Demonstration of thin-film lithium niobate high-bandwidth coherent driver modulator

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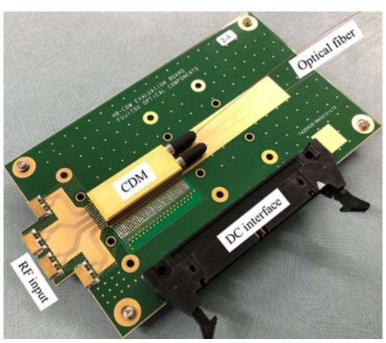
Abstract: We demonstrate the performance of a high-bandwidth coherent driver modulator device, based on thin-film lithium niobate DP-IQ MZI modulators with excellent DC drift characteristics making it suitable for commercial applications.

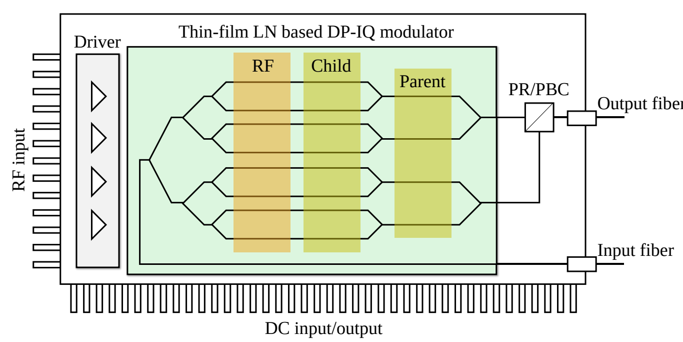
1. Introduction

The electro-optic (EO) modulator is one of the key components of fiber-optic transmission systems. The EO modulators have been realized using various platforms, such as silicon photonics, indium phosphide (InP), and lithium niobate (LN). The LN modulator has been widely used for long-haul transmission systems because of its high-linearity modulation performance and low optical loss. However, since current bulk LN uses titanium-diffused (Ti:$LiNbO_3$) waveguides, these modulators have weak optical confinement and it is difficult to downsize the EO modulator dimensions. Recently, thin-film LN technology has emerged to overcome this difficulty [1,2]. Thin-film LN technology can realize small EO modulators due to its ability to achieve strong optical confinement while keeping the benefits of bulk LN. Although the attractive potential of thin-film LN modulators has already been reported, the DC drift (time variation of DC bias voltage) remains a challenge for achieving practical use. In this work, we demonstrate that the DC drift characteristic for practical applications can be achieved in thin-film LN modulator by wafer process optimization leveraging bulk LN knowledge. The DC drift [3] can be compensated by using the existing feedback circuit based on the auto bias control (ABC) algorithm [4]. Additionally, we fabricate a dual polarization in-phase quadrature (DP-IQ) modulator based on thin-film LN and integrate this modulator in a coherent driver modulator (CDM) [5] package with a driver. The CDM is suitable as a high baud rate transmitter because the radio frequency (RF) loss can be suppressed due to the close distance between the modulator and the driver. So far, although InP-based CDM has been mainly reported [6, 7], our work is the first demonstration of a thin-film LN-based CDM device to our knowledge.

2. Structure of thin-film LN-based CDM



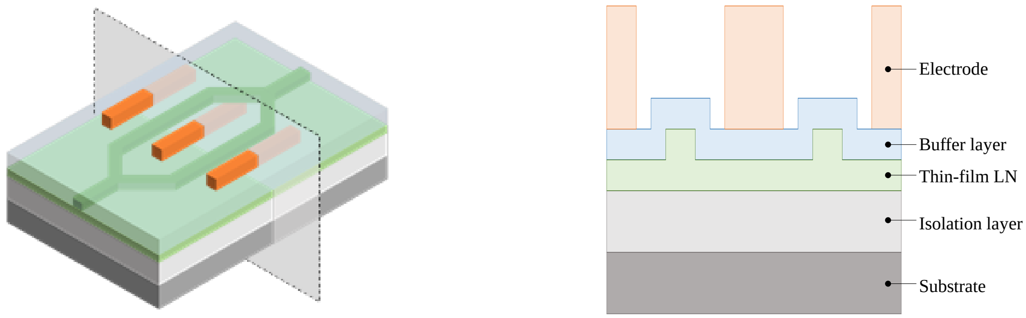
(a)



(b)

Fig. 1 (a) The thin-film LN-based CDM on the evaluation board (b) The block diagram of the CDM

