Analysis of TDECQ Dependence on Skew and Extinction Ratio with 106-Gb/s PAM-4 modulation of Directly Modulated Submicron Ridge Localized Buried Heterostructure Lasers

Kazuki Suga, Kouji Nakahara, Kaoru Okamoto, Shigenori Hayakawa, Masatoshi Arasawa, Tetsuya Nishida, Ryu Washino, Takeshi Kitatani, Masatoshi Mitaki, Hironori Sakamoto, Yasushi Sakuma, and Shigehisa Tanaka
Lumentum Japan, Inc., 4-1-55 Oyama, Chuo-ku, Sagamihara, Kanagawa, 252-5250, Japan
Kazuki.Suga@lumentum.com

Abstract: The importance of high relaxation oscillation frequency to obtain superior 106-Gb/s PAM-4 waveforms was revealed for SR-LBH lasers. In addition, clear 56-Gb/s NRZ eye openings were first demonstrated up to 85°C using SR-LBH laser. © 2020 The Authors
OCIS codes: (250.0250) Optoelectronics; (230.0230) Optical devices.

1. Introduction

With the recent remarkable development of the Internet, the amount of datacenter traffic is growing rapidly. To support increased transmission capacity, 100 Gb/s per lane using 50-Gbaud 4-level pulse amplitude modulation (PAM-4) was standardized for 400 Gb/s Ethernet (400GbE) [1]. For this application, a 106-Gb/s (53-Gbaud) PAM-4 uncooled operation of an Electro-Absorption modulator integrated DFB (EA/DFB) laser was demonstrated [2]. However, a directly modulated laser (DML) operating 106-G/112-Gb/s (53-G/56-Gbaud) is strongly demanded to achieve low cost, low power consumption, and small footprint of lasers. Concerning DML, a 112-Gb/s (56-Gbaud) PAM-4 transmission using the short-cavity distributed reflector (DR) laser at room temperature [3], and a 106-Gb/s (53-Gbaud) PAM-4 operation from 25°C to 80°C using RWG-DML were reported [4]. We also reported 112-Gb/s (56-Gbaud) PAM-4 operation at 85°C using submicron ridge localized buried heterostructure (SR-LBH) laser [5], which is an evolution of ridge-shaped BH (RS-BH) laser [6].

In PAM-4 modulation, skew is well-known to be a major problem of degrading waveforms for DML [7]. To evaluate the quality of PAM-4 waveforms, transmitter and dispersion eye closure quaternary (TDECQ) is widely used. There have been a few reports regarding TDECQ dependence on skews or extinction ratio (ER) [8, 9]. However, the mechanism of increase in TDECQ value by skew and ER has not been discussed using DML which can operate in a high-speed modulation even at high temperatures. Regarding direct non-return-to-zero (NRZ) modulation, although 56 Gb/s at 55°C [6], 53 Gb/s at 80°C [10], and 56 Gb/s at 25°C [3] were demonstrated, 56-Gb/s NRZ modulation at 85°C has not been reported yet.

In this paper, we analyzed TDECQ dependence on skew and outer ER of 106-Gb/s (53-Gbaud) PAM-4 modulation using a fabricated SR-LBH laser. We revealed the importance of high relaxation oscillation frequency f_r to obtain a good TDECQ value and confirmed that a high f_r structure like SR-LBH is effective for improving PAM-4 modulation performance. In addition, we demonstrated clear eye openings of 56-Gb/s NRZ modulation using a fabricated SR-LBH laser up to 85°C for the first time.

2. Device structure and experimental setup

Figure 1(a) shows the schematic cross sectional view of SR-LBH laser [5]. It consists of submicron n-InP upper ridge, MQW active layer, and buried InP current-blocking layers on a p-InP substrate. The upper ridge is not used as an optical waveguide due to its narrow width but as a current injection path. The SR-LBH laser achieved the record high bandwidth of 39.6 GHz and 27.0 GHz at 25°C and 85°C, respectively, due to high optical confinement of a quantum well per active layer width [5].

