Direct Modulation of a 54-GHz Distributed Bragg Reflector Laser with 100-GBaud PAM-4 and 80-GBaud PAM-8

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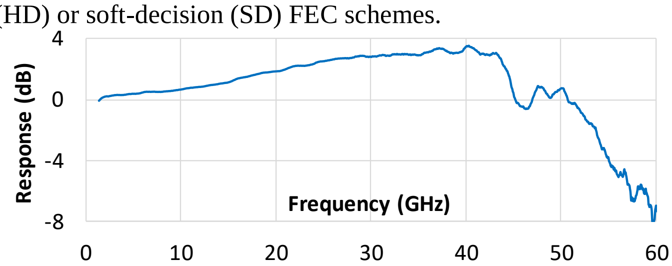
Abstract: We demonstrate both 100-GBaud PAM-4 and 80-GBaud PAM-8 transmissions over 10-km fiber using a 1315-nm 54-GHz distributed Bragg reflector laser with a transient chirp parameter of 1.0. The 80-GBaud PAM-8 system achieves a net bit rate of 200 Gb/s.

1. Introduction

With the completion of 400 Gb/s Ethernet (400GbE) task force a few years ago [1], it is expected 800GbE and 1.6TbE will soon follow in standardization. This calls for a capacity upgrade from 100 Gb/s to 200+ Gb/s per wavelength (Gb/s/λ) on a limited number of parallel coarse wavelength-division multiplexed (CWDM) or local-area network (LAN-) WDM channels. Intensity modulation (IM) has been dominating short-reach applications for years. 200+ Gb/s/λ IM has been achieved by external-modulator-based transmitters, such as Mach-Zehnder modulators (MZM) [2-4] and electro-absorption modulators (EAM) [5-7]. Compared to external modulation, directly modulated lasers (DMLs) offer higher power efficiency and more compact integration, but their bandwidth is usually constrained within 30 GHz, which impedes direct modulation (DM) towards 100-GBaud as well as 200-Gb/s/λ signaling. Among all the available DML wavelength windows, state-of-the-art DM transceivers were only shown to achieve around 100 Gb/s/λ net bit rate using advanced modulations such as PAM-4 [8], duobinary pulse shaping [9], multiband carrier-less amplitude-phase modulation (CAP) [10], Nyquist subcarrier multiplexing [11] and discrete multitone (DMT) [12].

To break the bandwidth ceiling of around 30 GHz, special physical effects including detuned-loading and photon-photon resonance (PPR) have been exploited which enhance the laser response in the high frequency region. A 3-dB bandwidth of 55 GHz was achieved by a short-cavity distributed reflector (DR) laser and demonstrated in a 56-GBaud PAM-4 system [13]. PPR even boosted the DML bandwidth beyond 100 GHz for a membrane short-cavity DR laser on a SiC substrate [14], but the fiber coupled power was limited to <0 dBm partly due to the short gain section. In this paper, we design a short-cavity distributed Bragg reflector (DBR) laser integrated with a short semiconductor optical amplifier (SOA) section to boost the laser power to 9.1 dBm without distortion, and achieve a DM bandwidth of 54 GHz and a small transient chirp parameter of 1.0. To prove such bandwidth in a transmission system context, we use Nyquist-pulse-shaped PAM to generate signals with flat power spectral densities within 50 GHz, and demonstrate both the 100-GBaud PAM-4 and the 80-GBaud PAM-8 DM. The small chirp leads to superior dispersion tolerance, which supports transmissions of both signals over 10-km standard single mode fiber (SSMF) at 1315-nm wavelength, the worst LAN-WDM channel in terms of chromatic dispersion. Excluding the 20% forward error correction (FEC) overhead, the 80-GBaud PAM-8 system achieves a net bit rate of 200 Gb/s. Table 1 summarizes all the claimed data rates with the corresponding assumed hard-decision (HD) or soft-decision (SD) FEC schemes.

