An Integrated Coherent Driver Modulator Enabled 1.6-Tb/s Coherent Transmission

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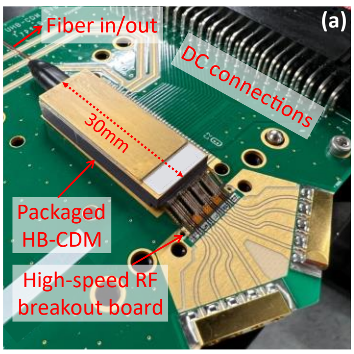
Abstract *We demonstrate a 1.6-Tb/s coherent transmission based on a fully packaged 80-GHz-class coherent driver modulation (CDM) compatible with OIF HB-CDM implementation agreement, indicating a practical single-channel 1.6-Tb/s solution is around the corner.*

Introduction

The dramatic success of 400ZR over the past few years has signaled the penetration of coherent optics to short-reach applications like metro and datacenter interconnect (DCI), and stimulated activities for next-generation 800G industrial interoperability like the OIF 800G Coherent [1] (800ZR/LR) project. In the meantime, both industry and academia are eagerly searching for a practical 1.6-Tb/s coherent solution which is expected to be in high demand in a few years. In the research lab, coherent transmissions with a single-channel speed above 1.6 Tb/s have been demonstrated since 2020 [2-4]. Nevertheless, these demonstrations are still not ready for mass production and commercialization due to various limitations of the coherent transmitter, especially from the driver or modulator. First, most of the works rely on sophisticated transmitter pre-distortion like Volterra nonlinear equalizer [3,4] or even deep neural network [2] to compensate for the transmitter bandwidth limit and nonlinearities, that has not yet been a common implementation in commercial products. Second, these works commonly apply optical pre-emphasis to compensate for the (driver/modulator) bandwidth limit, which not only brings cost concerns but also implementation challenges like the stabilization of the filter center frequency. Third, though novel higher-bandwidth drivers (like the InP DHBT amplifier module in [4]) and modulators (like the thin-film $LiNbO_3$ modulator in [3,5]) are being developed to improve the transmitter bandwidth, it takes time for these techniques to be mature for market introduction. Fourth, all the prior 1.6T-class transmitters are built with discrete components without packaging. It is questionable if the bandwidth/speed would be maintained after being fully packaged into a coherent driver modulator (CDM), one of the main building blocks for commercial coherent transceivers. In this paper, we demonstrate a 1.6T-class coherent transmission using an integrated CDM. The module is fully packaged to be compatible with the OIF Implementation Agreement for High-Bandwidth (HB) CDM [6] defined for prior-generation 64/96/128-GBd CDMs. The CDM [7] provides 80-GHz-class bandwidth to support dual-polarization (DP) 160-GBd signaling. We show successful transmission of a DP 162-GBd probabilistically-shaped (PS) 64-QAM signal (5.9 bits/symbol) with a net bit rate of 1.60 Tb/s after 21-km standard single mode fiber (SSMF) and 1.51 Tb/s after 81-km SSMF, without the need for digital or optical pre-equalization.

80-GHz Class CDM

The fully packaged CDM has a dimension of 12×30×5.3 mm^3 [6]. It consists of an InP-based DP-IQ modulator with a differential capacitively loaded traveling-wave electrode (CL-TWE), and a 4-channel linear SiGe BiCMOS driver integrated circuit (IC). The DP-IQ modulator has a footprint of 2.5×5.0 mm^2 and integrates a spot-size converter to stabilize the optical mode field and the lens coupling loss. Thermo-optic (TO)



