Demonstration of 120-GBaud 16-QAM Driver-less Coherent Transmitter with 80-km SSMF Transmission

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Abstract: We demonstrated a driver-less coherent optical transmitter enabled by a low-V_π high-bandwidth thin-film $LiNbO_3$ I/Q modulator. We successfully transmitted a 120-Baud 16-QAM signal with net data rate of 836.2 Gb/s over 80-km SSMF.

1. Introduction

The 400ZR agreement adopts a symbol rate of ~ 60 GBaud and 16-ary quadrature amplitude modulation (QAM). It is expected that the next generation coherent pluggables for short-reach applications use > 100 GBaud symbol rate and achieve 800 Gb/s per wavelength. As the symbol rate increases, it takes more effort to design and fabricate high-bandwidth electronic devices. Especially, the drivers in a coherent transmitter can be challenging, as the required gain is usually relatively high. One way to avoid such challenge is to use special electrical waveform generators where amplifiers can be integrated with DACs [1,2] or banded drivers can be utilized [3]. A more power efficient solution would be to use low-V_π modulators so that the modulator can be driven with CMOS compatible voltage (~ 0.5 V) therefore no driver is needed. Low-V_π modulators are usually made from new materials such as indium phosphide (InPh) [4], silicon-organic hybrid (SOH) [5], plasmonic [6], and thin-film lithium niobate ($LiNbO_3$) [7,8,9], etc. Among these technologies, InPh and thin-film $LiNbO_3$ are considered to most likely provide long term stability which is a necessary promise for telecommunication applications.

In this paper, we present a low-V_π thin-film $LiNbO_3$ in-phase (I)/quadrature (Q) modulator that is newly designed for ~100 GBaud signals, and exercise the possibility of building a short-reach coherent transmitter without RF drivers. We demonstrate a DAC-driving 120-Gbaud coherent transmitter modulating 16-QAM signals and transmitted the signal over 80-km standard single mode fiber (SSMF). With a 400ZR compatible 14.8 % overhead forward error coding (FEC) [10], the system achieves 960 Gb/s line rate and 836.2 Gb/s net data rate. The demonstrated transmitter can be a candidate for 800 Gb/s coherent pluggable applications.

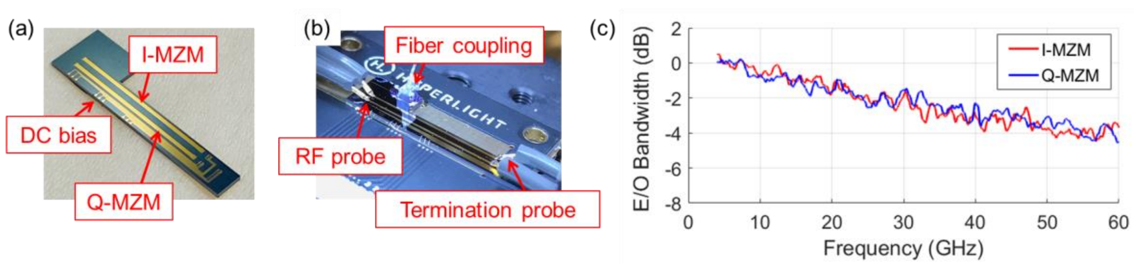

Fig. 1 (a) A photo of the thin-film $LiNbO_3$ I/Q modulator chip; (b) fiber and DC bias packaged chip on our experimental setup; (c) E/O bandwidth of the I and Q modulators, measured by comparing the optical spectrum and the electrical spectrum.

2. The high-speed I/Q Modulator

The modulator is a thin-film $LiNbO_3$ single polarization I/Q modulator. A photo of the chip is shown in Fig. 1 (a). Note that this modulator is designed for ~ 100 GBaud signal and is different than other thin-film $LiNbO_3$ modulators that are reported previously (e.g. in Ref. 11). Compared to previously reported modulators where the devices are designed for ultra-high speed signals (e.g. 200 GBd and beyond), this modulator has less 3-dB bandwidth as well as a reduced V_π, therefore is more suitable for ~ 100-GBd driver-less transmitters. Each of the MZMs has 1.5-cm long RF electrodes and the V_π is 1.7 V (@ 1 GHz). The extinction ratios of the MZMs are > 25 dB. The insertion loss of the I/Q modulator is 10.5 dB, among which ~ 9 dB is the loss from the two grating couplers for optical input and output. The on-chip waveguide loss is less than 1.5 dB [8]. The insertion loss can be reduced to ~ 5 dB if edge coupling is used (as shown in Ref.12). The RF signal is added via a 67-GHz RF probe as shown in Fig. 1 (b). The electrical-to-optical (E/O) bandwidth of the I and Q MZMs are shown in Fig. 1 (c). The blue and red curves are E/O responses of the I and Q MZMs (the RF probe is not de-embedded). This is measured by comparing (subtracting) the optical spectrum measured by a high-resolution (150 MHz) optical spectrum analyzer (OSA) and the driving signal's electrical spectrum measured by a real-time scope. We observe the modulator has a 3-dB bandwidth of ~ 30 GHz and a 5-dB bandwidth of > 60 GHz, which is good for the 120-GBd symbol rate.

