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Superior Lowest TDECQ (3.3 dB at 106 Gb/s, 4.4 dB at 112 Gb/s) under PAM-4 Operation at up to 85°C with High Extinction Ratio (4 dB) in 1.3-μm Uncooled Directly modulated InGaAlAs MQW-BH Lasers

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Abstract *The lowest TDECQ values are achieved under PAM-4 operation with 4-dB extinction ratio in improved submicron-ridge-localized-buried-heterostructure DFB lasers at up to 85ºC among uncooled DMLs ever reported. The lasers can attain transmission over 2-km standard single-mode-fiber with CWDM wavelength. ©2022 The Author(s)*

Introduction

The continuous massive growth of the Internet is demanding that all Internet service systems and hyperscale data centers increase the traffic capacity of their optical networks. In hyperscale data centers, which are the core system of the Internet communication, a large number of optical transceivers are installed for short reach transmission below 2 km. To increase the traffic capacity in the hyperscale data center, transceivers with 100-Gb/s PAM4 per lane, such as 100G-FR, 400G-DR and 400G-FR are being used [1]. For this type of transceivers, high-speed light sources of electro-absorption DFB lasers operating at 106-Gb/s PAM4 in the range from 25 to 85ºC have been developed [2]. To further improve performance of optical transceiver, such as reduction of power consumption, footprint, and cost, an uncooled directly modulated laser (DML) at 100-Gb/s PAM-4 operation is expected. There have been a few reports on cooled and uncooled DMLs operating at 100-Gb/s PAM 4 [3-8]. However, these DMLs had low extinction ratio not higher than 3.5 dB. It is difficult to simultaneously obtain high extinction ratio (ER) and low TDECQ with DMLs [9]. Increase in ER makes TDECQ worse. This phenomenon of DMLs becomes remarkable at high temperature.

In this paper, advanced BH layers and optimized InGaAlAs-MQW/SCH structure in submicron ridge localized buried heterostructure (SR-LBH) laser enable the superior lowest TDECQ values of 3.3 dB at 106 Gb/s and 4.4 dB at 112 Gb/s under PAM-4 operation with high extinction ratio (ER) of 4 dB in the temperature range from 25°C to 85°C. In accordance with low TDECQ values, bit error rate values of 106-Gb/s PAM4 at back-to-back much lower than KP-4 FEC threshold are stable within received optical power of 0.5 dBm against temperature from 25°C to 85°C. The investigation of dependence of the power penalty on chromatic dispersion of fibers shows that transmission over 2-km single mode fiber with the zero dispersion of 1310 nm can be achieved in this type of lasers with CWDM wavelength at up to 85°C.

Device structure

Figure 1 shows the schematic bird's eye view of the fabricated SR-LBH DFB lasers. The epitaxial layers of the device were grown on a p-InP substrate by low-pressure metal-organic chemical vapor deposition (LP-MOCVD). The active layer consists of an InGaAlAs MQW layer and InGaAlAs SCH layers. Both layers are optimized in terms of the optical confinement factor. The advanced buried InP layers comprise semi-insulating InP and p and n type InP in terms of reduced leak current. The lasers have a 150-μm cavity length with AR-HR coating at both facets.

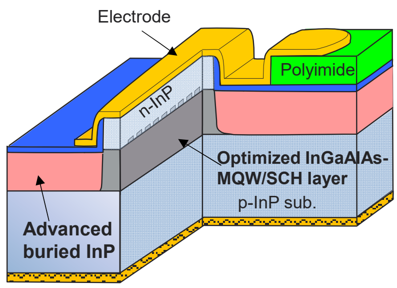


Fig. 1: Bird-eye view with section cut view of SR-LBH laser

Device characteristics

The typical light-current and slope efficiency characteristics of the SR-LBH DFB lasers of this work and previous work [6] under a continuous wave (CW) condition at 25°C and 85°C are shown in Fig. 2. The values of threshold current in this work are almost the same as those in previous work. However, I-L curve of this work has linear whereas the curves of the previous work are saturated in high current region. The slope efficiency of this work is maintained at constant value in high current region whereas it decreases in previous work. Inset of Fig. 2 shows measured lasing spectrum in this work. The single-mode spectra exhibit a high side-mode suppression ratio (SMSR) of more than 40 dB both at 25°C and 85°C.

