High-Speed and Presice Lightwave Modulation Technologies

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Abstract

We present recent progress of high-speed Mach-Zehnder interferometer based device technologies for advanced modulation formats. Parallel Mach-Zehnder modulators can be used for multi-level quadrature amplitude modulation, and also for high extinction-ratio modulation.

Introduction

Recently, huge-capacity transmission over 20 Tb/s was achieved by using differential quadrature-phase-shift-keying (DQPSK) which can provide enhanced tolerance to chromatic dispersion and polarization mode dispersion, together with high spectral efficiency [1, 2], where integrated lithium-niobate (LN) modulators consisting of sub Mach-Zehnder interferometers (MZIs) embedded in main MZIs were used for high-speed DQPSK signal generation over 40 Gbaud [3]. The integrated modulator is called a dual parallel Mach-Zehnder modulator (DPMZM), which can also used for various modulation formats, such as single-sideband (SSB) [4], frequency-shift-keying (FSK) [5], etc. In addition, high-speed 16-level quadrature-amplitude-modulation (16QAM) can be achieved by a quad-parallel MZM (QPMZM) consisting of two DPMZMs [6]. However, fabricated modulators have residual chirp or parasitic phase modulation due to manufacturing errors. Imbalance of the two interfering amplitudes at the output coupler of the MZI dominates the residual output in off-state, where a typical ER of a fabricated MZI is less than 35 dB. ER of 25 dB is high enough for conventional on-off-keying (OOK) modulation, however, higher ER can be required for advanced modulation formats [7]. For example, when ER is 25 dB, displacement of 256 QAM symbols generated by a DPMZM would be about 50% of the distance between neighboring symbols in a constellation. In addition, finite ER induced dispersion effect in binary on-off-keying and duobinary transmission systems was previously investigated by using numerical simulation, where the performance of duobinary was degraded by residual chirp due to finite ER [8]. Recently, highly sensitive duobinary signal generation using high-extinction ratio (ER) modulation was demonstrated by using active trimmers in an MZI to compensate imbalance due to fabrication error [9]. In this paper, we review recent progress of LN based lightwave modulation technologies, where the basic element is an MZI. Integrated modulators, such as DPMZM, QPMZM, etc., can synthesize complicated signals in lightwave circuits. Precise control of lightwave at each MZI element is also very important for advanced modulation formats.

Parallel MZMs for advanced modulation formats

A DPMZM consists of two sub MZIs embedded in a main MZI, as shown in Fig. 1. DPMZMs designed for over 40 Gbaud have two high-speed electrodes in each sub MZI, in order to achieve push-pull operation on z-cut LN substrate [3]. X-cut substrate with a single high-speed electrode can also provide balanced push-pull operation, however, modulation efficiency is smaller than in z-cut substrate [5]. For DQPSK modulation, two binary data streams are applied to the two sub MZIs (MZA and MZB), to control in-phase (I) and quadrature (Q) components, directly.

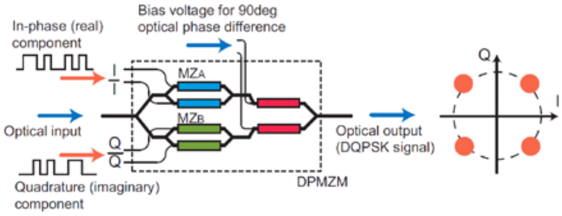


Figure 1 Schematic of DQPSK using a DPMZM.

Fig. 2 shows a schematic of 16QAM using a QPMZM, where a pair of two-bit codes for in-phase (I1, I2) and for quadrature (Q1, Q2) components are fed to four sub MZIs. A 16 QAM can be synthesized by superposing two QPSK signals with different amplitudes. The intensity difference between the QPSK signals is set at 6 dB. The lager-amplitude QPSK determines the quadrant where the symbol is mapped, while the small-amplitude QPSK fixes the position of the mapping in each quadrant. By the combination of QPSK signals, totally 16 symbols are mapped with equal spacing in a phaser diagram. Note that such a 16-QAM mapping can be achieved from binary data sequences without handling multilevel electric signals. Recently, 50-Gb/s 16 QAM transmission was demonstrated by using a QPMZM, where the modulation speed was 12.5 Gbaud [10]. While a DPMZM can generate a 2 bit/symbol DQPSK signal from two binary data streams, a QPMZM can achieve 4 bit/symbol from four binary data streams. In general, a parallel MZM with N sub MZIs can generate an N bit/symbol lightwave signal from N binary data streams. Bitrate of optical modulated output generated from N electric binary data streams can be expressed by B = N x R (R: symbol rate). Thus, to achieve high bitrate signal generation, we need integrated modulators with an array of sub MZIs designed for large symbol rate R.