3. Experimental Setup

The experimental setup for our 120-GBaud 16-QAM transmission is shown in Fig. 2. The optical transmitter consists of an external cavity laser (ECL), the thin-film $LiNbO_3$ I/Q modulator, two digital-to-analog converters (DACs), and a polarization division multiplexing (PDM) emulator. The laser has a linewidth of < 100 kHz and is operating at ~1550.1 nm. The modulator is driven by silicon germanium (SiGe) DACs operating at a sampling rate of 120 GSa/s with a 6-dB bandwidth of ~ 45 GHz. The DAC has a V_{pp} of ~ 0.5 V. The modulator is biased at its null transmission point. The optical input power to the modulator is 16.1 dBm, which is the same power level of a standard integrable tunable laser assembly (ITLA). This result in modulator output power of -19.3 dBm, which is ~ 9 dB lower than the 400ZR agreement specs (- 10 dBm) [10]. However, as explained, the excessive loss is caused by the grating couplers and can be solved by replacing them with edge couplers. To emulate the scenario where edge couplers are used, it will be shown later that we also test the system with 21 dBm modulator input power (by adding an Erbium-doped fiber amplifier (EDFA) before the modulator) and its corresponding modulator output power is – 14.4 dBm. Note the increased power is for compensating the coupling loss but not the driver-less modulation loss. After modulation, the signals are amplified via an EDFA and enter a PDM emulator. The PDM emulator consists of a 3-dB polarization maintaining (PM) power splitter, a 11-meter (55 ns) PM fiber delay, and a polarization beam combiner (PBC).

The transmission fiber consists of a single-span of 40-km or 80-km SSMF with a loss of 0.2 dB/km and a dispersion of 17 ps/nm/km. The optical power launched into the SSMF is 6.0 dBm. The optical signal-to-noise ratio (OSNR) before and after the 80-km transmission are 31.2 dB and 30.1 dB. The optical spectra before and after the transmission are shown as insets to Fig. 2. As seen, the 120-GBaud optical signal occupies a spectral width of more than 150 GHz. This is because we do not apply Nyquist pulse shaping at the transmitter, so that we can best utilize the V_{pp} from the DAC. In the application where wavelength division multiplexing (WDM) is used, the spectrum width can be cut down to its Nyquist bandwidth (~60 GHz in RF domain or ~120 GHz in optical domain) using electrical low-pass filters or an optical multiplexer, with little or no performance degradation expected. After the fiber transmission, the signal is amplified by another EDFA as our coherent receiver does not have transimpedance amplifiers (TIAs). Before entering the coherent receiver, the signal is filtered by an amplified spontaneous emission (ASE) noise rejection filter with a bandwidth of 200 GHz. The signal is then intradyne received by a dual-polarization coherent receiver. The local oscillator (LO) is a free running 100-kHz laser spaced ~0.7 GHz away from the transmitter laser. The received signal is down-converted to the electrical domain using four balanced photodiodes (PDs). The down-converted signal is then sampled by a 256-GSa/s real-time scope. The scope has a maximum bandwidth of 110 GHz. For this 120-GBaud signal, we enabled the bandwidth limitation function on the scope and limited the analog-to-digital converters' (ADCs') bandwidth to 65 GHz.

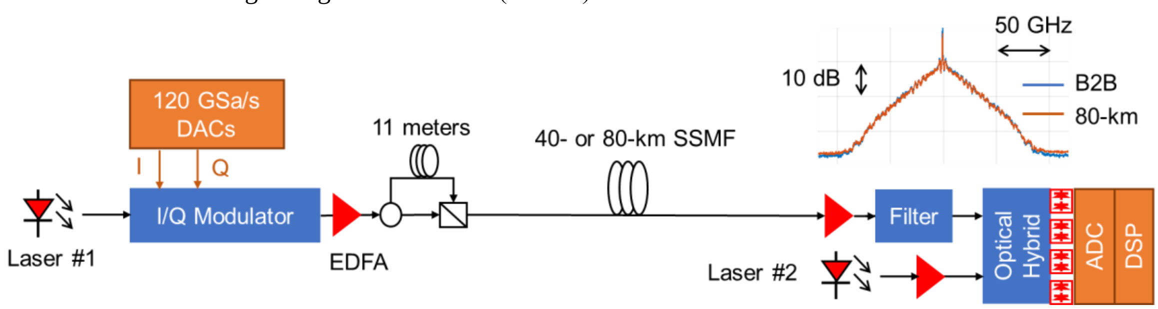

Fig. 2 Experimental setup for the driver-less 120-GBaud 16-QAM system with fiber transmission. The inset shows the optical spectra at the back-to-back and after 80-km SSMF transmission.