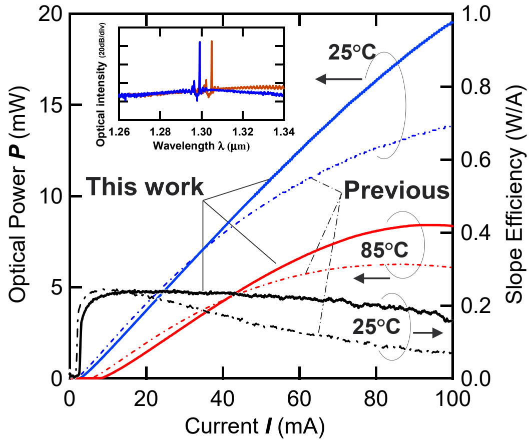


Fig. 2: lasing characteristics of SR-LBH laser

Figure 3 shows the relationship between measured relaxation oscillation frequency f_r and square root of bias current in this work and previous work. The values of f_r in this work are much higher than those in previous work both at 25°C and 85°C. The slopes of f_r in this work are 31% and 47% higher than those in previous work at 25°C and 85°C, respectively. The maximum f_r values of 39 GHz and 27GHz at 25°C and 85°C, respectively, which is 44% and 51% higher than those in previous work.

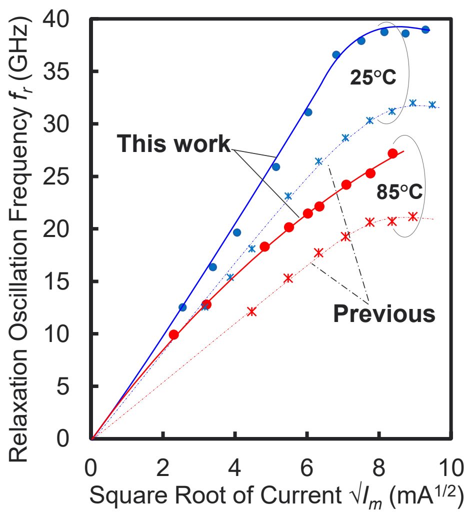


Fig. 3: L-I characteristics and lasing spectra of SR-LBH laser

PAM-4 Modulated properties

To evaluate the high bit-rate PAM-4 performance of the SR-LBH DFB laser, the digital modulated test was carried out at 106-Gb/s and 112-Gb/s PAM-4 operations of a SSPRQ pattern with a Keysight M8040A PPG. A 5-tap de-emphasis of the PPG is only applied to compensate an electrical input signal. Figure 4 (a) shows the results of the optical eye-diagrams with an equalizer of 5 taps evaluated at BTB at temperatures of 25, 55 and 85ºC, respectively. The values of ER are set to 4 dB in all measured temperature range. Note that clearly and equally open eye-diagrams with low TDECQ of 3.3 dB at 106 Gb/s and 4.2 dB at 112 Gb/s were achieved in the temperature range from 25ºC to 85ºC.

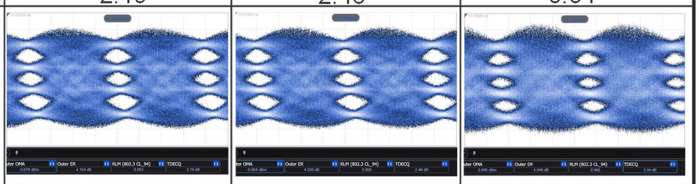
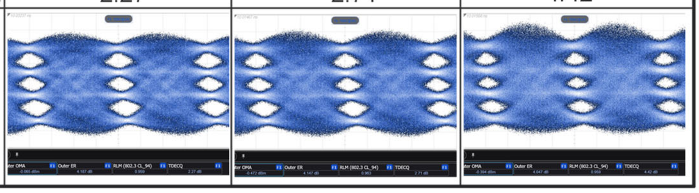
The values of TDECQ against temperature for this and previous work show in Fig. 4 (b). The TDECQ values at 106 Gb/s of this work are 31% to 76% lower than those of previous work in the temperature range from 25ºC to 85ºC even though values of ER in this work are higher than those in previous work. For 112 Gb/s, TDECQ values of this work are 29% to 49% lower than those in previous work. These improvements are due to low leakage current of advanced BH and high optical confinement of optimized MQW/SCH structure.