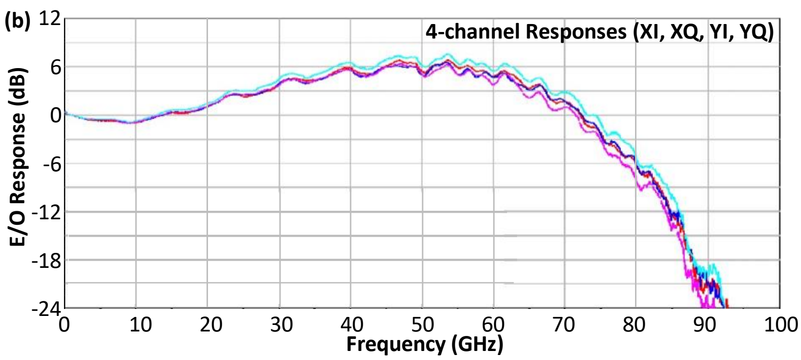


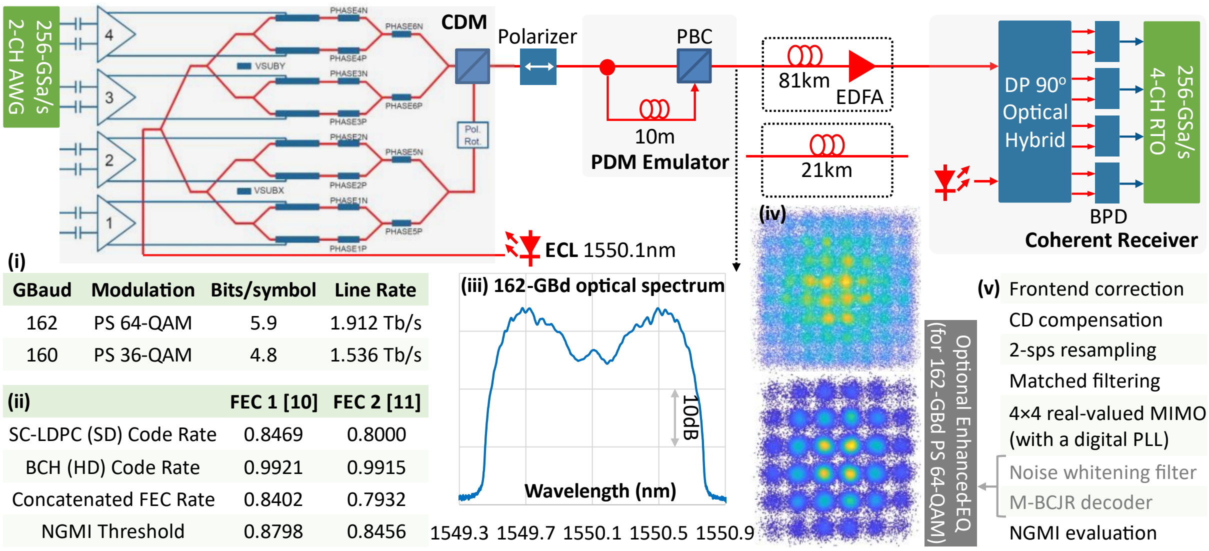
Fig. 1: (a) The fully packaged CDM mounted on an EVB; (b) E/O response of the entire module (at 1550 nm, room temperature).

heaters are used for modulator bias adjustment. The on-chip optical insertion loss is <6.0 dB across the C-band, which is equivalent to or less than that of a commercial bulk $LiNbO_3$ DP-IQ modulator. The modulation region comprises a novel n-i-p-n heterostructure diode [7]. Such structure allows a very thin p-cladding layer, which can greatly reduce the optical and RF losses therefore increase bandwidth (or reduces V_π at the same bandwidth). The modulator has a V_π of 2V and a 3-dB bandwidth >90 GHz. The 4-channel driver has a differential output amplitude of 2.5 V_{pp} for differential 60 Ω and a power dissipation of 3.5 W (or less) at a case temperature of 75°C. The 3-dB bandwidth is >90 GHz without considering wire inductance. All components in the CDM are connected by ball wires. The CDM is mounted on an evaluation board (EVB) shown in Fig. 1(a) with a flexible-printed-circuit RF interface and a surface-mount-type DC interface. The E/O response of the entire module (including EVB) is shown in Fig. 1(b), with a reduced 3-dB bandwidth to ~75 GHz.