The experimental setup for PAM-4 and NRZ modulation is shown in Fig. 1(b). 106.25-Gb/s (53.125-Gbaud) PAM-4 and 56-Gb/s NRZ signals were generated by Keysight M8040A PPG, amplified with SHF M827A RF amplifiers, combined with DC bias via bias tee, and applied to the DML chip on carrier. The output signal of DML was coupled to a lensed optical fiber and observed with Keysight N1092C DCA-M. The average optical input power to DCA-M is set around 0.5dBm. The temperature of the measured DML was set by TEC controller. 5-taps de-emphasis is applied to electrical signals in PPG. The 106.25 Gb/s (53.125-Gbaud) PAM-4 characteristics of a SSPRQ pattern at 25°C using a fabricated SR-LBH laser were analyzed. TDECQ values were measured after filtered with the reference filter of 26.6 GHz. On the other hand, the signal pattern of NRZ modulation is pseudo-random bit sequence (PRBS) 2^{15}-1 at 56 Gbaud.

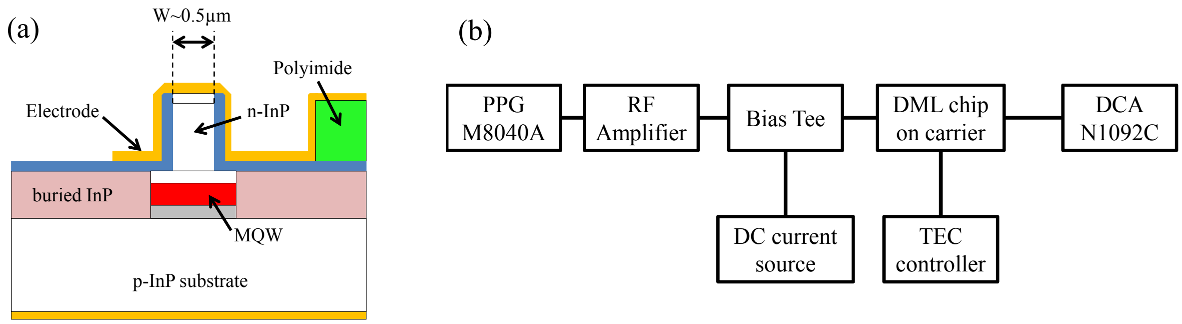


Fig. 1. (a) Cross sectional view of SR-LBH laser and (b) experimental setup for PAM-4 and NRZ modulation.

3. TDECQ dependence on skew and extinction ratio

Figure 2(a) shows an example of 106.25-Gb/s (53.125-Gbaud) PAM-4 eye diagram at 25°C using SR-LBH laser. Clear PAM-4 eye openings with small skew was observed.

Figure 2(b) shows the measured relationship between TDECQ and time skew. Bias DC current I_b in the case of 50 mA and 55 mA was measured. The time skew is defined as the time separation between the highest level and the lowest level. Each time of level is determined by the position which has minimum RMS value of the level thickness. This result shows that larger time skew increases TDECQ value. The measured relationship between TDECQ and outer ER is shown in Fig. 2(c). This result shows the trend that larger ER increases TDECQ value.

