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Journal of Semiconductors
(2020) 41, 032304
doi: 10.1088/1674-4926/41/3/032304

35 km amplifier-less four-level pulse amplitude modulation signals enabled by a 23 GHz ultrabroadband directly modulated laser

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Abstract: The 4-level pulse amplitude modulation (PAM4) based on an 23 GHz ultrabroadband directly modulated laser (DML) was proposed. We have experimentally demonstrated that based on intensity modulation and direct detection (IMDD) 56 Gbps per wavelength PAM4 signals transferred over 35 km standard single mode fiber (SSMF) without any optical amplification and we have achieved the bit error rate (BER) of the PAM4 transmission was under 2.9×10^{-4} by using feed forward equalization (FFE).

Key words: directly modulated laser; PAM4; FFE; IMDD

Citation: Y P Xiao, Y Liu, Y M Zhang, H T Bao, and N H Zhu, 35 km amplifier-less four-level pulse amplitude modulation signals enabled by a 23 GHz ultrabroadband directly modulated laser[J]. *J. Semicond.*, 2020, 41(3), 032304. http://doi.org/10.1088/1674-4926/41/3/032304

1. Induction

As the significant development of data center, real-time video, and online social networks, there are rapid growth of the transmission capacity in the optical fiber communication system[1]. To deal with the large capacity in the optical transmission 400G Ethernet (400 GbE) has been discussed for this standardization[2]. One attractive candidate for this 400 GbE is to adopt 56 Gbps/λ because such high bit rate can greatly reduce the number of lanes in optical transmission and it can significantly reduce power consumption[3]. Currently, in order to improve the bit rate per wavelength, various modulated formats based on IMDD have been proposed to meet such low power consumption, such as discrete multi-tone (DMT)[4], non-return to zero (NRZ), orthogonal frequency division multiplexing (OFDM)[5], PAM[6–8] and carrier-less amplitude and phase (CAP)[9]. For DMT modulation format, the advantage of DMT is that it can use low cost optical devices. However, the high complex digital signal processing (DSP) will be required and the linearity requirement is more stringent than PAM[8]. The greatest advantage of NRZ modulation format is simple modulation and high nonlinear tolerance, whereas its signal bandwidth is large so it is limited by bandwidth of optical devices. So compared with above modulation formats, PAM4 is a better solution due to its half signal bandwidth, flexible implementation and simple structure[10]. However, compared to NRZ modulation format, PAM4 is sensitive to the linearity of components both at receiver and transmitter sides, so we should employ equalization schemes to mitigate the impact of devices' non-linearity. Because of the low dispersion characteristic, the major challenge of band transmission is no longer waveform distortion. The dispersion mainly comes from bandwidth limitation totally can be compensated by FFE and employing (decision feedback equalization) DFE will not have significant improvement[11].

The data centers are extremely sensitive to power consumption, footprint and cost. In order to satisfy the requirements, we should consider the reliability and power consumption of devices. The power consumption of electro-absorption modulated laser (EML) is larger compared to the DMLs, which will cause the larger power consumption in the data centers. Besides, it is difficult for us to characterize the reliability of EMLs due to its increased complexity[12]. IEEE 802.3 Beyond 10 km Optical PHYs Study Group is in the developments stage of 50, 100, 200, 400 Gbps Ethernet in which DML has been considered as a suitable candidate due to its low cost, high linearity, and simple configuration[13]. The performance and reliability of DML play a significant role in our PAM transmission system, since the DML made in our laboratory owns a low threshold current and high linearity so we can set the bias-current at a relative low level which will not introduce reliability and low extinction ratio (ER) problem[14]. Based on the above features, we are able to adopt a lower complexity DSP.