Regarding the digital signal processing (DSP), at the transmitter, we generate 120-GBaud uniformly distributed 16-QAM signal. The DACs are operating at one sample per symbol (1SPS). There is neither Nyquist pulse shaping nor digital pre-emphasis, for the purpose of maximizing the electrical driving voltage. In other words, four-level waveforms are sent to the modulator from the DACs. There are ~ 0.5 million random symbols used to form each of the transmitter patterns. At the receiver, the DSP procedures are i) frequency offset compensation; ii) dispersion compensation; iii) frame synchronization; iv) equalization of the waveform by a complex-valued 2x2 least mean square (LMS) equalizer; v) symbol decision. The LMS filter has 161 taps (670 ps), significantly shorter than the PDM emulation delay. Note that our filter is relatively long because of the long RF cables (~20 cm) that we have to use to connect the DAC output and the modulator RF probe. The RF circuits on the DAC evaluation board as well as the cables create reflections which lead to inter-symbol interference (ISI) that require a longer filter to correct. In a product where everything is in a compact form, we expect the filter to be significantly shorter. About 5,000 symbols are used for pre-convergence followed by blind equalization. Only the blindly recovered data are used for BER calculation. We use a 400ZR compatible 14.8% overhead concatenated FEC (C-FEC) [10] which has a bit error ratio (BER) threshold of 1.25 x 10^{-2}. Besides the BER, we also calculate normalized generalized mutual information (NGMI) for future reference. About 2 million symbols are used for BER and NGMI calculation.

4. Results and Discussions

The BER as a function of transmission distance of the 120-GBaud 16-QAM signal is shown in Fig. 3 (a). At the back-to-back condition, the BER is 8.5 x 10^{-3}, and the corresponding signal-to-noise ratio (SNR) is 14.4 dB (measured from the recovered constellation). After 80-km SSMF transmission, the BER increases to 1.1 x 10^{-2}, and the SNR is reduced to 13.9 dB. The received digital spectra is shown in Fig. 3 (b). It can be seen that the spectra have a 65-GHz brick wall cut off from the scope bandwidth limitation. The recovered constellation after 80-km SSMF transmission is shown in Fig. 3 (c). We calculate the system line rate as [4 bits/sym* 120 GBaud * 2 polarizations =] 960 Gb/s, and the net data rate is [960 Gb/s /1.148 =] 836.2 Gb/s. The blue curve in Fig. 3 (a) as well as Fig. 3 (b), (c) are taken with 16.1 dBm standard laser output. As explained, we expect higher output power if the modulator chip has edge couplers. To emulate a transmitter that is not limited by coupling loss, we increased the laser power to 21 dBm and take the measurement again for the 80-km transmission. The result is shown as the red dot in Fig. 3 (a), and the recovered constellation is shown in Fig. 3 (d). The corresponding SNR is 15.2 dB. The BER is 5.1 x 10^{-3}, which is comfortably lower than the FEC threshold.

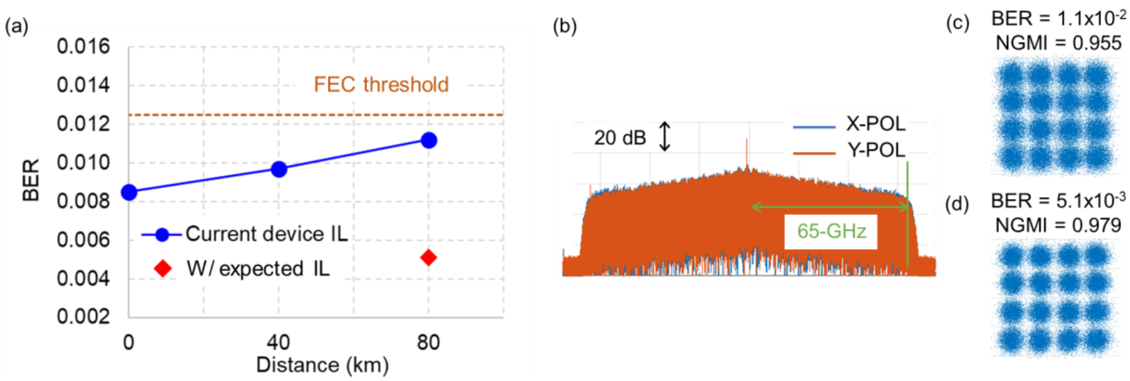

Fig. 3 (a) Measured BER as a function of transmission distance with the current device insertion loss (IL) 10.5 dB, and expected IL of 5.5 dB with edge couplers (emulated by adding laser power); (b) received digital spectrum after 80-km SSMF transmission; (c) recovered constellation after 80-km transmission, with 10.5 dB device loss; (d) recovered constellation after 80-km transmission, with emulated 5.5-dB device loss.

5. Conclusions

We demonstrated a 120-GBaud 16-QAM driver-less coherent transmitter. With 14.8% FEC overhead, the achieved net data rate is 836.2 Gb/s with 80-km SSMF transmission. Such transmitter architecture can be considered for 800 Gb/s coherent pluggable applications.

6. References

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