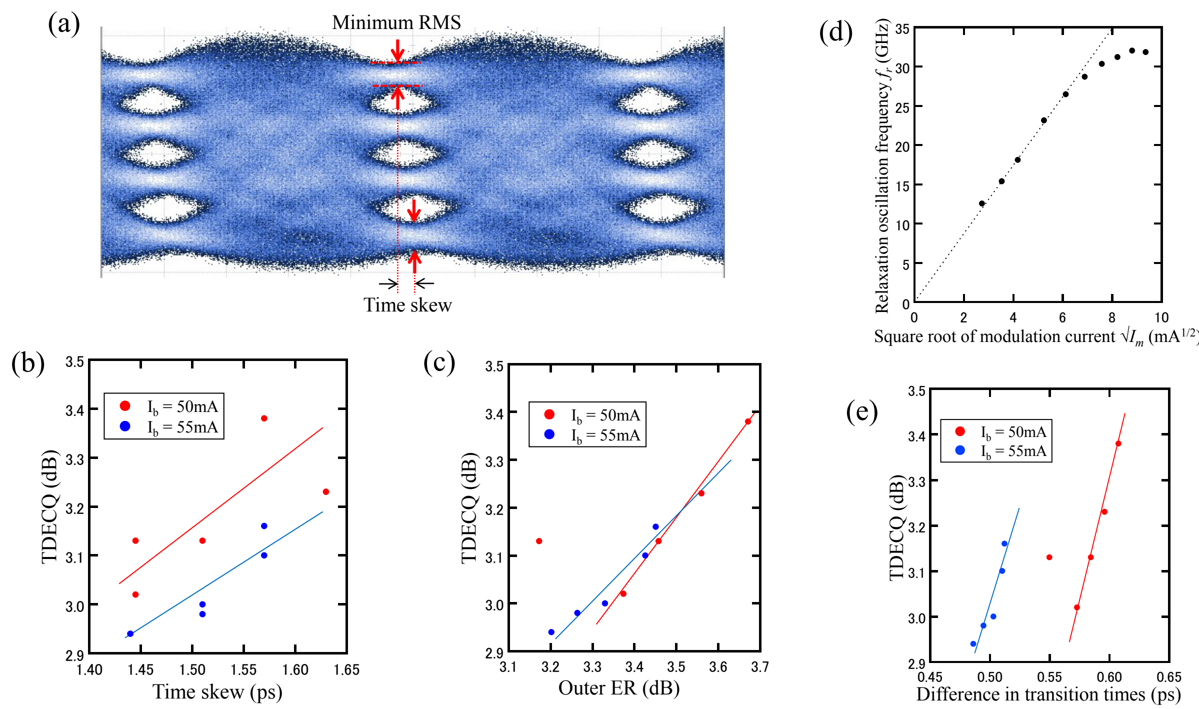


Fig. 2. (a) Eye diagram of 53.125-Gbaud PAM-4 modulation, measured TDECQ as a function of (b) skew and (c) outer ER, (d) estimated f_r as a function of square root of modulation current $\sqrt{I_m}$, and (e) estimated TDECQ as a function of the difference in transition times.

Figure 2(d) shows the measured f_r values with their fittings as small signal frequency responses. The f_r values depend on modulation current and level in DMLs. The f_r value of each level was calculated and the transition time between levels was derived. The TDECQ values as functions of the differences in the transition times between the highest and lowest levels and between the second lowest and lowest levels are shown in Fig. 2(e). The difference in transition times means the size of time skew. The PAM-4 waveform with large outer ER has large modulation amplitude, so f_r of the lowest level is small and f_r of the highest level is large. Therefore, larger outer ER causes larger difference in transition times between the highest and lowest levels and between the second lowest and lowest levels, resulting in larger skew and higher TDECQ value. These results indicate that higher f_r is one of the dominant factors to obtain better TDECQ value. The SR-LBH structure is promising for high-speed PAM-4 modulation because it is suitable for high f_r.

4. 56-Gb/s NRZ waveforms

Figure 3 shows the 56-Gb/s NRZ optical eye diagrams at back to back (BTB) and after 10-km transmission through SSMF at 25, 55, and 85°C, using a fabricated SR-LBH laser. Clear eye openings with over 3.5dB extinction ratio were obtained in the temperature range from 25°C to 85°C both at BTB and after transmission over 10-km SSMF. This is the 56-Gb/s NRZ operation at the highest temperature ever.

