56Gbps Signal Generation from one 10-G Class Laser Diode for 400G Intra-data Center Interconnection

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Abstract: We have demonstrated up to 56-Gb/s cost-efficient transmission for intra-data center interconnection over 10-km SMF-28 with negative power penalty. This 56-Gb/s transmitter comprises a low-cost 10-G-class directly-modulated distributed-feedback (DFB) laser without requiring expensive digital to analog converter (DAC), analog-to-digital converter (ADC) and power-consuming digital signal processing (DSP).

Keywords: directly-modulated distributed-feedback, interconnection, data center, optical fiber communication.

1. Introduction

With the popularization of data centre and other bandwidth hungry inter-connect applications, the desired capacity of short reach optical network has exponentially increased to 400Gbit/s or even more. Recent standardization efforts for 400G intra-data center connections specify link lengths of up to 2 km [1,2]. 8×56 Gb/s could enable such 400-G networks. Relative to coherent detection [3], intensity modulation/direct detection (IM/DD) is a good candidate in inter-connect due to its low cost [4-8]. For 56-Gb/s signal generation, a few modulation formats or schemes, such as pulse-amplitude-modulation (PAM4) [3-5] and discrete multi-tone (DMT) [6-8], are proposed and experimentally demonstrated. However, these modulation formats need expensive DAC and ADC as well as DSP processing [3-8]. Here we propose and experimentally demonstrate to use 56Gb/s CML signal to transmit over 10km SMF-28 with one negative power penalty. This 56-Gb/s transmitter comprises a 10-G class directly modulated distributed-feedback (DFB) laser and a subsequent optical interleaver. Large dispersion tolerance of this transmitter is realized by chirp control through the phase correlation between adjacent bits for the destructive interference in order to erase the power of “0” bits while enhancing the extinction ratio (ER) [9-12]. In our system, we do not need any DAC, ADC or DSP, so it is one real low-cost solution for high-speed intra-data connection. After transmission over 10-km SMF-28 without any optical amplifier, there is 6.3-dB power margin.

Fig. 1. (a)Schematic of chirp-managed DML transmitter. (b) Solution of 400G (8x56Gps CML signal) data interconnection.

2. Principle

The CML transmitter comprises a DML and the subsequent optical filter, and its schematic diagram is shown in Fig. 1(a) [10-13]. It is based on low cost and simple architecture with intensity modulation and direct detection. The laser is operated at high DC bias and RF driving voltage. One optical filter is used to manage the chirp and enhance the ER. This optical filter can be one regular optical bandpass filter, AWG, WDM coupler, optical interleaver or other optical filter [10-13]. To realize the proper phase flip between the bits, a much higher driven bias compared to the conventional direct modulation is employed. The additional benefits of the higher bias are the higher output power and wider modulation bandwidth due to the high operation point [9-10,13]. We can also achieve the stable signal mode operation and low timing jitter, and make the laser to be the adiabatic chirp dominated via suppression of the transient chirp because the working condition is far away from the threshold of the laser. Fig. 1(b) shows the solution of 400G optical interconnection based on 8x56G CML. We can use one WDM-coupler or AWG to combine the eight CML signals operated at 56Gb/s. At the receiver we use another WDM-coupler or AWG to separate them before direct detection. We assume that the output power from DML is 10dBm, WDM coupler has 1.5dB insertion loss, optical fiber has one insertion loss of 0.2dB/km, and fiber length is 10km. There is additional loss of ~1dB caused by the CML generation when the center wavelength of the signal is tuned away from the passing wavelength of the optical filter. In this case, the optical power after transmission over 10km and two WDM couplers is $10 - 1.5 - 2 \times 1.5 - 1 = 4\text{dBm}$. If consider one WDM-PON system with two 8:1 optical couplers with one total of 18dB loss, then, the optical power is only -14dBm. In our following experiment in Fig. 3(c), we can see that the required optical power is -2dBm. It means that we do not have enough power budget because over 12dB ($14 - 2 = 12$) power increase is needed. To solve this problem, we can use one Avalanche photodiode (APD) receiver, one PIN receiver integrated one semiconductor optical amplifier (SOA), or one EDFA in the transmitter side. One APD usually has over 15dB receiver sensitivity higher than one PIN, and one SOA or EDFA can easily provide over 15dB gain [15]. There are a few schemes for 50Gb/s signal generation and used in the intra-data center interconnection. These schemes include PAM4, DMT, CML, and On-Off keying (OOK). Table 1 summarizes the system performance when we consider the cost, transmission distance, bandwidth requirement for optical and electrical devices and power consumption. If the scheme needs ADC or DAC, usually the power consumption will be high. For PAM4 signal generation, one two bit DAC or one electrical multiplexer is necessary at the transmitter side, and one ADC or multi-level electrical signal detection is required at the receiver side. For DMT signal, DAC is required at the transmitter side, and ADC is required at the receiver side. For 56Gb/s OOK signal, over 40GHz bandwidth of optical and electrical devices is required for high-quality OOK signal generation.

