$LiNbO_3$ Integrated Optical QPSK Modulator and Coherent Receiver

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Abstract:

These devices, reported for the first time, are X-Cut highly integrated $LiNbO_3$ Optical Modulator and Hybrid Receiver developed for coherent QPSK (Quadrature Phase Shift Keying) fiber optical communications, as well as other applications. Preliminary tests of the integrated LN optical hybrid were conducted.

Keywords: integrated optics, $LiNbO_3$, modulator, receiver, QPSK, coherent communication.

1. Introduction

Coherent optical communications utilizes the transmission of phase information instead of amplitude (i.e. on/off) modulation. When used in fiber links it requires considerably lower SNR/Bit and lower transmit power, while providing enhanced receiver sensitivity and longer reach [1]-[2]. In free-space it supports signal amplification for near quantum (shot noise) limited operation (fewer photons per bit). PSK is inherently frequency-selective which eliminates the requirement for optical filtering enabling lower cost/complexity. Down-conversion to baseband allows the cost-effective electrical filtering and digital signal processing. Figure 1 illustrates the QPSK Modulation principle that has been effectively exploited in CeLight original architecture.

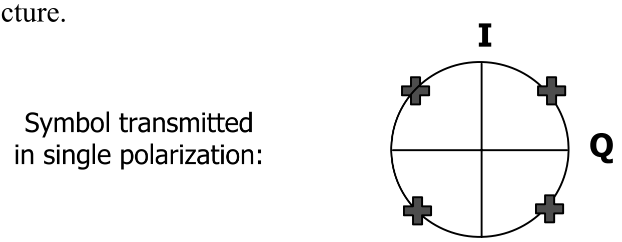


Figure 1. QPSK modulation principle (2 bits/symbol).

CeLight's coherent optical communications architecture, originally developed to deliver innovative optical networking, is based on the following *Ti*-in-diffused $LiNbO_3$ components:

- **Integrated $LiNbO_3$ optical coherent modulator.**
- **Integrated optical coherent receiver based on $LiNbO_3$ hybrid.**

The system Implementation of these components is schematically shown in Figure 2.

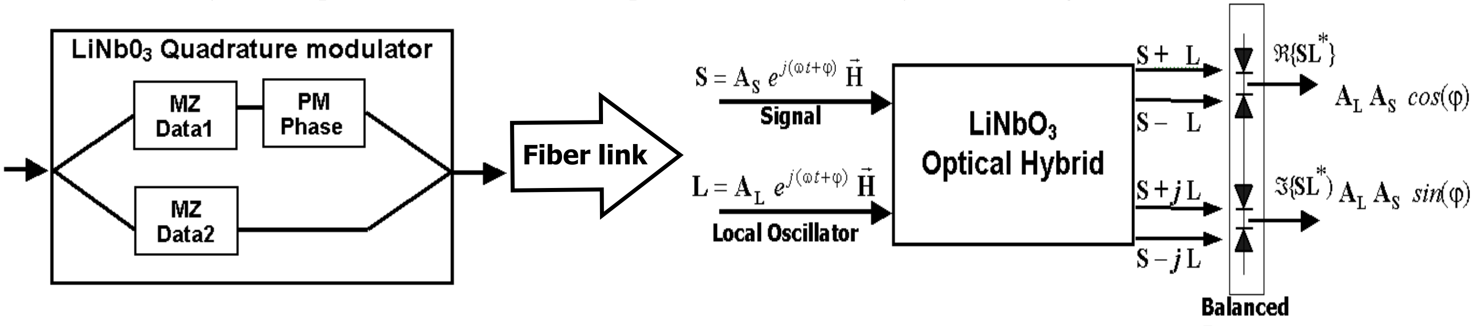


Figure 2. Coherent communications technology $LiNbO_3$ core elements.

In the modulator design, the carrier is separated into two branches, an in-phase (I) branch and a quadrature-phase (Q) branch. The two branches are kept at 90° using the phase modulator (PM). Each branch is amplitude and phase modulated using a Mach-Zehnder (MZ) interferometer. Finally, the two branches are combined.

In the receiver, the signal S is combined with the local laser L using directional couplers (DCs) to produce four optical outputs: S+L, S-L, S+jL and S-jL. The phase relations between S and L are controlled by two phase-modulators (not shown in diagram). Two pairs of balanced diodes are used to produce the real (I) and imaginary (Q) parts of the product SL^*. These signals are then used to decode the received bits.

2. Design and Fabrication

2.1 $LiNbO_3$ Quadrature modulator

The main advantage of the proposed optimized design is the high integration level of electro-optical components within a single $LiNbO_3$ crystal wafer [3]-[4]. A quadrature modulator with the structure shown in Figure 3 was designed and fabricated.

