112-Gb/s PAM-4 Uncooled Directly Modulated BH Lasers

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Abstract *Uncooled 112-Gb/s and 106-Gb/s PAM-4 directly modulated BH lasers are reviewed. High frequency properties of submicron ridge localized buried heterostructure lasers achieve 112-Gb/s PAM-4 modulation from 25ºC to 85ºC. Moreover, low BER values below KP4 FEC threshold are demonstrated with uncooled 106-Gb/s PAM-4 direct modulation.*

Introduction

Continuous extensive growth of the Internet becomes pressuring all of Internet service systems and mega data centres to increase the optical network traffic capacity. The 400-Gb/s Ethernet [1] for next generation data center interconnects applies optical 4-level pulse amplitude modulation (PAM4) at 53 Gb/s instead of conventional non-return to zero (NRZ) modulation to increase twofold transmission capacity. However, eight optical signal lanes and cooled lasers scheme make assembly of optical transceivers complicated. To simplify the structure of optical transceiver modules, uncooled 106-Gb/s PAM-4 electro-absorption integrated DFB lasers have been developed [2, 3] in order to decrease the optical signal lanes and eliminate thermoelectric coolers. 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 [4-7].

Recently, newly proposed InGaAlAs-MQW buried heterostructure (BH) lasers, namely, submicron ridge localized buried heterostructure (SR-LBH) lasers were achieved to operate 112-Gb/s PAM-4 direct modulation at up to 85ºC [7].

In this paper, uncooled 112-Gb/s and 106-Gb/s PAM-4 directly modultion with SR-LBH lasers are reviewed. High optical confinement of SR-LBH lasers enable high relaxation oscillation and high bandwidth in the wide temperature range. These properties of the SR-LBH laser attain 112-Gb/s PAM-4 waveforms with clear eye-opening in the temperature range from 25ºC to 85ºC. Moreover, the laser transmits 106-Gb/s PAM-4 signals with superior low BER below KP4 FEC threshold at BTB and after transmission over 10km SMF in the temperature range from 25ºC to 85ºC.

Device structure and design

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. The current-blocking layers of InP are only buried at both sides of the active layer. The width of the active layer (W_a) is 0.8 µm, which is wider than that of the upper ridge width of 0.5 µm. This structure enable to increase the square root of the optical confinement factor (Γ) per W_a that is proportional to relaxation oscillation frequency. Figure 2 shows calculated results of Γ of a single quantum well (Γ_{QW}) per W_a against W_a for SR-LBH and ridge-shaped-BH (RS-BH) that we previously proposed [8]. The

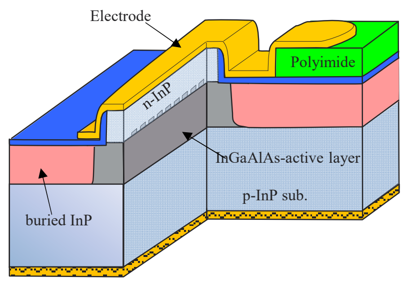

Fig. 1: Bird-eye view with section cut view of SR-LBH laser

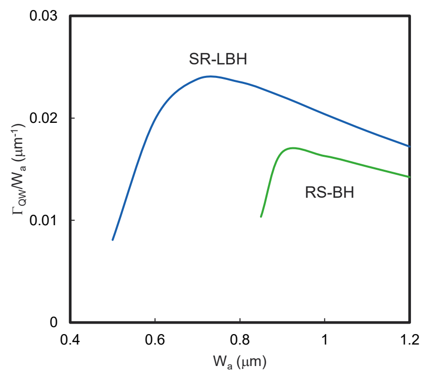

Fig. 2: Optical confinement factor per the width of the active layer against the width of the active layer

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values of Γ_{QW}/W_a for the SR-LBH laser are higher than those for the RS-BH laser because the optical field intensity in the ridge of the SR-LBH laser is low as compared with that of the conventional RS-BH laser that has wide ridge waveguide.