Fig. 1 (a) shows the thin-film LN-based CDM on an evaluation board. The package size has a width of 12 mm, height of 5.5 mm and length of 30 mm, which is compliant to the OIF HB-CDM specification. In the length direction, one side has the input and output optical fibers and the opposite side has the RF input port composed by the lead pins. The lateral side has DC input and output ports that control and monitor the modulator and the driver. Fig. 1 (b) shows the block diagram of the thin-film LN-based CDM. The driver, the DP-IQ modulator and the bulk optics are integrated in the package. The thermo-electric cooler and the thermistor are not necessary for the thin-film LN-based CDM compared with the InP-based CDM. Fig. 2 (a) shows the schematic of the thin-film LN Mach-Zehnder Interferometer (MZI) modulator, which is a part of the DP-IQ configuration. Fig. 2 (b) shows the cross section of the thin-film LN MZI modulator. The isolation layer, which has a lower optical refractive index than LN to achieve strong optical confinement, is located on top of the substrate. The thin-film LN on top of the isolation layer has rib-type optical



(a) (b)

Fig. 2 The thin-film LN MZI modulator (a) Schematic (b) Cross section

waveguides. The electrodes are located on both sides of the optical waveguides since the crystal orientation of the thin-film LN is X-cut. The buffer layer, which is based on SiO_2, is formed between the thin-film LN and the electrodes. The wafer process optimization has been carried out under the various process conditions to achieve the DC drift characteristics for practical use.

3. DC drift

The DC drift is defined as the variation of DC bias voltage for locking the modulation operating point. For example, the DC drift can be measured as the optical power variation after the MZI output is set the peak level by DC voltage. However, this method requires the high stability of the laser and the photodetector for the long-term reliability test. Therefore, we define the DC drift by Equation 1, and evaluate by the following method.

$$\text{DC drift } S\,[\%] = \frac{V_a(t) - V_a(0)}{V_{DC}} = \frac{\Delta V(t)}{V_{DC}} \qquad (1)$$

Fig. 3 shows the concept of the DC drift evaluation method. First, only AC voltage is applied to the MZI modulator and the specific peak, *a*, is set. Then, the DC voltage, V_{DC}, is added and the time variation of the peak, ΔV, is measured over time, *t*. Since the DC drift is proportion to the applied DC voltage, the DC drift is evaluated by the ratio of ΔV and V_{DC}.

Since it is difficult to realize the ideal zero DC drift characteristic, the bulk LN modulator has been controlled by the combination of the ABC algorithm and the minus DC drift. The voltage compensating the modulation operating point, V_c, is defined by Equation 2.

$$V_c = \frac{V_{offset}}{S - 1} \qquad (2)$$

The V_{offset} is the offset voltage that should be compensated. Regarding the plus DC drift, when the DC drift becomes +100 % ($S = 1$), the compensating voltage reaches the uncontrollable infinity (∞) magnitude. On the other hand, when the DC drift becomes −100% ($S = -1$), the DC drift can be compensated by the $-V_{offset}$ / 2, which is lower than the offset voltage. The minus DC drift can be achieved by the low-resistance buffer layer [8]. We optimize the wafer process under various conditions and the minus DC drift characteristic of the thin-film LN is achieved as shown in Fig. 4 that shows the time dependence of the DC drift under the high temperature of 140 °C. The gray region

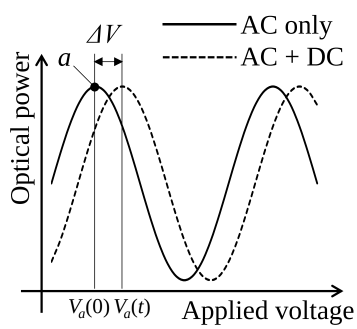


Fig. 3 The concept of the evaluation method of the DC drift

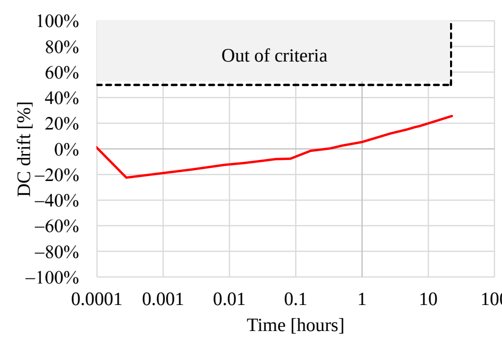
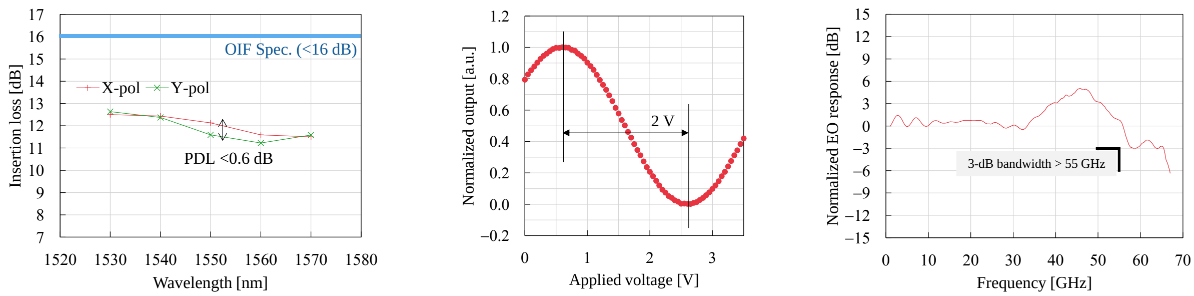


