

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of the amplifier are 12 dB, 15 dBm, and 65 GHz, respectively. In other words, the amplifier power in our study is smaller than that in conventional and ordinary-baud-rate DQPSK modulation schemes. This is because amplifiers with a very high 3-dB bandwidth are not commercially available.

A bit shifter that shifts data by a length of six bits was inserted into data lines to decorrelate the electric signals of the in-phase and quadrature components. The bias voltage applied to the main MZI was controlled for an optical phase difference of a half of π in order to generate the DQPSK signal. The light source was a wavelength-tunable single-mode laser diode (TLD) operated at 1550 nm. A polarization controller (PC) was used to maintain the polarization of the lightwave incident on the modulator. The output lightwave from the modulator was transmitted to a Michelson delay-line interferometer (DLI) for demodulation. The demodulated optical signals were boosted by an erbium-doped fiber amplifier (EDFA). Later, the signals were boosted by an optical sampling oscilloscope (OSO) with a temporal resolution of approximately 1 ps. A 2-nm optical band-pass filter (BPF) centered at 1550 nm was used to detect the demodulated signals.

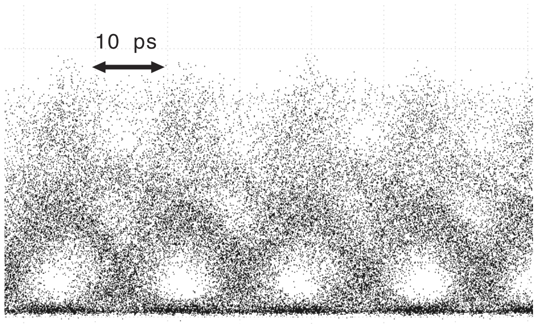

Fig. 4. Eye diagram of 120-Gb/s DQPSK demodulated signal

Figure 4 shows an eye diagram of the 120-Gb/s (60 Gbaud) DQPSK-demodulated signal. Approximately opened eye patterns are observed in the figure. At a frequency of 50 GHz, the electric power transmitted to the modulator and Vπ of the modulator were estimated to be approximately 2.3 V and 2.6 V, respectively. This indicated that the experiments were performed under conditions of almost full-swing operation Therefore, the use of an ultra-broadband amplifier, which has limited amplifier gain and output power, helps realize modulation at bit rates greater than 100 Gb/s.

4 Conclusion

We fabricated a high-speed DQPSK modulator with a ridge-type optical waveguide structure on a thin Z-cut LN substrate With a 0.1-mm-thick substrate, we could increase the resonant frequency of the substrate mode coupling to more than 100 GHz; thus, the propagation loss of the incident electric signals could be reduced. The ridge structure on the Z-cut LN modulator

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helped enhance the electric field applied to the waveguide and a consequential reduction in $V\pi$. We successfully demonstrated 120-Gb/s (60 Gbaud) DQPSK signal generation with the full-ETDM technique. We finally concluded that signal generation at bit rates greater than 200 Gb/s would be possible if a complex optical vector modulator such as a quad-parallel MZM [11] with a similar structure is used.

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