Experimental Setup

We embed the CDM into a standard coherent transmission setup as shown in Fig. 2. The light source is an external cavity laser (ECL) tuned at 1550.1 nm with a linewidth <100 kHz and an output power of 16 dBm. The electrical signal is generated by a 2-channel 256-GSa/s arbitrary waveform generator (AWG) (Keysight 8199B prototype) with a 3-dB bandwidth of around 80 GHz. Its peak-to-peak voltage (V_{pp}) is set to 270mV for each single-ended output (540mV differential), a typical V_{pp} for commercial CDM [6]. Because there are only two available 256-GSa/s AWG channels, only one polarization of the DP CDM is modulated as shown in Fig. 2. The other polarization provides a similar performance according to the characterization in [7] and the 4-channel E/O response in Fig. 1(b). The driver gain at 1 GHz is set to be 15 dB (differential). A fiber inline polarizer follows the CDM to reject the residual DC tone from the other polarization (due to its non-ideal manually controlled bias condition). The DP signal is emulated by polarization-combining the single-polarization signal with its decorrelated copy after 10-m SSMF delay. The output optical power after the single-polarization modulation is around -10 dBm. The signal is amplified by an erbium-doped fiber amplifier (EDFA) and then transmitted over either 21-km or 81-km SSMF. For the 81-km case, a second EDFA is inserted ahead of the receiver as a pre-amplifier (PA). The signal is intradyne detected by a DP coherent receiver consisting of a local oscillator (same as the transmitter laser), a DP 90° optical hybrid and four 100-GHz balanced photodiodes (BPD). The BPD outputs are digitized by a 4-channel 113-GHz 256-GSa/s real-time oscilloscope (RTO).

We select two modulation formats targeting net bit rates of 1.6 and 1.2 Tb/s, respectively. The first one is a 162-GBd PS 64-QAM signal with an entropy of 5.9 bits/symbol, and the second one is a 160-GBd PS 36-QAM with 4.8 bits/symbol. The 36-QAM signal is generated from the 64-QAM template in a PS manner which sets zero probability to the outer constellation points [8]. The transmitter offline digital signal processing (DSP) simply consists of root-raised cosine (RRC) filtering (roll-off factor of 0.01), resampling and 0.4% clipping. The receiver DSP is listed in Fig. 2(v). Besides the routine multiple-input multiple-output (MIMO) equalization, for the 1.6-



GBaud	Modulation	Bits/symbol	Line Rate
162	PS 64-QAM	5.9	1.912 Tb/s
160	PS 36-QAM	4.8	1.536 Tb/s

(ii)	FEC 1 [10]	FEC 2 [11]
SC-LDPC (SD) Code Rate	0.8469	0.8000
BCH (HD) Code Rate	0.9921	0.9915
Concatenated FEC Rate	0.8402	0.7932
NGMI Threshold	0.8798	0.8456

Fig. 2: Experimental setup. Inset (i) modulation formats evaluated in the experiment; (ii) two concatenated FEC schemes [11,12]; (iii) transmitter output spectrum; (iv) (back-to-back) received PS 64/36-QAM constellations at the maximum OSNR of 41.2 dB; (v) receiver offline DSP. PBC: polarization beam combiner; PDM: polarization division multiplexing; PLL: phase locked loop.

Tb/s signal, we add a 5-tap noise whitening filter (NWF) followed by a simplified M-BCJR ($M = 64$) decoder [9,10] to boost the performance. The reason of using such enhanced equalization (noted as enhanced-EQ below) is to compensate for the gradually enhanced driver noise beyond the peaking frequency of 60 GHz for this early engineering sample. Such enhanced-EQ is not essential for the CDM sample at the same class of bandwidth with a higher peaking frequency, like the 70-GHz one shown in [7]. We use normalized generalized mutual information (NGMI) as the performance metric. The NGMI is evaluated by the log-likelihood ratio (LLR) calculated from the constellation (w/o enhance-EQ) or the LLR output from the M-BCJR decoder (w/ enhanced-EQ). To claim the net bit rate, we select two forward error correction (FEC) schemes both concatenating a soft-decision (SD) spatially coupled low-density parity-check (SC-LDPC) code with a hard-decision (HD) BCH code as summarized in Fig. 2(ii).

