Reach Extension for 100 Gb/s PAM-4 IM/DD Transmission by Chirp Managed Laser

Son Thai Le[1,*] Yasuhiro Matsui[2], Gregory Raybon[1], Ashish Verma[2], Martin Kwakernaak[2], and Tsurugi Sudo[2]
[1]*Nokia Bell Labs, NJ, USA, *son.thai_le@nokia-bell-labs.com*
[2]*II-VI Incorporated, 41762 Christy Street, Fremont, CA 94538, United States*

Abstract: We demonstrate the first chirp managed laser (CML) supporting 100 Gb/s PAM-4 IM/DD transmissions over a record dispersion range of -70 ps/nm to +53 ps/nm considering KP4 FEC and a low complexity 7-tap FFE.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

Currently, there have been a lot of discussions within the IEEE 802.3 group on the feasibility of 800 Gb/s LR4 and 800 Gb/s ER8 using PAM4 IM/DD [1]. For such applications, reducing the dispersion-induced performance penalty represents the biggest challenge. For 800G, one prominent proposal, which is under intense discussions, is to limit the chromatic dispersion (CD) tolerance to -60 ps/nm to + 37 ps/nm to support 40 km of reach [1]. This CD range limits the wavelength from 1308 nm to 1309 nm in consideration to handling the manufacturing variation of fiber dispersions, which is very tight to fit 8 wavelengths. As a result, techniques for increasing the dispersion tolerance of 100 Gb/s PAM-4 IM/DD are of great interest.

In such cooled environment to support tight channel spacing, the advantages of directly modulated lasers (DMLs) in terms of power consumption, footprint, and production cost of transceiver modules become even more attractive [2, 3] in comparison to externally modulated lasers. Recently, the first 400 Gb/s CWDM-4 transmission over a CD range from -66 ps/nm to 41 ps/nm with DML has been reported [4]. To achieve this performance, strong receiver equalizer (FFE-81) and a higher FEC threshold (e.g. 4E-3, instead of commonly considered 2.4E-4 for KP4 FEC) were used. With the KP4 FEC and low-complexity Rx equalizer (e.g. 7-tap FFE), achieving a CD tolerance of -60 ps/nm to + 37 ps/nm for 100 Gb/s PAM-4 IM/DD with DML is extremely challenging.

To overcome this challenge, the concept of chirp managed laser (CML) was proposed [5, 6] by passing the output of the DML through an optical filter (OF) for FM discrimination [4]. Despite the simplicity of CML, the interaction between the chirp of DMLs and the OF produces a rich variety of effects such as FM-AM conversion, , the suppression of transient chirp, the optical duobinary (ODB) effect, the dispersion supported transmission (DST) effect, minimum shift keying (MSK) format generation, the vestigial sideband (VSB) effects. These effects can significantly extend the reach of DML-based transmission systems. In [6], 250 km of reach in C-band for 10 Gb/s NRZ transmission was achieved with a CML, which is ~ 3 times longer than the reach of EML.

In this work, we present the first CML using a 25-GHz class DML and a commercially available AWG filter, which can also be used for channel MUX/DEMUX, for supporting 100 Gb/s PAM-4 IM/DD transmissions. We experimentally demonstrate a record CD range of -70 ps/nm to +55 ps/nm (with 2 dB sensitivity penalty) with KP4 FEC and a low-complexity 7-tap Rx FFE.

2. Experimental setup

The experimental setup for 100 Gb/s PAM-4 IM/DD CML transmission is shown in Fig. 1. At the Tx, 53.125 Gbaud PAM-4 signal was generated offline. Next, digital pre-emphasis was performed to pre-compensate for the Tx response, including DAC, electrical amplifier (EA) and DML. The digital pre-emphasis was performed in an iterative manner for maximizing the performance in the B2B scenario. After digital pre-emphasis, the PAM-4 was