Table. Performance comparison for 50Gb/s signal generation and used the intra-data center interconnection.

Scheme	Bandwidth requirement for O/E devices	Transmission distance without dispersion compensation	Power consumption	Cost
OOK [16]	Larger than 40GHz for OOK signal and	Less than 2km	low	high

	larger than 30GHz for duo-binary [15]			
DMT [6]	~18GHz	Less than 20km	high	high
PAM4 [4]	~20GHz	Less than 10km	high	high
CML [9,11]	~15GHz	Less than 15km	low	low

3. Experimental setup

Fig. 2. Experimental setup of CML signal generation, transmission and direct detection. Red solid line: optical signal path. EA: electrical amplifier, PD: photodiode.

Fig. 2 shows the experimental setup. We use one electrical multiplexer to combine four channels 14Gb/s signal with different time delay for de-correlation purpose to generate 56 Gb/s electrical signal. The 14Gb/s signal is generated from one PPG and the PRBS pattern length is $2^{31}-1$. Then we use one 40GHz RF amplifier to boost the signal to 3.5V before it is used to drive one 10-G class $1.55 \mu\text{m}$ DML (NEL model number: NLK1551SSL). The electrical eye diagram after this RF amplifier is inserted in Fig.2 as inset (i). This DML is DC biased at 130mA with one output power of 10dBm. The DC bias for the operated linear region of this laser is from 20~45mA. Obviously this laser operates at the nonlinear area, and it has one large output power of 10dBm and wide modulation bandwidth. The eye diagram before the optical interleaver is inserted in Fig. 2 as inset (ii). The measured ER is 2dB. We use one 100/200GHz optical interleaver to generate CML signal. This 100/200GHz interleaver has one 3dB passband of 100GHz and 1.2dB insertion loss. The eye diagram after passing through this optical interleaver is inserted in Fig. 2 as inset (iii) with one measured ER of 3.8dB. Insets (ii) and (iii) are measured by using one 65GHz optical port of the sampling oscilloscope. We measured BER performance after this 56Gb/s signal passing through 4.4~20km SMF-28 with one insertion loss of 0.2dB/km and GVD of 17ps/nm/km. At the receiver, one 40GHz optical receiver and a subsequent 40GHz low noise amplifier is used to realize O/E conversion and amplification. We use one electrical de-multiplexer (Centellax MD1S4M) to de-multiplex the signal into four sub-channels with $1/4$ bit rate before BER test (Agilent 70843C). All BER of the four sub-channels are measured, and they show identical BER performance. The threshold of the electrical de-multiplexer is fixed in the middle value when the BER is measured. One optical attenuator is added before optical receiver for optical power change. There is no dispersion compensation or optical amplifier employed.

4. Experimental results

(c)

Fig. 3. (a) BER curves of 42.8Gb/s signal before and after 20km SMF-28 transmission. (b) BER curves of 50Gb/s signal. (c) BER curves of 56Gb/s signal.

We evaluated the BER performance of this CML operated at bit rates from 42.8~56Gb/s with different transmission distance. Fig. 3(a) shows the results at 42.8Gb/s. We can see that there is no power penalty before and after transmission over 20km SMF-28. The measured eye diagrams after detected by the 40G PD before and after 20km SMF-28 are inserted in this figure. The eye is clearly opened. The required optical power is -7.6dBm to get BER of 3.8×10^{-3} . Fig. 3(b) shows the BER curves when the signal is operated at 50Gb/s. Due to fiber dispersion to change pulse shape of the CML signal, we can see that there is one quite large negative power penalty after transmission over 10km SMF-28. But after transmission over 20km, the BER will be error-floor at 3×10^{-3} . Fig. 3(c) shows the BER curves at 56Gb/s. After transmission over 10km, the power penalty is -2dB at FEC threshold of 3.8×10^{-3} . But it gets error-floor at 1×10^{-2} after transmission over 20km. After transmission over 10km, we measured the optical power is 4dBm, and it means that we have 6.3dB ($4 - (-2.3) = 6.3$) power margin after transmission over 10km SMF-28.