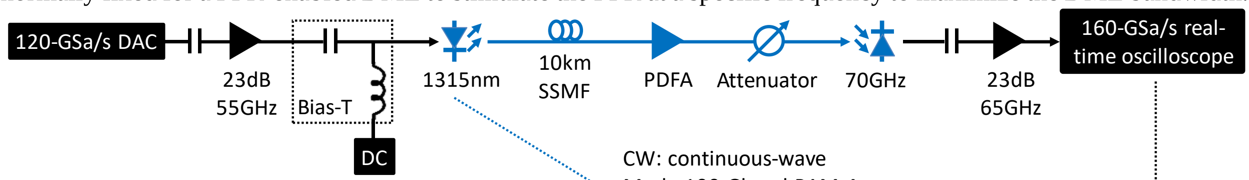
	100-GBaud PAM-4		80-GBaud PAM-8	
	B2B	10-km	B2B	10-km
Line rate	200	200	240	240
FEC	7% HD	20% HD	20% HD	20% SD
Net rate	187	167	200	200



(Left) Table 1. Line rate and net bit rate (Gb/s) achieved in this paper. (Right) Fig. 1. AM response of the modified-grating DBR laser.

2. Laser characteristics

The new DBR laser uses both detuned-loading and PPR effects to enhance the bandwidth while offers a more relaxed design space compared with the previous DR laser [13]. The common short-comings of DBR lasers compared to DR lasers (i.e. the effective reduction of the longitudinal confinement factor and the differential gain due to the passive section in the cavity) are overcome by a novel DBR grating design, which results in a transient chirp parameter as small as 1.0. Fig. 1 shows the amplitude modulation (AM) response of the DBR laser with a 3-dB bandwidth of 54 GHz at 54-mA bias, in which conditions both detuned-loading and PPR effects are maximized. The laser could operate at a high junction temperature of 86ºC, estimated from the bias-dependent wavelength shift. A 50-µm SOA section is integrated to boost the power to 9.1 dBm without distortion, which requires a bias current of only 5 mA. The SOA offers a critical capability of controlling the laser output power independently from the bias current of the laser that is normally fixed for a PPR-enabled DML to stimulate the PPR at a specific frequency to maximize the DML bandwidth.



Transmitter DSP	Receiver DSP
PAM mapping (2^{17} symbols)	Resampling to 2 sps
2-sps upsampling	Matched filtering (RRC)
0.05 roll-off RRC	Timing recovery
Resampling to 120 GSa/s	Frame synchronization
Pre-emphasis	2-sps 1024-tap LMS
Quantization to 8 bits	Symbol decision

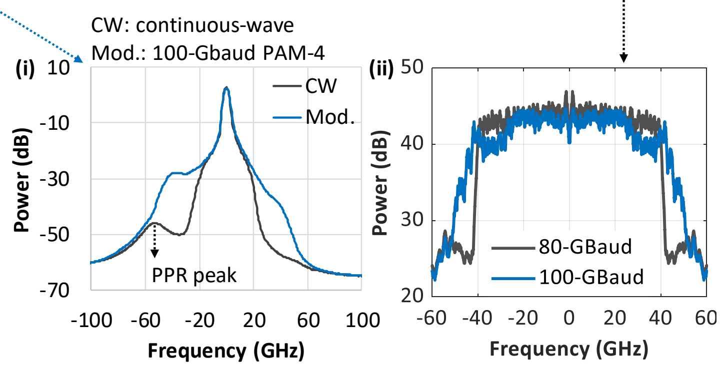


Fig. 2. Experiment setup. Inset (i) optical spectra; (ii) received RF spectra for 80/100-GBaud signals. DAC: digital-to-analog converter; DC: direct current; PDFA: praseodymium-doped fiber amplifier; sps: sample per symbol; RRC: root raise cosine; LMS: least-mean-square equalization.