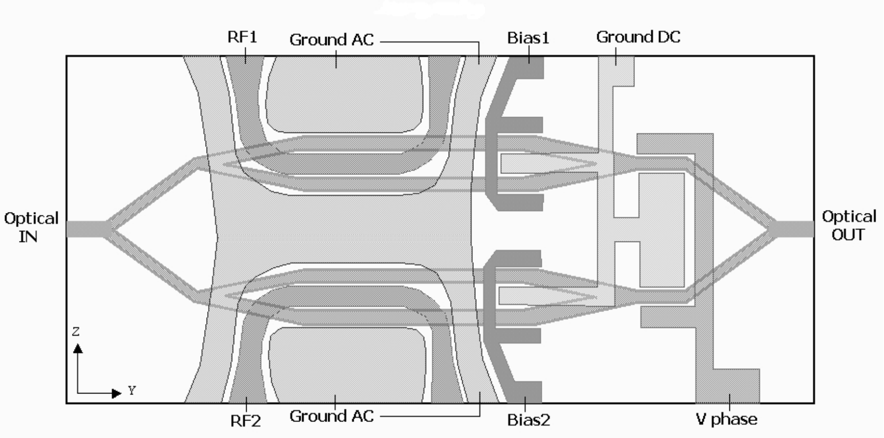


Figure 3. Schematic of the integrated $LiNbO_3$ Quadrature Modulator.

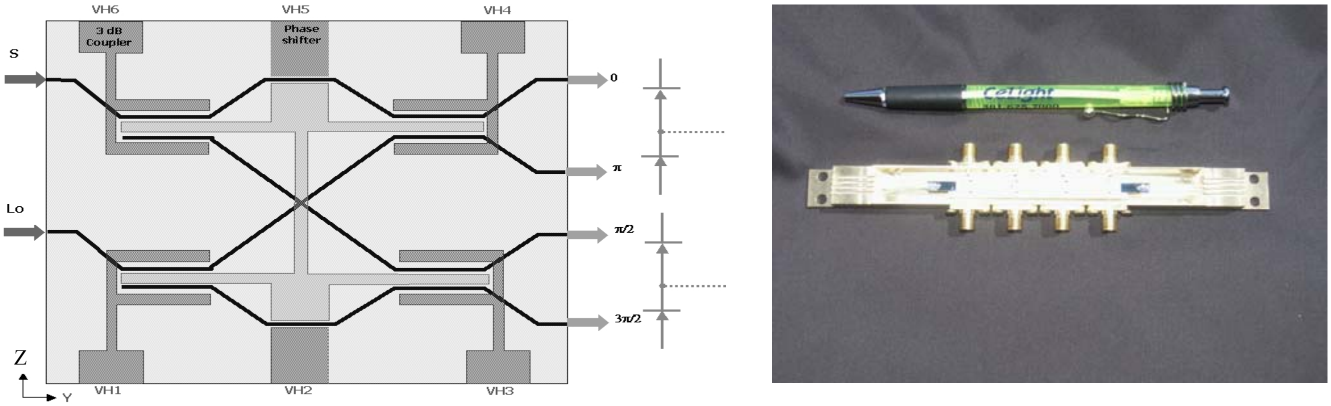
The single X-cut $LiNbO_3$ chip consists of:

- Two passive 3dB Y-Junctions for separating and combining the optical signals.
- Two MZ electro-optical “push-pull” modulators.
- Two “push-pull” phase shifters for the MZ modulators’ bias adjustments.
- One phase shifter for phase difference introduction between the two modulated signals before combining.

The device was designed for a 4” $LiNbO_3$ wafer, using titanium in-diffused technology. The waveguides are designed for single-mode TE operation on X-cut, Y-propagation crystal. Diffusion time and temperature were 10 hours and 1000 °C, respectively. The substrate is coated with a buffer layer of silicon dioxide. A thick plated gold coplanar-waveguide (CPW) traveling-wave type electrode structure is formed on the buffer layer. SiO_2 and gold thickness were optimized for velocity matching of the optical and electrical signals. Each MZ is driven by RF signals applied to the on-chip CPWs. The CPWs were designed for 50 Ohms impedance. The lengths of the RF electrodes are about 40 mm. The integrated phase modulator package was designed for at least for tens of Giga symbol/s quadrature or binary phase shift keying modulation. The actual device was optimized for 12 GHz. Two MZ type modulators are combined using two 3-dB Y-junctions at the input and output. The MZ modulator is an optical switch that splits the incoming lightwave into two optical beams and then combines them after an appropriate distance. Separate bias pads are utilized to optimize the DC bias point of each MZ modulator. An additional V-phase pad has been added to obtain quadrature phase difference between the two Mach-Zehnder modulators. The modulator is pigtailed with polarization maintaining fibers. The half wavelength voltages were designed to be 5V at DC and 7V at 10 GHz. The optical insertion loss, including waveguide propagation loss, branch loss, and connection loss between the waveguide and fibers was optimized to be less than 8 dB.