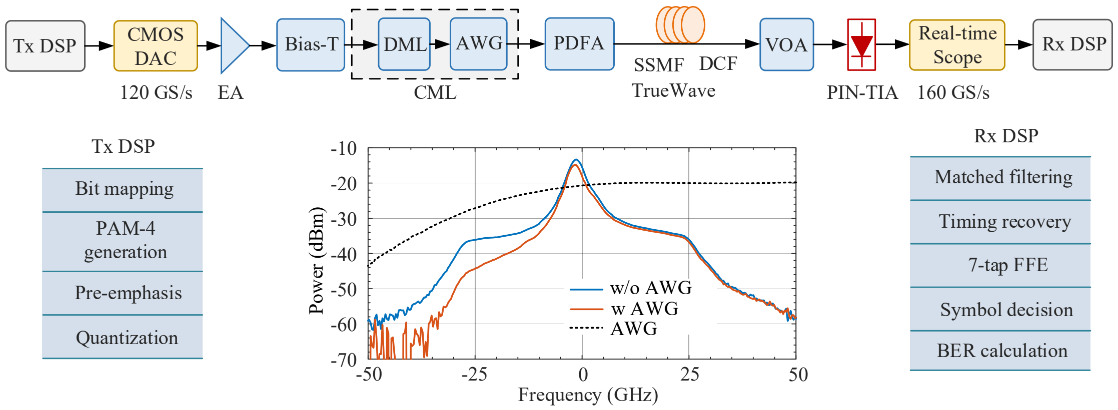

Fig. 1. Experimental setup. Insets show the Tx DSP and Rx DSP and optical spectra of 100 Gb/s PAM-4 signal with conventional DML (w/o AWG) and the proposed CML (w AWG). The center wavelength is 1312.9 nm. DSP – digital signal processing; EA – electrical amplifier; VOA – variable optical attenuator; PDFA – O-band optical amplifier

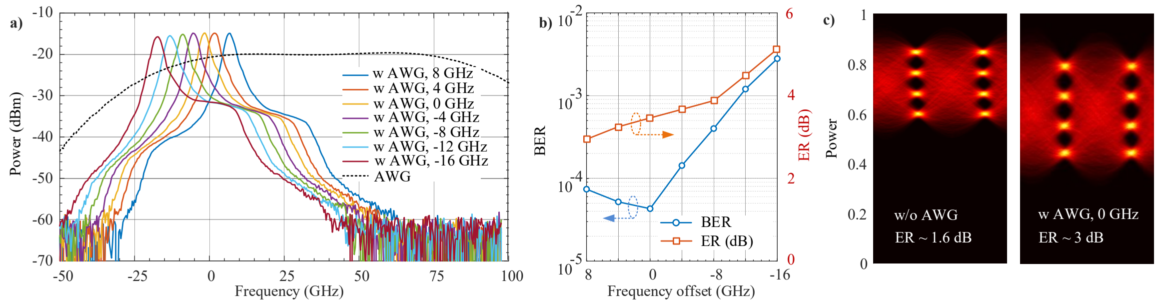

Fig. 2a) – Optical spectra of 100 Gb/s PAM-4 signal after AWG with various values of frequency offset related to the optimum DML frequency; b) – BER and ER as the function of frequency offset; c) – Eye diagrams for the case of w/o AWG (conventional DML) and w AWG and zero frequency offset when the Prx was fixed 2.5 dBm (received with a DC-coupled PIN)

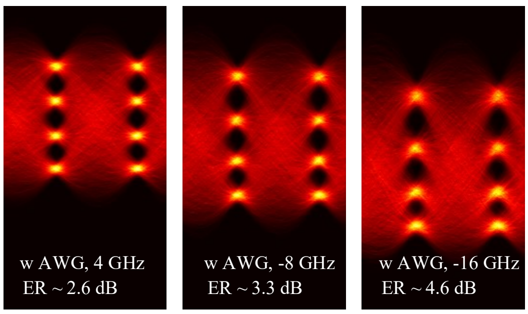

Fig. 3. Eye diagrams and ER for CML with various values of frequency offset

loaded into the memory of a CMOS DAC running at 120 GS/s. After that, the signal at the output of the DAC was amplified by a 55-GHz EA with a fixed gain of 23-dB, which amplifies the modulated PAM-4 signal to ~ 30 mApp. The amplified signal was then fed to a 45-GHz bias Tee for directly driving a 25-GHz class DML. The DML is stabilized by a thermal electric cooler (TEC) and the its output is passed through a fiber-pigtailed athermal AWG (NTT Electronics) with a 125 GHz of channel spacing and an insertion loss of 6 dB. The optical spectra of PAM-4 signal with and without AGW where the DML emits at ~ 1312.9 nm are shown in an inset of Fig. 1. One can clearly note the impact of the AWG on the signal spectrum, where the edge of left sideband is suppressed by ~ 10 dB. To emulate the impact of dispersion, SSMF (0.51 ps/nm/km), UltraWave SLA (2.83 ps/nm/km), TrueWave (-11.39 ps/nm/km) and DCF (-65.67 ps/nm/km) were combined. In order to compensate for the fiber loss, a PDFA with a gain up to 30 dB was used.

At the receiver, the signal is passed through a variable optical attenuator (VOA) which controls the Rx signal power and then the signal was received by a PIN-TIA with a variable gain up to 3000 V/W. The signal was then digitized by a 160 GS/s real-time scope and stored for off-line processing. The Rx DSP is shown in one inset of Fig. 1, which includes matched filtering, timing recovery and a 7-tap FFE.

