# Ultrahigh Speed EA-DFB Lasers beyond 200 Gbps per Lane

**Kazuhiko Naoe**
*Lumentum Japan, Inc., 4-1-55 Oyama, Chuo-ku, Sagamihara, Kanagawa, 252-5250, Japan*
*kazuhiko.naoe@lumentum.com*

**Abstract:** We describe 224 Gbps-PAM4 uncooled operation by EA-DFB. Moreover, 330.8-Gbps PAM6 (128-Gbaud PAM6), 384 Gbps PAM8 (128-Gbaud PAM8) and 420 Gbps PAM8 (140-Gbaud PAM8) operations by ultrahigh speed EA-DFB are reviewed. 

## 1.Introduction

Global IP data traffic is increasing rapidly, and the trend is expected to be continue indefinitely. The pulse amplitude modulation (PAM) format is one of the promising transmission schemes for increasing total data rate because it is defined as a simple intensity-modulation direct-detection (IM/DD) scheme that does not increase baud rate. For short reach inter-connections in data centers, 400GbE transceivers, which consist of a 4-lane x 100 Gbps PAM4 optical interface, have started to be deployed widely. To be used for 100-Gbaud PAM4 format, 800-Gbit Ethernet (800GbE) and 1.6-Tbit Ethernet (1.6TbE) are under discussion [1].

Electro-absorption modulator integrated distributed feedback (EA-DFB) lasers have the advantages of high bandwidth, low driving voltage, and high extinction ratio, which is suitable for PAMx operation. 100-Gbaud-class PAM4 operation using EA-DFB lasers has been demonstrated by several researchers since 2016 [2-4]. 200G-PAM4 operation with uncooled EA-DFB was firstly demonstrated by our team in 2021 [3].

In this paper, recent progress of ultrahigh speed EA-DFB lasers operating at beyond 200 Gbps per lane is reviewed. First, 224 Gbps PAM4 (112-Gbaud PAM4) operation utilizing lumped element (LE) type EA-DFB lasers with 2-km transmission for 200 Gbps per lane applications is described [3]. Next demonstration of both 330.8 Gbps PAM6 (128-Gbaud PAM6) and 384 Gbps PAM8 (128-Gbaud PAM8) transmission via 500 m and 2-km single mode fiber (SMF) by high-speed EA-DFB with 1.2 Vpp modulation is reviewed [5]. Finally, 420 Gbps-PAM8 (140-Gbaud PAM8) operation using an EA-DFB with 93 GHz bandwidth is described [6].

## 2. PAMx operation by EA-DFB Lasers

### *1.1. 224 Gbps PAM4 (112-Gbaud PAM4) operation by EA-DFB laser*

Figure 1 shows the EA-DFB laser device structure for 112-Gbaud PAM4 operation. The buried hetero structure with semi-insulated InP is applied to reduce parasitic capacitance of the EA modulator. The structure is described in more detail in ref. [3]. The EA modulator is designed as a LE-type electrode structure in the same manner as conventional 100 Gbps-PAM4 EA-DFB. This design makes it possible to reduce chip size and simplify the packaging of the laser module.

Optical output power was obtained over than 15 mW from 20 to 70°C and 9.7mA at 85°C with 100mA laser current. Lasing wavelength was 1311 nm at 50°C with side-mode suppression ratio (SMSR) of more than 40 dB. 3-dB bandwidth (f3dB) on chip carrier was confirmed about 67 GHz, which is enough to obtain clear eye-openings and low transmitter dispersion eye closure quaternary (TDECQ) for 112-Gbaud PAM4 operation.

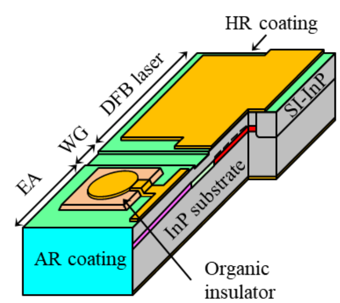



Fig.1 Schematic view of EA-DFB

224 Gbps PAM4 optical eye waveforms from 20 to 80°C are shown in Fig. 2. An arbitrary waveform generator (AWG, Keysight M8199A) was used to generate the 224-Gbps PAM4 signal and it was set to pseudo-random bit sequences (PRBSs) $2^{15}$-1. The PAM4 electrical signal was sent to the EA modulator mounted on a chip carrier via a GSG probe. The drive voltage of the EA modulator was set to 1.2 Vpp from 20 to 80°C. The waveforms on the upper and lower sides represent back-to-back (BTB) and 2-km transmission, respectively. Extinction ratio (ER) at each temperature was set to around 3.6 dB by adjusting EA bias voltage. Thanks to the high bandwidth of 67 GHz, clear eye openings at 20, 50, 70, and even 80°C with ER over 3.5 dB and low TDECQ less than 2.8 dB are confirmed. Additionally, clear eye openings after 2-km SMF transmission were also obtained at all temperatures.