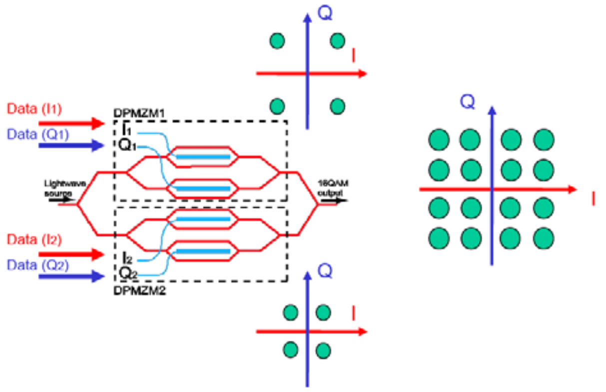
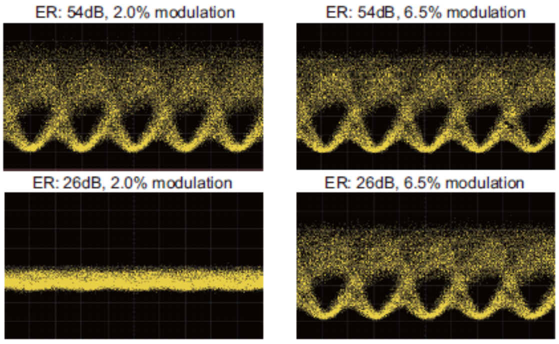


Figure 2 Schematic of 16QAM using a QPMZM.

High ER and low-chirp modulation for precice lightwave control

A DPMZM can be used as a high ER modulator or an ER tunable modulator. Two sub MZIs compensate imbalance in a main MZI due to fabrication error. By using this technique, highly sensituve duobinary signal generation was demonstrated, recently, where imbalance in lightwave circuits were compensated [9]. Fig. 3 shows eye-diagrams of demodulated duobinary signals with modulation depths of 2.0% and 6.5% of full swing operation. When ER = 54 dB, clear eye-opening was observed both in 2.0% and 6.5% depth modulation. On the other hand, when ER = 26 dB, the eye diagram for 2.0% depth modulation was completely closed, while that for 6.5% modulation depth was clearly open. This results shows importance of high ER in particular modulation formats.



ER: 54dB, 2.0% modulation

ER: 54dB, 6.5% modulation

ER: 26dB, 2.0% modulation

ER: 26dB, 6.5% modulation

Figure 3 Eye-diagrams of demodulated duobinary signals with ER=54dB and 26dB.

Chirp parameter which is an index to show the magnitude of undesired parasitic phase modulation can be largely reduced by using imbalance compensation of electric field in addition to the that of lightwave circuits for high ER. A DPMZM with six electrodes as shown in Fig. 4 can provide imbalance compensation both in the electric field and lightwave circuit, so that we can suppress the chirp and enhance the ER, simultaneously. An MZM with ultra low-chirp and high-ER can control the amplitude of the optical output precisely without any undesired phase rotation. Thus, we can achieve precise and pure control of optical amplitude. Recently. very precise lightwave modulation at 10.5 GHz was demonstrated where the ER was 66dB and the chirp parameter was less than 0.01 [11]. Fig. 5 shows very pure two-tone signal generated by ultra low-chirp and high-ER modulation. This technique can be applied to complicated lightwave signal synthesis and highly sensituve modulation.

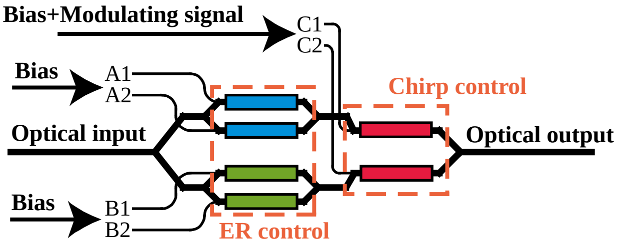


Figure 4 Precice optical modulation using a DPMZM

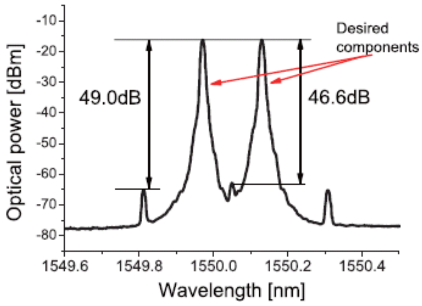


Figure 5 Spectrum of pure two-tone optical signal generated by ultra low-chirp and high-ER modulation

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