3. Experimental transmission results and discussions

First, we optimized the frequency offset between the DML and AWG by thermally tuning the DML. The impact of the frequency tunning on the optical spectra is shown in Fig. 2a, where 0 GHz offset represents the optimum configuration (~ 1312.9 nm) providing the best transmission performance. The dependency of BER and ER on the frequency offset are shown in Fig. 2b, where one can see that reducing the frequency offset increases the ER by converting adiabatic chirp into the intensity modulation on the edge of AWG. Without the AWG, the ER is ~ 1.6 dB. Such low ER can suppress the nonlinear behaviour of DML. With the AWG, the ER can be enhanced by ~ 3.0 dB (~ 0.3 dB/GHz slope x 10 GHz adiabatic chirp) at an offset of -16 GHz. On the other hand, a higher ER does not guarantee a lower BER due to the steeper local filter slope for lower eye (Fig. 3). The optimum BER is observed when the ER was enhanced to ~ 3 dB.

The B2B sensitivity measurements for DML and CML systems are depicted in Fig. 4a. One can see that due to the ER enhancement, CML provides ~ 2 dB sensitivity enhancement at KP4 FEC limit, e.g. -8 dBm compared to -6 dBm. The eye diagrams for DML and CML at -9 dBm of Rx power are shown in Fig. 4b, where one can clearly

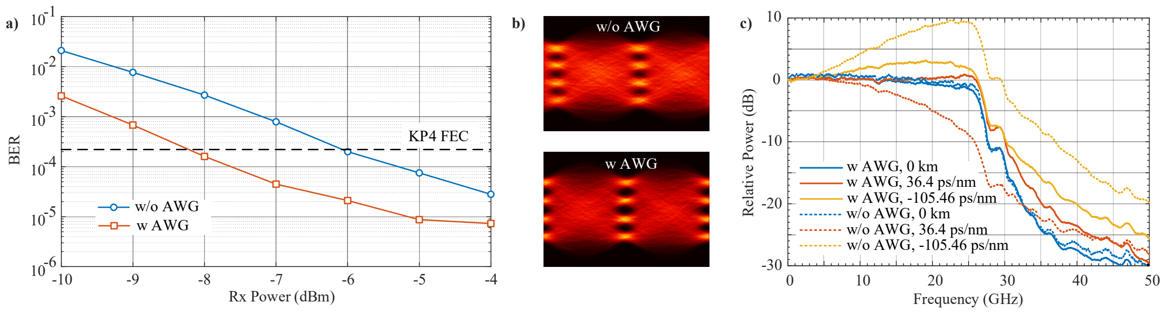

Fig. 4a) – B2B sensitivity measurements for the case of without AWG and with AWG and optimum frequency locking; c) – Eye diagrams at Prx = -9 dBm; c) – Electrical spectra after PIN-TIA for various transmission scenarios, with and without AWG

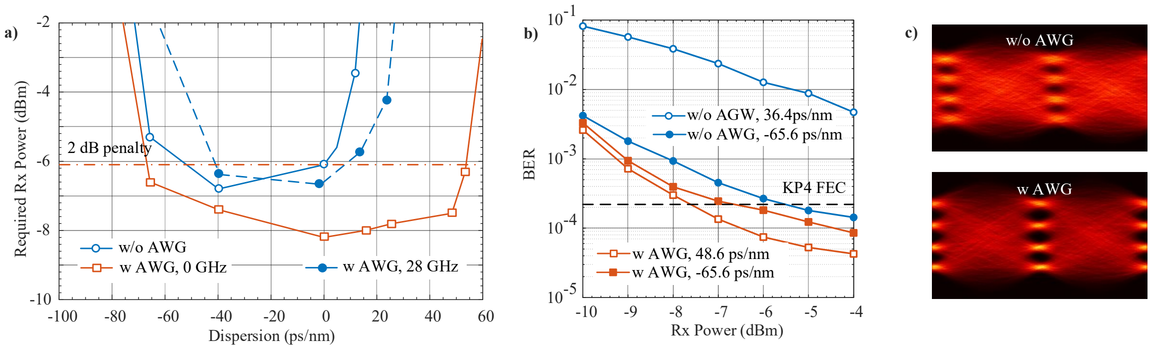

Fig. 5a) – Transmission performances of 100 Gb/s CML and DML systems in fiber link with positive and negative dispersion; b) – Required received signal power at KP4 FEC limit as function of dispersion for CML and DML transmissions; c) – Eye diagrams for DML and CML transmission with + 36.4 ps/nm and a Rx optical signal power of -6 dBm

observe the wide opened eye after AWG.