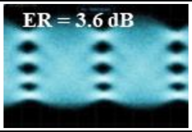
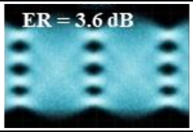
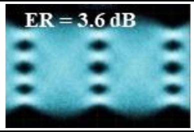
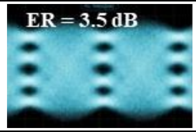
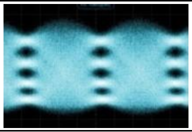
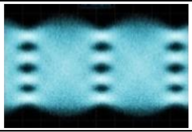
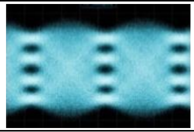
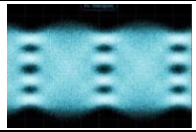
| 224 Gbps PAM4 | 20°C | 50°C | 70°C | 80°C |
|---|---|---|---|---|
| BTB |   |   |   |   |
| 2-km transmission |  |  |  |  |
| $P_{ave}$ (dBm) | 8.2 | 7.7 | 7.2 | 6.0 |
| TDECQ after 2 km (dB) | 2.3 | 1.9 | 2.3 | 2.8 |

Fig. 2. Optical waveforms in BTB and 2-km transmission of 224 Gbps PAM4 signal with TDECQ filter.

### *1.2. 330.8 Gbps PAM6 (128-Gbaud PAM6) and 384 Gbps PAM8 (128-Gbaud PAM8) operations*

The enormous expansion of cloud data is motivating research and development that aim to attain transmission rate beyond 200 Gbps per lane. To further increase total data rate, an IM/DD scheme such as PAMx is attractive in terms of transceiver power consumption and cost for short reach datacenter interconnection.

We have demonstrated 128-Gbaud PAM6 and PAM8 operations using our enhanced EA-DFB with 1317.5 nm wavelength. EA-MQW modification and low inductance assembly were implemented to increase the f3dB while maintaining ER. The f3dB was successfully improved from 67 to 76 GHz from our previous work [3].

330.8 Gbps PAM6 and 384 Gbps PAM8 waveforms, namely, electrical waveform and optical waveform at BTB, 500 m and 2 km transmission at 50°C are summarized in Fig.3. The upper and lower waveforms show 128-Gbaud PAM6 and PAM8 operation, respectively. The electrical waveforms, shown in left boxes, were generated by AWG through a driver amplifier and bias tee. Modulation voltage was fixed as 1.0-Vpp due to the experiment setup. The BTB waveforms show clear eye openings and replicate the electrical waveforms well in the case of both 330.8 Gbps PAM6 and 384 Gbps PAM8. The eye openings after 500 m and 2 km SMF transmission can still be observed with slight degradation. Average optical output power ($P_{ave}$) and the ER were 9.8 dBm and more than 4.4 dB at 50°C, respectively.

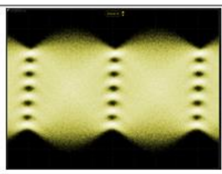
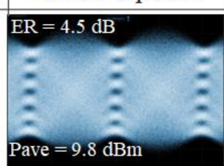
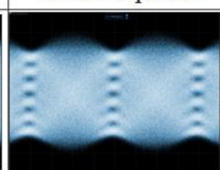
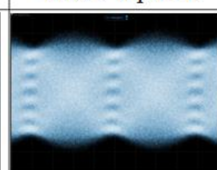
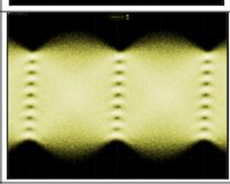
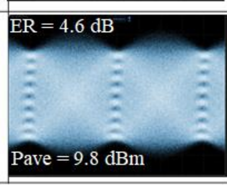
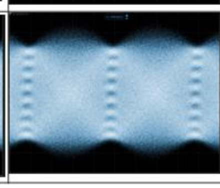
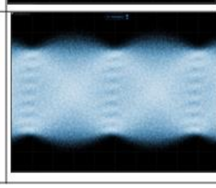
| Modulation format | Electrical waveform | BTB with 5-tap FFE | After 500-m with 5-tap FFE | After 2-km with 5-tap FFE |
|---|---|---|---|---|
| 330.8-Gb/s PAM6 (128-Gbaud) |  |   |  |  |
| 384-Gb/s PAM8 (128-Gbaud) |  |   |  |  |

Fig. 3. 330.8 Gbps PAM6 (128-Gbaud PAM6) and 384 Gbps PAM8 (128-Gbaud PAM8) waveforms at 50°C.