3. Transmission experiments

We tested the DBR laser using the transmission setup shown in Fig. 2. Both 100-GBaud PAM-4 and 80-GBaud PAM-8 signals were generated by an 8-bit CMOS digital-to-analog converter (DAC) sampling at 120 GSa/s. The DAC output was amplified by a 55-GHz RF amplifier, which drove the DML chip via a 65-GHz RF probe. The bias to the gain section was 54 mA, and the laser output power was 9.1 dBm before coupling to the fiber. Fig. 2(i) shows the optical spectra for both the continuous-wave (CW) output and the 100-GBaud signal. The CW spectrum indicates a PPR peak at around 53 GHz, leading to an asymmetric modulation spectrum similar to a single-sideband signal. The signal was tested with both back-to-back (B2B) and 10-km SSMF. The accumulated chromatic dispersion of this 10-km SSMF was around 9 ps/nm at 1315 nm. In front of the receiver, a Praseodymium-doped fiber amplifier (PDFA) and an attenuator were inserted for sensitivity measurements. The signal was sent to a 70-GHz PIN photodetector (PD). Due to the lack of a transimpedance amplifier (TIA), a 65-GHz RF amplifier was inserted after the PD, whose

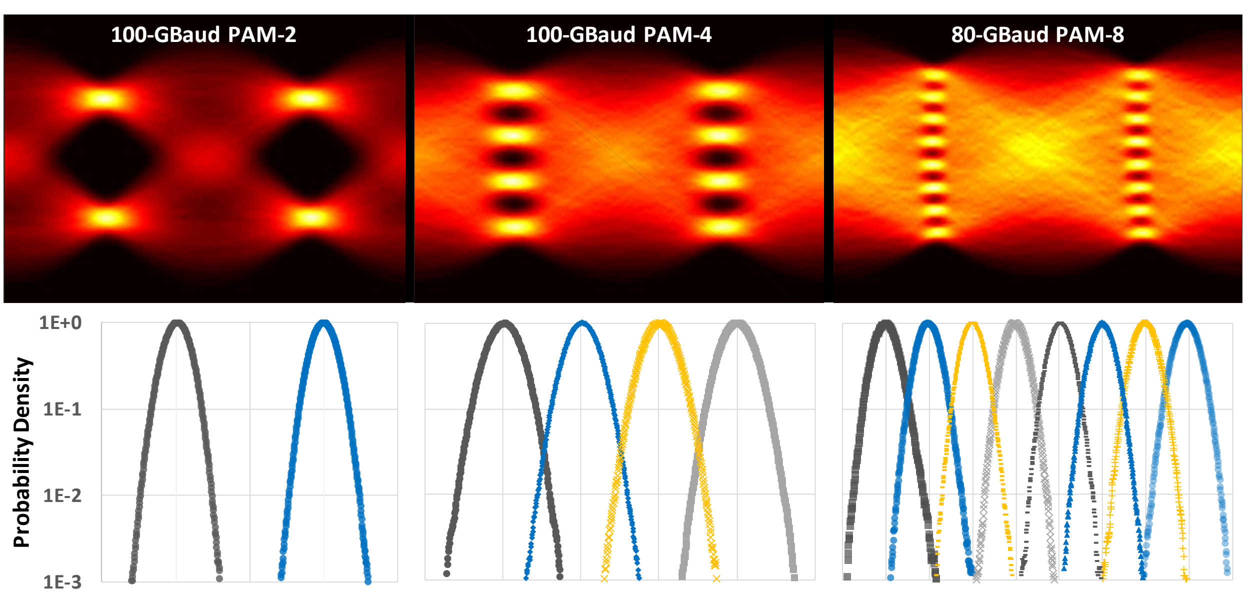


Fig. 3. Eye diagrams and histograms of back-to-back Nyquist-pulse-shaped PAM signals after 2-sps digital equalization at 7-dBm received power.

output was digitized by a 63-GHz 160-GSa/s real-time oscilloscope. Fig. 2(ii) shows the B2B received spectra. The symbol rate was 100 GBaud for PAM-4. The limited DAC bandwidth distorted the signal beyond 40 GHz, and thus we reduced the symbol rate to 80 GBaud for PAM-8. Offline digital signal processing (DSP) was performed at both transmitter and receiver with key steps summarized in Fig. 2. All the PAM signals were Nyquist-pulse-shaped by a root raise cosine (RRC) filter with a roll-off factor of 0.05. At the receiver, signals were processed using 2 samples per symbol (sps) with RRC matched filtering, timing recovery and 1024-tap least-mean-square (LMS) equalization.