In our previous work, we have experimentally demonstrated that PAM4 transmission system over 40 km SSMF with the complex electrical equalization processing of DFE and FFE, which will result power consumption in the practical application[15]. So in this paper, we further extend the investigation using a ultrabroadband DML module with 3 dB bandwidth up to 23 GHz and low threshold voltage operated at O-band. We experimentally demonstrated 56 Gb/s PAM4 transmission over 35 km SSMF only by employing a simple DSP of different sizes of FFE to figure out the equalization requirements of limited bandwidth system without light amplification, optical chromatic dispersion (CD) compensation or other optical processing. This paper is organized as follows. We

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Received 13 AUGUST 2019; Revised 26 SEPTEMBER 2019.

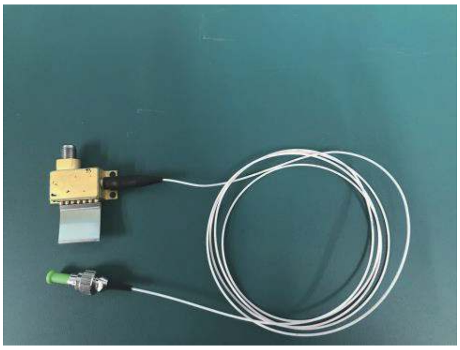

Fig. 1. (Color online) Assembly schematic of proposed DML.

first illustrate the performance of the DML module Finally, an experiment of 56 Gbps with various transmission distance based on this DML module has been carried on.

2. Analysis of the performance of DML

In our laboratory, we have packaged a batch of DMLs and the paper[15] selected a DML with higher threshold current compared this paper. As we all know the lower threshold-current will not introduce serious low ER problems because the DML is able to enter the linear region by using lower direct bias current. Fig. 1 shows the assemble picture of the proposed DML in which the chips operating in O-band were fabricated by nanoimprint lithography technology. The DML chips was packed in a butterfly housing with high-frequency coaxial connector and seven pins. Moreover, the high-reflection and anti-reflection films were coating on the front and rear fronts to emit high power laser[15].

Fig. 2(a) shows the center wavelength of the DML (1310.19 nm) is in the range of zero dispersion point, which is able to greatly reduce the complexity of DSP. Besides, the Fig. 2(a) also shows the side mode suppression rations (SMSR) is able to reach at 50 dB, which it is advantageous for DML to work in single longitudinal mode (SLM). As shown in Fig. 2(b), the degradation reaches at 3-dB at 23 GHz. We can reduce the degradation of bandwidth in the high frequency range[16] by setting wiring bonding optimally. From the Fig. 2(b), we can see that when the current was set at 20 mA, the bandwidth of the DML is 20 GHz, but when the current is larger than 30 mA, the bandwidth of this DML was almost stable at 23 GHz, so during the experiment, considering the optimal linearity and ER problem, the range of 30 to 40 mA was adopted as optical driving current for the DML module. Fig. 2(c) shows the *P–I–V* characteristics of this DML module, it has a threshold current of 5 mA when the temperature was set at 25 °C, besides, the lower threshold current allows the DML to enter the linear region with lower direct current, which plays a significant role in improving the ER. The maximum optical power can be extended to 15 mW when the bias-current was set at 80 mA, and larger output power is advantageous for signal to noise ratio (SNR) of long PAM-4 distance transmission.

3. Experiment setup and results

The experimental setup is shown in Fig. 3, which shows the transmission of the single channel 56 Gbps PAM-4 signal based on DML over 35 km SSMF. Four copies of pseudo-random bit sequences (PRBS) of length 2^{15}–1 was generated by