The measured P-I curve of the DML is shown in Fig. 4(a). The optical spectra at 56Gb/s before and after optical interleaver are shown in Fig. 4(b). The optical transfer function of optical interleaver is also shown in this figure by blue line. The DML wavelength is 1532.8nm. We use one edge of the optical interleaver to realize the CML signal generation. Because of the periodical response of the optical interleaver, one optical interleaver can be used to realize multi-channel CML generation at different wavelength. Another advantage of optical interleaver is small insertion loss of only 1.2dB. Fig. 5 shows the eye diagrams after transmission over 4.4, 10 and 20km SMF-28.

Fig. 4. (a) P-I curve of the DML, and (b) optical spectra before and after optical interleaver at 56Gb/s.

Fig. 5. Eye diagrams (10ps/div) after (a) 4.4, (b) 10, and (c) 20 km.

4. Conclusion

We have successfully transmitted 56 Gb/s CML signal by using one 10-G class 1532.8 nm DML and a subsequent optical interleaver. After transmission over 10 km SMF-28 without any dispersion compensation, there is -2 dB power penalty and 6.3 dB power margin without any optical amplifier. In our demonstration, no expensive ADC, DAC and application-specific integrated circuit (ASIC) DSP chips are needed, which realizes low-cost operation for future 400G (8x56) intra-data center interconnection.

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5. References

1. Cisco Global Cloud Index. 2014-2019, white paper.
2. IEEE802.3bs 400 Gb/s Ethernet task force.
3. C. Xie, et al., "Generation and transmission of 100-Gb/s PDM 4-PAM using directly modulated VCSELs and coherent detection," OFC 2014, Paper Th3K2.
4. C. Chen, et al., "Transmission of 56-Gb/s PAM-4 over 26-km single mode fiber using maximum likelihood sequence estimation," OFC 2015, paper Th4A.5.
5. F. Karinou, et al., "56 Gb/s 20-km transmission of PAM-4 signal employing an EML in C-band without in-line chromatic dispersion compensation," ECOC 2016, paper W.4.P1.SC5.5.
6. A. Dochhan, et al., "56 Gb/s DMT transmission with VCSELs in 1.5 μ m wavelength range over up to 12 km for DWDM intra-data center connects," ECOC 2016, paper Th.1.C.1.
7. F. Li, et al., "Demonstration of four-channel CWDM 560 Gbit/s 128QAM-OFDM for optical inter-connection," OFC 2016, paper W4J.2.
8. A. Dochhan, et al., "56 Gb/s DMT Transmission with VCSELs in 1.5 μ m Wavelength Range over up to 12 km for DWDM Intra-Data Center Connects," ECOC 2016, Tu.3.C.4.
9. Y. Matsui, et al., "Chirp-managed directly modulated laser (CML)," IEEE Photon. Technol. Lett. **18**, 385-387 (2006).
10. J. Yu, M. F. Huang, P. N. Ji, and T. Wang, "42.8 Gb/s chirp-managed signal transmission over 100 m graded-index plastic optical fiber," OFC 2008, paper PDP28.
11. J. Yu, Z. Jia, M. F. Huang, M. Haris, P. N. Ji, T. Wang, G. K. Chang, "Applications of 40-Gb/s chirp-managed laser in access and metro networks," Journal of Lightwave Technology **27** (3), 253-265 (2009).
12. J. Yu, J. Zhang, H. C. Chien, et al., "56 Gb/s Chirp-managed Symbol Transmission with Low-cost, 10-G Class LD for 400G Intra-data Center Interconnection," OFC 2017, W4D.2.
13. B. Dagens, A. Martinez, D. Make, O. L. Guezigou, J. G. Provost, V. Sallet, K. Merghem, J. C. Harmand, A. Ramdane, and B. Thedrez, "Floor free 10-Gb/s transmission with directly modulated GaInNAs-GaAs 1.35- μ m laser for metropolitan applications," IEEE Photon. Technol. Lett., vol. 17, pp. 971-973, 2005.
14. J. Yu, P. N. Ji, Z. Jia, T. Wang, X. Zheng, Y. Matsui, D. Mahgerefteh, K. McCallion, Z. F. Fan, and P. Tayebati, "42.8 Gbit/s chirp-managed signal transmission over 20 km standard SMF at 1550 nm without DCF," Electron. Lett., vol. 43, 2007.
15. L. Yi, H. Ji, Z. Li, X. Li, et al., "Field-trial of a real-time 100 Gb/s TWDM-PON based on 10G-class optical devices," Proc. ECOC, W 3.E.1, (2016)
16. S. H. Bae, Hoon Kim, and Y. C. Chung, "Transmission of 51.56-Gb/s OOK signal using 1.55- μ m directly modulated laser and duobinary electrical equalizer," Optics Express, **24**, 22555-22562 (2016).