2.2 Balanced 90^o LiNbO$_3$ coherent receiver (hybrid)

The architecture of the integrated balanced phase diversity receiver [5]-[6] comprising the optical hybrid is shown in Figure 4a. X-cut LiNbO$_3$, titanium diffused integrated 3" wafer technology was used. The single hybrid chip includes four tunable 3dB couplers for mixing the optical signals and two electro-optical phase-shifters.



(a) **(b)**

Figure 4: a. Schematic of the integrated LiNbO$_3$ Coherent Receiver
b. LiNbO$_3$ Coherent Receiver package

The design is optimized for use with balanced photodetectors for coherent detection of QPSK and BPSK signals.

The design includes the following features:

- Optical "I" (in-phase) and "Q" (quadrature) outputs.
- External DC biasing capability of optical hybrid for optical amplitude and phase compensation.
- Separate optical input for Local Oscillator (LO) laser to heterodyne (or homodyne) with signal on chip.
- Package includes the option for Thermo Electric Cooler (TEC) and thermistor for temperature control and monitoring.

The input signal is fed into input S and split by tunable 3dB coupler VH6. The phase between the signals at the upper ports of VH4 and VH3 can be tuned by phase-shifter VH5. The local oscillator signal is fed into input LO and split by VH1. If the phase between the LO signals at the lower ports of VH4 and VH3 is adjusted to 90^o, the signals at the device output ports will show the desired phase relation of the 90^o hybrid: {180, 90, 270} with respect to the first output. Figure 4b shows the actual packaged LiNbO$_3$ Coherent Receiver.

4. Experiment

Typical measured insertion loss of the hybrid is about -10 dB including fiber-to-fiber coupling loss, waveguide absorption/scattering, and bending losses. Preliminary testing of the integrated hybrid was conducted using an optical differential binary phase-shift-keyed (DBPSK) input signal at 12.5 Gbits/s (Figure 5a). A self-homodyne detection scheme with one symbol relative delay was used to demodulate and detect the signal. The one symbol delay was achieved by fusion splicing an external 3-dB fiber coupler with a relative length difference corresponding to the one symbol period. Bias voltages in the 10-20V range were applied to four couplers providing the 3dB operation. The output of the hybrid (R1) was directed to a photodetector to examine the eye diagram. An open eye was obtained when the differential phase shift was 0 or π for DBPSK signal at the R1 output of the hybrid (Figure 5b).

Slow drift of the eye (gradual opening and closing) was observed due to environmental perturbations on the fibers of the 3-dB coupler connected to the input of the hybrid. Stabilization of the output eye was obtained using a phase control loop (Figure 5a). A control voltage was applied to the phase shifter sections of the hybrid. It was shown that the drift of the hybrid itself was completely dominated by the drift of the fiber coupler.

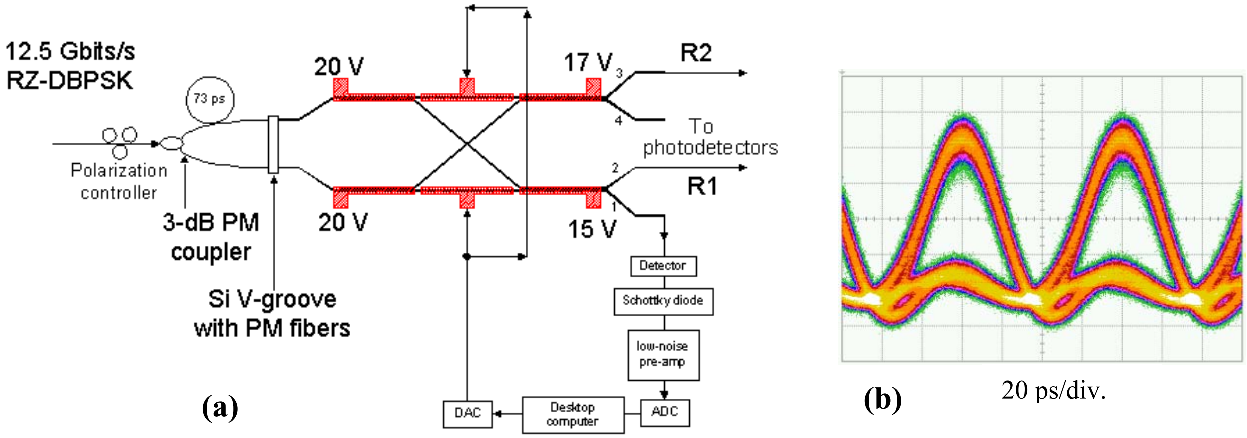


Figure 5: a) Demodulation setup; b) Eye diagram of the demodulated 12.5 Gbits/s RZ-DBPSK signal

5. Conclusions

A novel $LiNbO_3$ electro-optical device has been developed for use in coherent communication technology. These highly integrated devices will enable low manufacturing cost and high SNR in coherent optical communication systems. The integration of all components in a single $LiNbO_3$ chip dramatically reduces the cost, improves performance, and provides better stability and control to increase communication distance. Some particular parameters of the proposed devices will be discussed during the presentation.

6. References

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