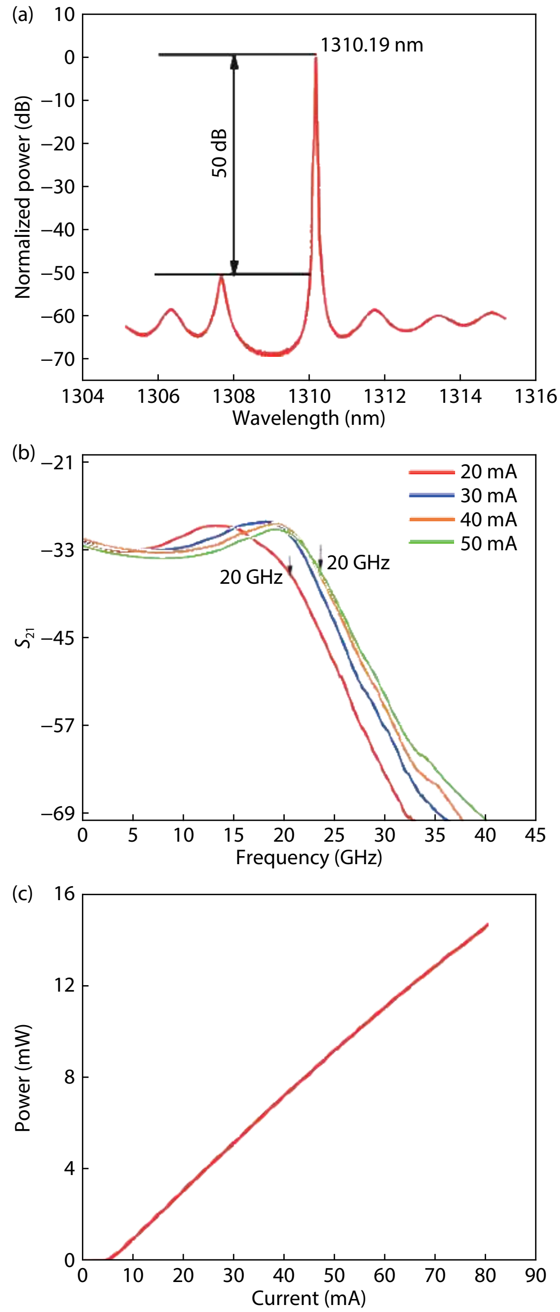

Fig. 2. (Color online) (a) Measured optical spectrum of DML. (b) Frequency response of DML. (c) Measured *P–I* curve of DML.

arbitrary waveform generator (Keysight M8195A) operating at 65 GSa/s with 23 GHz analog bandwidth. In order to reduce the inter-symbol interference (ISI), the roll-off coefficient of root rising cosine was set at 0.35 by its attached software. The signal was amplified by electric amplifier (EA), then this signal directly drives the DML. The output of DML was launched into SSMF, and the received optical power (ROP) was controlled by a variable optical attenuator (VOA). Then the signal was detected by a P–I–N type photodiode with a transimpedance amplifier (TIA). The signal was sampled at 80 GSa/s by a real-time digital sampling oscilloscope (Keysight DSOZ634A) with 32 GHz analog bandwidth. The stored signal was processed by FFE with different tap numbers offline compensating ISI induced by bandwidth limitation. It is worth to note that the network has not adopt any optical amplification.

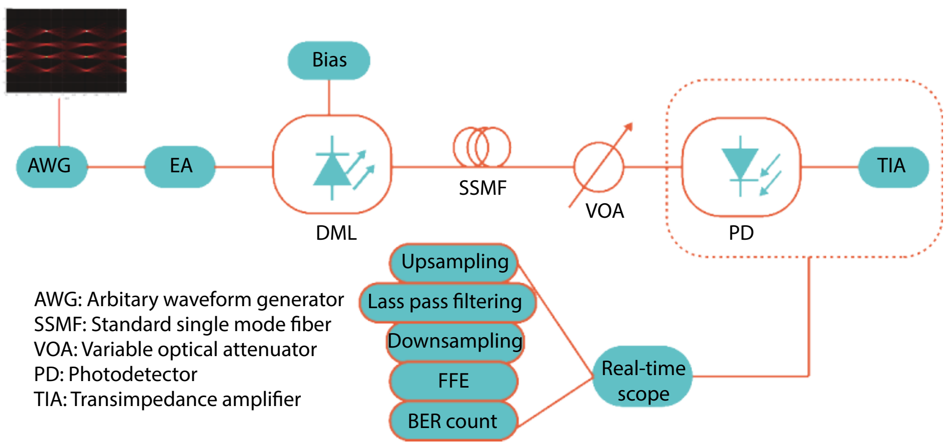

Fig. 3. (Color online) Experimental setup of single wavelength PAM-4 signal transmission.