Results

We first evaluate the system signal-to-noise ratio (SNR) as a function of symbol rates using uniform 64-QAM as probe signals. Though the SNR (calculated from the received constellation) takes into account all system impairments, it is mainly determined by the transmitter as the receiver bandwidth is sufficiently high. In Fig. 3(a), the SNR is about 20 dB at 100 GBd and drops down to 16.4 dB at 160 GBd. The steeper decline after 150 GBd indicates an enhanced high-frequency noise, which motivates the enhanced-EQ as shown in Fig. 2(v). Then, we show the optical SNR (OSNR) sensitivity in Fig. 3(b) for the two 160-GBd-class signals listed in Fig. 2(i). For the PS 64-QAM, the enhanced-EQ improves the OSNR sensitivity by more than 2 dB, similar to the gain reported in [9]. The gain becomes smaller for lower OSNR, because the transmitter impairment is less dominant when the optical noise is higher. Using the 1st FEC scheme with an NGMI threshold of 0.8798 [11], the required OSNR is 40.0 dB for the PS 64-QAM signal (w/ enhance-EQ) and 28.6 dB for the PS 36-QAM signal (w/o enhanced EQ). Excluding the FEC overhead, their net bit rates are 1.60 Tb/s and 1.23 Tb/s, respectively. Without using a PA, we receive the 1.6-Tb/s signal (w/ enhance-EQ) after 21-km SSMF with an NGMI above the 1st FEC threshold. The PA becomes essential after the 81-km link and degrades the received OSNR to about 37 dB. The NGMI of the PS 64-QAM signal cannot meet the 1st FEC threshold after 81-km SSMF, and we choose the 2nd FEC with a lower NGMI threshold of 0.8456 [12]. This leads to a net bit rate of 1.51 Tb/s. Fig. 3(inset) shows the NGMI at different launch power to the 81-km SSMF, and the optimum power is around 8-9 dBm.

Conclusions

We demonstrate 160-GBd coherent signaling by a fully packaged CDM. We successfully transmit a DP 162-GBd PS 64-QAM (5.9 bits/symbol) signal (with neither digital pre-equalization nor optical pre-emphasis at the transmitter) over 21-km (1.60-Tb/s net bit rate) and 81-km (1.51-Tb/s net bit rate) SSMF.

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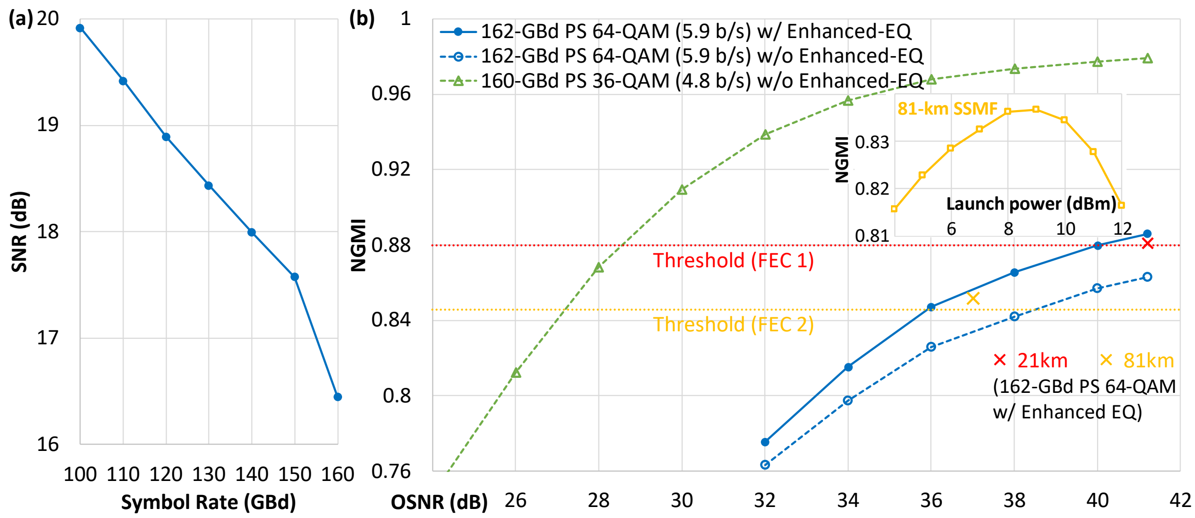

Fig. 3: (a) System B2B SNR as a function of symbol rate (evaluated by uniform 64-QAM signals); (b) OSNR sensitivity for the two formats as summarized in Fig. 2(i); (b-inset) NGMI of the PS 64-QAM signal as a function of fiber launch power (81-km SSMF).

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