Fig. 4 The time dependence of the DC drift under high temperature of 140 °C

shows the threshold to guarantee the long-term reliability based on the high temperature accelerated aging test using the Arrhenius equation, whose activation energy is assumed the same as the bulk LN. We can see that the optimized thin-film LN modulator has the potential for ensuring long-term reliability. Furthermore, this EO-based phase shifter has an advantage of low power consumption. Although the thermo-optic (TO) heater-based phase shifter can avoid the DC drift issue, its power consumption becomes large because of the low TO coefficient of LN and the large number of phase shifters needed to configure the DP-IQ modulator.

4. Demonstration of thin-film LN based CDM



(a) (b) (c)

Fig. 5 The performance of thin-film LN-based CDM (a) Insertion loss per polarization (b) Waveform of the RF modulation section (c) Normalized EO response

Fig. 5(a) shows the CDM insertion loss per polarization at C-band. It includes the intrinsic polarization splitting loss (3 dB). All MZI are controlled at the peak level. Owing to the low propagation loss of the LN waveguide (~0.5 dB/cm), the low CDM insertion loss can be achieved under 13 dB, which is compliant to the OIF HB-CDM specification (<16 dB). The polarization-dependent loss (PDL) can be also suppressed under 0.6 dB, which is also compliant to the OIF HB-CDM specification (<1.0 dB). The additional absorption loss does not occur for actual RF modulated operation. Fig. 5(b) shows the waveform of the RF modulation section at the low frequency and at the 1550-nm wavelength. The V_π = 2.0 V and the extinction ratio > 25 dB are obtained. Fig. 5(c) shows the EO response of the CDM with the 1-GHz normalized and 3% smoothing. The 3-dB bandwidth achieves over 55 GHz, which can be used for 96 Gbaud modulation. Since the cutoff of the bandwidth comes from the package RF interface, we consider that the thin-film LN modulator has the potential for 128 Gbaud operation if the RF interface is changed to the flexible printed circuit (FPC) standardized by the OIF HB-CDM implementation agreement [5].

5. Conclusion

We have fabricated a thin-film LN-based DP-IQ MZI modulator. The wafer process optimization has been carried out under the various process conditions, and a minus DC drift characteristic was achieved in the thin-film LN modulator. Additionally, the thin-film LN-based CDM is the first demonstrated to our knowledge. Further transmission characterization of this CDM is being planned. We consider that the thin-film LN-based CDM has the potential for 128 Gbaud operation by using the enhanced package and driver.

6. References

[1] C. Wang, *et al.*, "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," Nature, vol. 562, no. 4, pp. 101-104, Oct. 2018.
[2] M. Xu, *et al.*, "High-performance coherent optical modulators based on thin-film lithium niobate platform," vol. 11, no. 6, pp. 1-7, Aug. 2020.
[3] M. Seino, *et al.*, "A low DC-drift Ti:$LiNbO_3$ modulator assured over 15 years," OFC 1992, Post-Deadline Paper, PD-3, pp. 325-328.
[4] N. Kuwata, *et al.*, "Automatic bias control circuit for Mach-Zehnder Modulator," (in Japanese), Spring National Convention IEICE, Japan, B-976, pp. 4-155, 1990.
[5] OIF-HB-CDM-02.0 – Implementation Agreement for High Bandwidth Coherent Driver Modulator (July 2021)
[6] T. Tatsumi, *et al.*, "A Compact Low-Power 224-Gb/s DP-16QAM Modulator Module with InP-based Modulator and Linear Driver ICs," OFC 2014, Tu3H.5.
[7] J. Ozaki, *et al.*, "500-Gb/s/λ Operation of Ultra-Low Power and Low-Temperature-Dependence InP-Based High-Bandwidth Coherent Driver Modulator," vol. 38, no. 18, pp. 5086-5091, Sep. 2020.
[8] S. Yamada, *et al.*, "DC Drift Phenomena in LiNbO3 Optical Waveguide Devices," Japanese J. of App. Phys., vol. 20, no. 4, pp. 733-737, Apr. 1981.