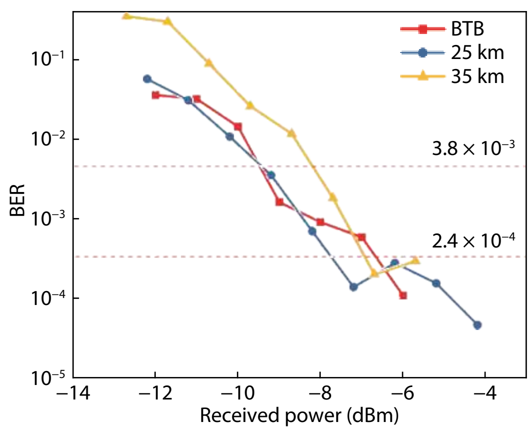

Fig. 4. (Color online) BER performances versus ROP for different distance.

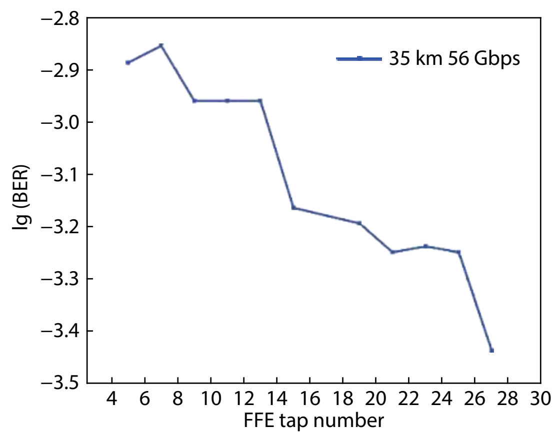

Fig. 5. (Color online) BER versus FFE tap number.

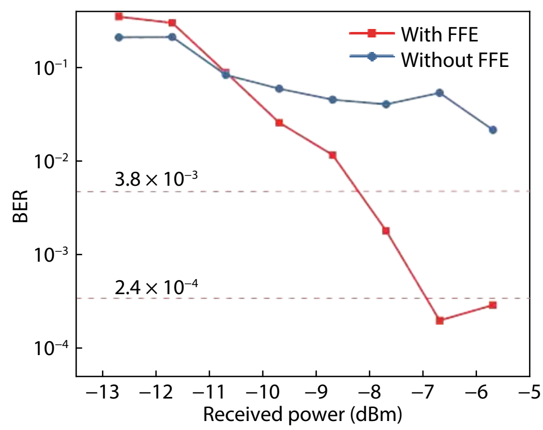

Fig. 6. (Color online) BER performance with FFE and without FFE versus ROP for 35 km.