Figure 4c shows the electrical spectra of the received PAM-4 signals after transmitting through fiber links with various value of dispersions. One can note that for CML transmission, due to the VSB effect, CD (both positive and negative dispersion up to 105.46 ps/nm) shows moderate impact on the received signal spectrum. On the other hand, for the conventional DML case, positive dispersion strongly attenuates high frequency components while negative dispersion enhances high frequency components. These effects lead to strong inter-symbol interference (ISI) which degrade the overall transmission performance. Fig. 4c also indicates that due to the small impact of dispersion observed on the electrical signal spectrum, low complexity equalizers are much more effective for CML transmission compared to DML transmission.

The sensitivity at KP4 FEC limit as a function of the dispersion for CML and DML transmissions are shown in Fig. 5a. As expected, the dispersion tolerance of DML is better on the negative dispersion than on the positive dispersion due to the transient chirp with a positive alpha parameter (2.7). When considering a 2 dB sensitivity penalty, the conventional DML can support a large negative dispersion of -66 ps/nm, however the positive dispersion window is limited only to ~ +10 ps/nm (total span: 76 ps/nm). On the other hand, AWG filter can remove the transient chirp while passing through the adiabatic chirp. This makes the dispersion window symmetric on both negative and positive dispersions while improving the sensitivity due to ER enhancement. Here we consider two cases of CML, namely the optimum case at 0 GHz frequency offset with VSB effect and 28 GHz frequency offset where the modulated PAM4 channel is placed in the middle of the AWG passband (therefore no ER enhancement or VSB effect). The CML with 28 GHz frequency offset (no VSB effect) also supports a similar dispersion range as conventional DML with a slightly shifted bathtub curve due to residual dispersion of AWG filter. At the optimum offset of 0 GHz, the CML shows a much higher tolerance to CD, supporting ~ 120 ps/nm (-70 ps/nm - +53 ps/nm), which is sufficient to support CWDM-4 transmission over 20 km. In addition, according to the dispersion range defined by ITU specification, -70 ps/nm to 53 ps/nm dispersion range corresponds to 1306 nm - 1314 nm, which is sufficient for fitting 8 wavelengths with 400 GHz of channel spacing.

The transmission performances of CML and DML based systems with dispersion of 36. 4 ps/nm, 48.6 ps/nm and - 65.6 ps/nm are shown in Fig. 5b. For conventional DML with 7-tap FEE, a BER below KP4 FEC limit could not be achieved at +36.4 ps/nm of dispersion. On the other hand, for CML-based transmission systems, a BER below KP4 FEC limit could be comfortably achieved with a Rx power of -7.5 dBm, even at +48 ps/nm. This clearly indicates the benefit of the proposed CML.

4. Conclusion

We have demonstrated the first CML for 100 Gb/s PAM-4 IM/DD transmissions. In comparison to the conventional DML, CML significantly enhances the ER and the receiver sensitivity. In addition, due to the VSB effect, CML can greatly extend the dispersion tolerance to supporting emerging applications such as 400 Gb/s CWDM-4 over 20 km or 800 Gb/s over 40 km in a newly proposed wavelength plan with 400 GHz spacing.

5. References

1. Rang-Chen Yu et al, "Feasibility of 800G LR4 and 800G ER8 with PAM4 IMD," IEEE 802.3 Ethernet study group [Online] https://grouper.ieee.org/groups/802/3/B400G/public/21_08/yu_b400g_01b_210819.pdf
2. K. Nakahara et al., "112-Gb/s PAM-4 Uncooled (25°C to 85°C) Directly Modulation of 1.3-μm InGaAlAs-MQW DFB BH Lasers with Record High Bandwidth," ECOC, PD.2.4, 2019
3. Y. Matsui, “Datacenter Connectivity Technologies: Principles and Practice,” (ed. Chang F.) Ch. 3 (River Publishers, 2018)
4. S. T. Le, Y. Matsui, A. Verma, M. Kwakernaak, and T. Sudo, “400 Gb/s CWDM-4 PAM-4 Uncooled (22°C to 70°C) Directly Modulation Transmission over 20 km”, ECOC 2021, France, 2021
5. Y. Matsui, D. Mahgerefteh, Xueyan Zheng, C. Liao, Z.F. Fan, K. McCallion, and P. Tayebati, “Chirp-managed directly modulated laser (CML),” IEEE Photon. Technol. Lett., vol. 18, pp. 385–387, 2006.
6. D. Mahgerefteh et al, “Error-free 250 km transmission in standard fibre using compact 10 Gbit/s chirp-managed directly modulated lasers (CML) at 1550 nm,” Electron. Lett., vol. 41, pp. 543–544, 2005