The ridge structure consists of n-InP in order to reduce the device resistance. The laser has the CPM grating to reduce roll-off response in low frequency region [8-9]. The lasers have a 150-μm cavity length with AR-HR coating at both facets.

Measurement set up

To measure the PAM-4 waveform and bit error rate test (BERT), Keysight M8040A PPG was used to generate 112-Gb/s and 106-Gb/s PAM-4 signals with a SSPRQ pattern for waveforms measurement and a 2^{15}-1 pseudo-random bit stream (PRBS) for BERT. Keysight N1092A DCA-M with the reference filter of 26.6 GHz was used to observe PAM-4 waveforms, TDECQ and the extinction ratio of the laser. The values of TDECQ were obtained in accordance with IEEE 802.3cd specification. For BERT measurement, the optical PAM-4 waveform is received at the front-end, which consists of a PIN-PD and a TIA with a 3-dB bandwidth of 30 GHz. A real-time digital oscilloscope (RTO: Keysight UXR1104A, sampling rate: 256Gsa/s, CDR inside) was applied to an error detector. An adaptive linear equalization filter (LEQ) was utilized for the received sequence. A nonlinear equalizer was not employed whereas the DMLs have non-linear characteristics. One million sampling points were stored to the RTO for bit-error counting.

Results and discussion

The fabricated SR-LBH laser has low threshold current of 2.4, and 6.9 mA at 25, and 85°C, respectively under a continuous wave (CW) condition. The measured 3-dB bandwidth in the SR-LBH DFB laser is 40 GHz and 27 GHz at 25 and 85°C, respectively [7]. The values of relaxation oscillation frequency f_r estimated by fitting the small signal frequency response are plotted in Fig. 3. The maximum f_r values of 32.0 and 21.2 GHz are obtained at 25 and 85°C, respectively. The dumping factor Γ estimated by fitting the small signal frequency response is shown in Fig. 4. The values of Γ against square of f_r at 25°C and 85°C are on the same straight line. The value of K factor obtained by the slope of the line is 0.22. The bandwidth of the laser estimated by K factor is 40.4 GHz, which is

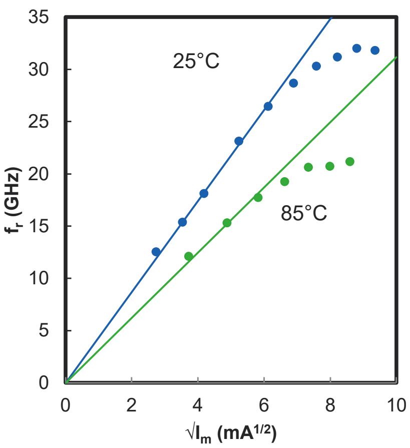


Fig. 3 Relaxation frequency against square root of modulation current

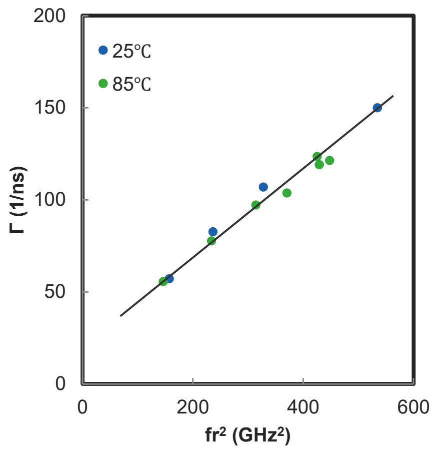


Fig. 4 Dumping factor K against square of Relaxation frequency

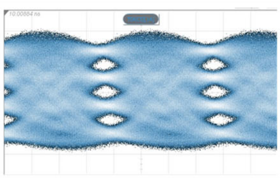
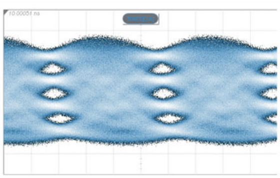
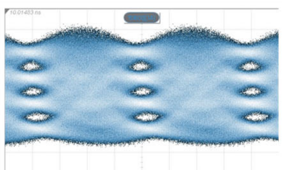
temp. (°C)	25	55	85
I_b(mA)	50	55	62
Outer ER (dB)	3.2	3.3	3.0
TDECQ (dB)	3.1	3.7	7.3
5-taped waveforms BTB 4.46ps/div			