We tested that the BER performances versus ROP for the proposed scheme. The Fig. 4 shows the BER against the ROP for BTB, 25 km, 35 km distance. From this figure, it can be seen that the BER performance degrades as the ROP decreases and the back to back (BTB) PAM-4 transmission and 25 km PAM-4 transmission have the some change tendency. From the Fig. 4 the BTB PAM4 transmission and 25 km PAM4 transmission almost have the same BER of different ROP and this phenomenon can be explained by the fact that a small amount of negative chirp in distributed feedback (DFB) laser can reduce ISI[17]. Besides, when the ROP is –6 dBm, BER for BTB transmission will be 0 after FFE equilibrium but BER for 25 km transmission system is to be 0 after FFE equilibrium with the ROP is –4.2 dBm, so for the ROP greater than –6 dBm of the BTB transmission and the ROP greater than –4.2 dBm of the 25 km transmission have not been displayed in the figure. Considering sensitivities of photodiode, the ROP should be greater than –12 dBm and in order to achieve all the 56 Gbps PAM-4 transmission cases. The BTB PAM-4 transmission has satisfied HD-FEC 3.8×10^{-3} KP4-FEC 2.4×10^{-4} with ROP greater than –9 and –7 dBm, the 25 km PAM-4 transmission meets HD-FEC 3.8×10^{-3} and KP4-FEC 2.4×10^{-4} with the ROP greater than –9 and –8 dBm and the 35 km PAM-4 transmission meets HD-FEC 3.8×10^{-3} and KP4-FEC 2.4×10^{-4} with the ROP greater than –7.7 and –6 dBm, respectively.

The Fig. 5 plots BER curves versus tap number of 35 km 56 Gbps PAM4 transmission with ROP of –5.7 dBm. As expected, BER reduces with the FFE Tap number increase. From this graph, we can learn that BER will stable at around 3.5×10^{-4} with FFE tap coefficients reaches at 27, considering the DSP complexity and BER performance, 27 taps were fixed during the off-line processing. Fig. 6 presents the BER against different ROP of PAM4 35 km transmission system with FFE and without FFE, respectively. We can see that the BER of the system has greatly decreased greatly after FFE equilibrium, When the ROP is lower, the role of FFE equilibrium is more obvious but the effect of FFE equilibrium has degraded as the ROP decreased due to the sensitivity of the P–I–N photodiode. Fig. 7 shows that the eye diagram of different distance (BTB, 25 km, 35 km) of 56 Gbps. After the 25 and 35 km transmission, we

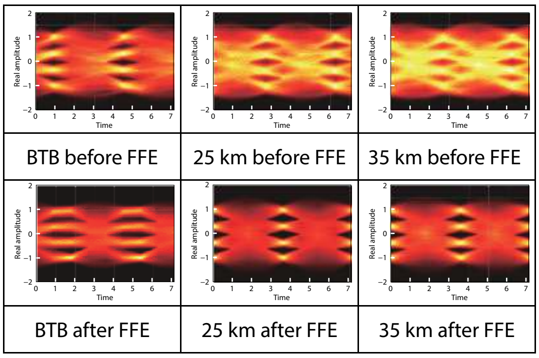

Fig. 7. (Color online) The eye diagram performance for different distance.

are able to see the horizontal eye opening and vertical eye opening becoming worse showing that the BER of the system is terrible. After the FFE Equilibrium we can see that the horizontal eye opening and vertical eye opening have been improved and it also makes lower jitter time, which can obviously show that the FFE equilibrium have better equilibrium effect and It effectively reduces the bit error rate.

4. Conclusion

In this paper, we have experimentally demonstrated that the 56 Gbps single wavelength PAM-4 signal transmission system transferred over 35 km SSMF only using the different size of FFE equilibrium without any optical amplification. We experimentally demonstrated that the BER of BTB, 25 km, 35 km PAM-4 transmission system is below the 7% FEC limit of 3.8×10^{-3} with the receiver sensitivity of –8 dBm and is below the KP4-FEC 2.4×10^{-4} with the receiver sensitivity of –6 dBm. Our DMLs with high bandwidth play a significant role in reducing ISI induced by device bandwidth, which significantly help to reduce the complexity of the algorithm. The DML made in our laboratory with good linearity is suitable for PAM-4 modulation due to high nonlinear tolerance of PAM-4 modulation. Besides, our DML also owns high output power and low threshold current playing an important role in simplifying transmission system, which will be a low cost choice in the practical application.

Acknowledgments

This work was supported by National Key Research and Development Program of China (No. 2018YFB2201101) and the National Natural Science Foundation of China (Nos. 61635001 and 61575186).

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