Transmission properties

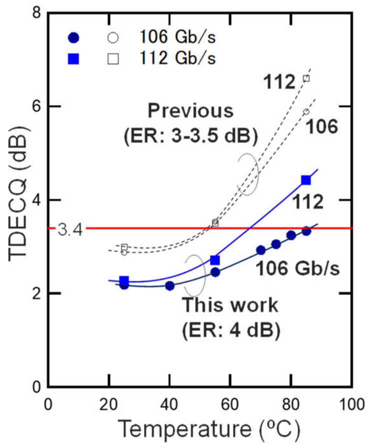
In the bit error rate test (BERT), 106-Gb/s PAM-4 signals with a pseudo-random binary sequence (PRBS) 2^{31}-1 pattern are applied to the SR-LBH laser and optical signals are received by a commercially available QSFP28 transceiver of 100GBASE-FR1 as a BER tester. Measured BER against received optical power shows in Fig. 5 (a). In Fig. 5 (a), circle marks indicate BER at back-to-back (BTB). Increase in received optical power of BER curve from 25ºC to 85ºC is only 0.5 dBm. This small increased value is consistent with small deviation of TDECQ values. Square marks indicate measured BER after transmission over a 10-km single mode fibre (SMF) with zero dispersion wavelength (λ_o) of 1305 nm. The power penalties after transmission over SMF exhibit minus values at 25 and 55ºC, whereas it exhibits a plus value at 85ºC, which is mainly due to chromatic dispersion (CD) of the fiber. The corresponding CD at 85 ºC is estimated to be 0.68 ps/nm. Inverted triangle marks indicate measured BER at 85ºC after transmission over a 10-km SMF with λ_o of 1300 nm. The corresponding CD is estimated to be 3.28 ps/nm. The power penalty (PP) after transmission of the fiber is small value of 1.4 dB. Moreover, Low BER values below KP4 FEC threshold (2.2×10^{-4}) were successfully achieved at all measured conditions. Relation between PP from measured BER curves and estimated chromatic dispersion of fibers is shown in Fig. 5 (b). PP increases with chromatic dispersion due to chirp of the laser. When the L3-lane laser for CWDM is transmitted (λ_{LD}=1335.1 nm at 85ºC), the value of chromatic dispersion of 2km SMF with λ_o of 1310 nm is estimated to be 4.49 ps/nm. Power penalty of this case is expected to be less than 2 dB from Fig. 5(b). Hence, these lasers are applicable for 106-Gb/s short reach CWDM light sources.

Conclusion

We demonstrated that superior lowest TDECQ values of 3.3 dB at 106 Gb/s and 4.4 dB at 112 Gb/s are achieved under PAM-4 operation with high extinction ratio (ER) of 4 dB in improved submicron ridge localized buried heterostructure (SR-LBH) DFB lasers at up to 85ºC. Advanced BH structure that comprises semi-insulating semiconductor and p/n-semiconductor and optimized InGaAlAs-MQW/SCH structure enables improved I-L characteristics and higher relaxation oscillation frequency at both 25 ºC and 85 ºC. These results improve TDECQ values from 31% to 76% at 106 Gb/s and from 29% to 49% at 112 Gb/s under high ER of 4 dB, as compared with previous work, which are the lowest among uncooled DMLs ever reported. The values of bit error rate (BER) at 106-Gb/s PAM4 test are much lower than KP-4 FEC threshold value at all condition. The change of received optical power of BER curves at back-to-back are only 0.5 dBm from 25ºC to 85ºC. The dependence of the power penalty on the chromatic dispersion of fibers indicates transmission over 2-km single mode fiber with the zero dispersion of 1310 nm can be achieved in this type of lasers with CWDM wavelength. Hence, this type of DFB lasers is suitable for cost effective and small footprint 400-Gb/s Ethernet light sources, such as 100G-FR, 400G-DR, and 400G-FR.

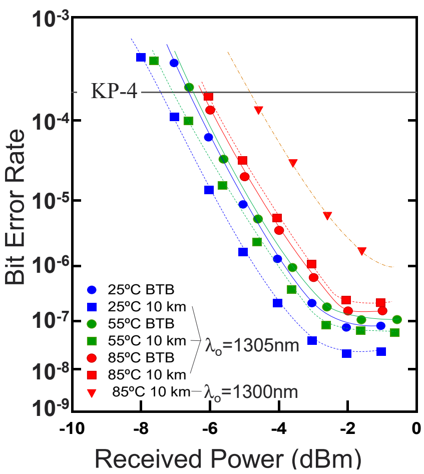
temp. (ºC)	25	55	85
I_b(mA)	40	45	62
TDECQ (dB)	2.19	2.46	3.34
106 Gb/s ER: 4dB 4.71ps/div			
I_b(mA)	45	48	62
TDECQ (dB)	2.27	2.71	4.42
112 Gb/s ER: 4dB 4.46ps/div			

(a) 5-taped optical waveforms of BTB at 106Gb/s and 112 Gb/s ER: 4dB

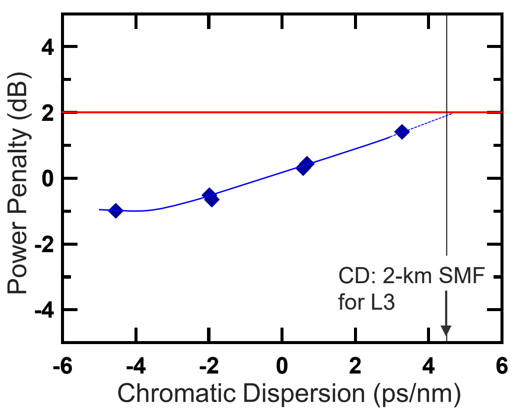


(b) Measured TDECQ against temperature

Fig. 4 Experimental results of SR-LBH laser under 106 Gb/s and 112 Gb/s PAM-4 operation



(a) BER against received optical power



(b) Relation between power penalty and chromatic dispersion

Fig. 5: Bit error rate test of SR-LBH laser at 106-Gb/s PAM-4 signals

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