Fig. 5 Optical 112-Gb/s PAM-4 waveforms with 5-tap equalizer at BTB

almost the same as measured value at 25°C.

The 112-Gb/s optical eye-diagrams with 5-tap equalizer under BTB at 25, 55 and 85ºC is shown in Fig. 5. Clear and equal eye openings with small skews and low TDECQ at 56 Gbaud PAM-4 operations are achieved in the range from 25ºC to 85ºC. However, the value of TDECQ increases as increase in temperature due to decrease in bandwidth of the laser.

Figure 6 shows the measured 53-Gbaud PAM-4 BER of the laser at BTB and after transmission over a 10-km standard single mode fibre (SSMF) against the received optical power in the temperature range from 25ºC to 85ºC. Water fall BER curves were obtained both at BTB and after transmission over 10 km SMF in the temperature range from 25ºC to 85ºC. Moreover, Low BER values below KP4 FEC threshold value (2.2×10^{-4}) were successfully achieved at all measured conditions. The values of BER at 85ºC increase as compared with 25ºC and 55ºC. The increase is due to decrease in bandwidth of the laser at high temperature.

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 of the fiber.

These superior 106-Gb/s (53.125-Gbuad) PAM-4 BER properties are due to high f_r and bandwidth of proposed SR-LBH DFB lasers over wide temperature range.

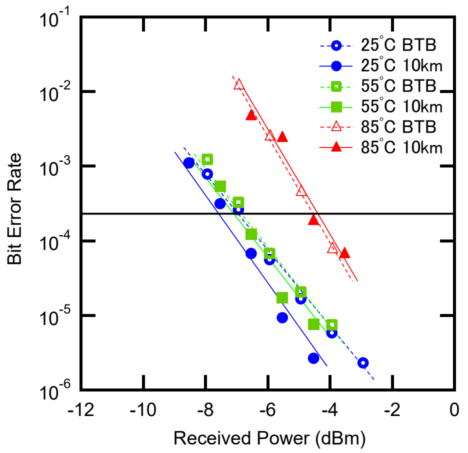


Fig. 6: Bit error rate against received optical power at 106-Gb/s PAM4

Conclusion

We fully reviewed uncooled 112-Gb/s and 106-Gb/s PAM-4 directly modulted BH lasers for next generation of 400-Gb/s Ethernet. The submicron ridge localized buried heterostructure (SR-LBH) DFB laser attained high bandwidth of 40 GHz and 27 GHz, and high relaxation oscillation frequency of 32.0GHz and 21.2 GHz at 25 ºC and 85ºC, respectively. Moreover, dumping factor K was low value of 0.22 ns^{-1} from 25 to 85ºC. These high bandwidth values are due to high optical confinement and low leakage current of SR-LBH lasers with ACPM grating that suppresses longitudinal hole burning.

Owing to these high frequency properties of SR-LBH lasers, the laser can successfully operate 112-Gb/s PAM-4 modulation with clearly and equally open eye-diagrams over the 4-level with small skews in the wide temperature range from 25 ºC to 85ºC. Moreover, the laser transmits 106-Gb/s PAM-4 signals with superior low BER below KP4 FEC threshold at BTB and after transmission over 10km SMF in the temperature range from 25ºC to 85ºC.

Hence, this type of DFB lasers is suitable for cost effective and small footprint 400-Gb/s Ethernet light source.

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