Fig. 3 shows the eye diagrams for 100-GBaud PAM-2 and PAM-4, as well as 80-GBaud PAM-8, respectively, after the 2-sps digital equalization. The signals were upsampled 100 times to generate density plots. Considering the receiver used offline DSP with feed-forward timing recovery, the BER is simply determined by the eye-opening at the optimum sampling instant. Thus, we illustrate the signal histograms after the digital equalization (including down-sampling) below the eye diagrams in Fig. 3. The histogram clearly shows an error-free performance for the 100-GBaud PAM-2 signal. The probability densities obey Gaussian distributions, indicating SD-FEC can be applied to predict the post-FEC performance. Fig. 4 shows BER performance for PAM-4 and PAM-8. For 100-GBaud PAM-4, the BER is 3.7e-3 at 7-dBm received power, leading to a 200-Gb/s line rate and a 187-Gb/s net bit rate assuming a 7% HD-FEC with a 4e-3 BER threshold [15]. The BER is 9.8e-3 after 10-km SSMF transmission, corresponding to a 167 Gb/s net bit rate assuming a 20% HD-FEC with a BER threshold of 1.5e-2 [15]. For 80-GBaud PAM-8, the BER is 1.3e-2 at 7-dBm received power, leading to a 240-Gb/s line rate and a 200-Gb/s net bit rate assuming a 20% HD-FEC. The BER is 1.8e-2 after 10-km SSMF. For such Gaussian-distributed received signals, state-of-the-art 20% SD-FEC can correct such a BER [16], which results in a net bit rate of 200 Gb/s after 10-km transmission.

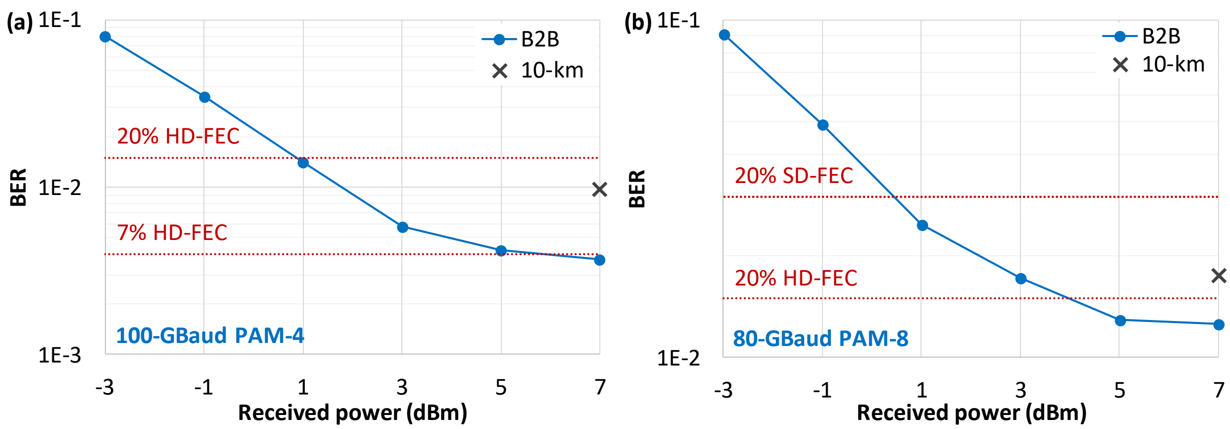


Fig. 4. BER measurements for (a) 100-GBaud PAM-4; (b) 80-GBaud PAM-8. HD-FEC threshold [15]; SD-FEC threshold [16].

4. Conclusions

We demonstrate a net bit rate of 200 Gb/s over 10-km fiber transmission for direct modulation using a newly-designed 1315-nm distributed Bragg reflector laser with a 3-dB modulation bandwidth of 54 GHz. This sheds light on promising solutions with low power consumption and small footprint for short-reach interconnects beyond 400 Gb/s.

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