### *1.3. 420 Gbps PAM8 (140-Gbaud PAM8) operation for beyond 400 Gbps per lane*

As a basis of our 200G-PAM4 EA-DFB structure [3], the EA-DFB laser was additionally optimized to increase bandwidth for 420 Gbps PAM8 operation. In particular, the design of the EA modulator design was optimized for 50°C operation to increase bandwidth while maintaining extinction ratio.

As shown in Fig.4, the threshold current and the optical output power at 100 mA were 10.5 mA and 22.0 mW at 50°C, respectively. Lasing wavelength was 1321.5 nm. Figure 5 shows the EO-response at 50°C measured by lightwave component analyzer (Keysight N4372E). The f3dB was 93 GHz which was improved from the 76 GHz obtained in previous work [6] due to optimum EA modulator design.

Electrical and optical eye diagrams of 420 Gbps (140-Gbaud) PAM8 signal under BTB, 500 m, and 2 km transmissions are shown in Fig. 6. The experimental setup is described in ref. [6]. The BTB waveform shows a clear eye-opening almost equivalent to that of the electrical waveform with 3.7 dB ER. $P_{ave}$ is 9.1 dBm at the chip facet. After 500 m transmission, the waveform shows similar clear eye-openings to those of BTB with only a 5-tap feed-forward equalizer (FFE). The eye-opening is recognizable even after 2 km transmission despite fiber dispersion.

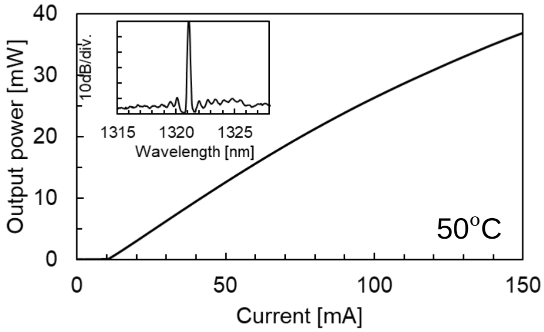



Fig. 4. I-L curve and lasing spectrum at 50°C

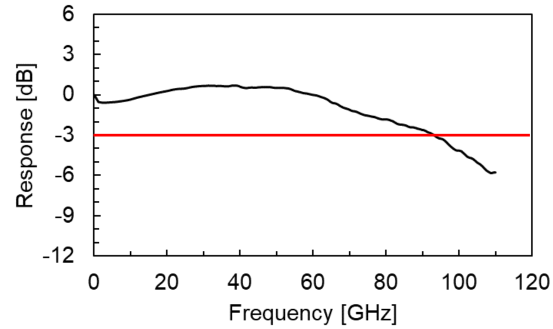



Fig. 5. EO-response at 50°C

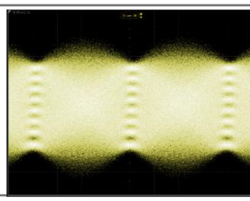
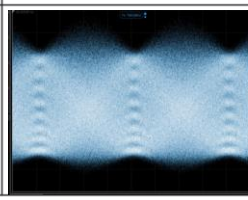
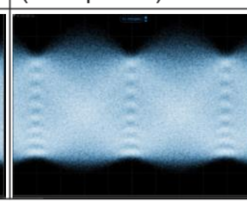
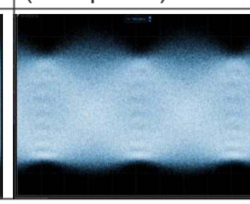
| | Electrical waveform (0.9 Vpp) | Optical waveform with 5-tap FFE, 50°C | | |
|---|---|---|---|---|
| | | Back-to-Back | After 500 m (+0.7 ps/nm) | After 2 km (+1.9 ps/nm) |
| 420 Gbps PAM8<br>ER = 3.7 dB<br>$P_{ave}$ = 9.1 dBm |  |  |  |  |

Fig. 6. Electrical and optical waveform of 420 Gbps (140 Gbaud) PAM8 at BTB, 500 m and 2 km transmissions

## 3. Conclusions

An uncooled LE EA-DFB laser, which demonstrated 2-km SMF transmission of 224-Gbps PAM4 with TDECQ of less than 2.8 dB from 20 to 80°C, was developed. The optimized LE-EA-DFB laser demonstrated 330.8 Gbps PAM6 and 384 Gbps PAM8 operations. Additionally, an ultrahigh speed EA-DFB with 93 GHz bandwidth demonstrated 420 Gbps PAM8 operation at BTB and after 2 km transmission. The ultrahigh speed EA-DFB thus represents one of the best light sources for upcoming 400 Gbps per lane applications with IM/DD scheme.

## 4. Acknowledgements

The author thanks the device design and the process engineering team at Lumentum Japan for their contribution to this work.

## 5. References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