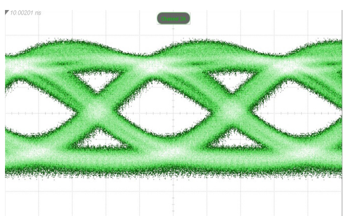
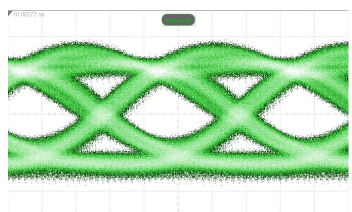
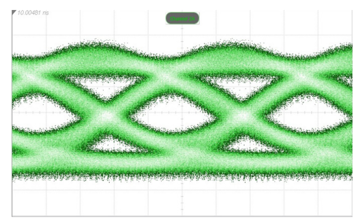
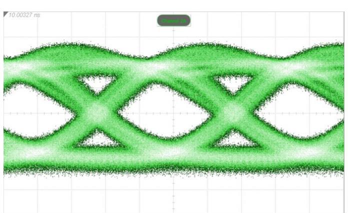
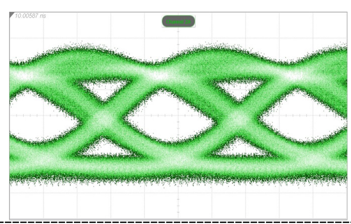
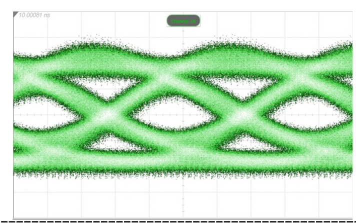
	25°C	55°C	85°C
BTB			
	ER: 3.6dB	ER: 3.9dB	ER: 3.8dB
10 km			
	ER: 3.7dB	ER: 4.0dB	ER: 4.0dB

Fig. 3. 56-Gb/s NRZ waveforms of SR-LBH laser.

5. Conclusion

In order to improve PAM-4 performance of DMLs, we investigated the cause of increase in TDECQ value using high-speed DML. We analyzed the TDECQ dependence on skew and outer ER of PAM-4 waveforms using a fabricated SR-LBH laser. These dependences reveal that the high relaxation oscillation frequency is one of the dominant factors to obtain good PAM-4 waveforms. In addition, clear 56-Gb/s NRZ eye openings were demonstrated up to 85°C using this high-speed SR-LBH laser for the first time.

This result indicates that SR-LBH laser, which has an advantageous structure for a high relaxation oscillation frequency, is a promising candidate for low-cost uncooled 56-Gbaud PAM-4 and NRZ modulation.

6. References

[1] http://www.ieee802.org/3/bs/
[2] Y. Nakai, et al., "Uncooled Operation of 53-GBd PAM4 (106-Gb/s) EA/DFB Lasers With Extremely Low Drive Voltage With 0.9 V_{pp}," J. Lightwave. Technol., Vol. 37, No. 7, pp. 1658-1662, 2019.
[3] Y. Matsui, et al., "55 GHz Bandwidth Distributed Reflector Laser," J. Lightwave. Technol., Vol. 35, No. 3, pp. 397-403, 2017.
[4] N. Sasada, et al., "Wide-Temperature-Range (25–80 °C) 53-Gbaud PAM4 (106-Gb/s) Operation of 1.3-µm Directly Modulated DFB Lasers for 10-km Transmission," J. Lightwave. Technol., Vol. 37, No. 7, pp. 1686-1689, 2019.
[5] 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," Proc. ECOC2019, PD2.4, 2019.
[6] K. Nakahara, et al., "Direct Modulation at 56 and 50 Gb/s of 1.3-µm InGaAlAs Ridge-Shaped-BH DFB Lasers," IEEE Photon. Technol. Lett., Vol. 27, No. 5, pp. 534-536, 2015.
[7] K. Nakahara, et al., "Superior BER Transmission of 106-Gb/s/lane Skewless PAM4 over 10 km by Utilizing 1.3-µm Directly Modulated InGaAlAs-MQW BH Lasers and Incoherent Multiplexing of Two NRZ Signals," Proc. OFC2018, Th3B.3, 2018.
[8] S. Echeverri-Chacón, et al., "Transmitter and Dispersion Eye Closure Quaternary (TDECQ) and Its Sensitivity to Impairments in PAM4 Waveforms," J. Lightwave. Technol., Vol. 37, No. 3, pp. 852-860, 2019.
[9] P. P. Baveja, et al., "Impact of laser dynamics on 56 Gbps PAM-4 modulation of 25G class, 1310 nm, directly modulated lasers," Proc. IEEE Photon. Conf., pp.475-476, 2017.
[10] T. Nakajima, et al., "Wide Temperature Range Operation (20–80°C) of 53.2 Gbit/s NRZ Directly Modulated 1.3-µm DFB Lasers Transmitted Over 2 km," Proc. ISLC2018, MC4, 2018.