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Research Article

100G PAM4 High-extinction Ratio EML Manufacturing for 400G and 800G Artificial Intelligence (AI) Optical Transmissions

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Abstract

This study presents the chip- and transceiver-level performance data of high Extinction Ratio (ER) 100 Gb/s Electroabsorption Modulation Lasers (EMLs) for 400G & 800G artificial intelligence (AI) optical transmission and computing applications. Our 100 Gb/s EML demonstrates high extinction ratio, high output power, and low threshold current—features well-suited for four-level Pulse Amplitude Modulation (PAM4). The combination of high power and low threshold current also contributes to reduced power consumption at the module level. Additionally, the high extinction ratio helps achieve a low Bit Error Rate (BER), which is critical for 800G optical switches.

Introduction

Electro-absorption Modulation Lasers (EMLs) are indispensable semiconductor lasers used in long-distance optical communication systems [1,2]. By combining the functions of a Laser Diode (LD) and an Electro-absorption Modulator (EAM) into a single device, EMLs offer performance advantages over Directly Modulated Lasers (DMLs), such as higher speed and higher Extinction Ratio (ER). In addition, EMLs exhibit lower chromatic dispersion compared to their DML counterparts. This is because the laser diode section operates in Continuous Wave (CW) mode without directly involving signal modulation or experiencing property changes. The optical output signals are generated when ON/OFF electrical signals are applied separately to the EAM section.

The extinction ratio of an EML plays a critical role in determining the performance of a fiber optic link [3]. The ER is defined as the ratio of optical power in the "ON" state to that in the "OFF" state. A higher ER indicates greater contrast between the ON and OFF states, resulting in clearer signal distinction at the receiver. With a higher ER, the likelihood of bit errors caused by noise or signal degradation over the fiber link is reduced. Therefore, a higher ER leads to a better Bit Error Rate (BER) and can also effectively improve the Signal-to-Noise Ratio (SNR) at the receiver.

In modern Artificial Intelligence (AI) datacenters, 400G FR4 and 800G 2xFR4 optics are commonly deployed in high-performance computing systems [4]. In 400G FR4 optics, 4×100 Gb/s transmission over 2 km is achieved by operating four EML chips at 100 Gb/s per lane. Using four-level Pulse Amplitude Modulation (PAM4) modulation, a 53 Gbaud EML can deliver a 100 Gb/s data rate. In 800G optics, the 2xFR4 configuration is typically used, where eight 53 Gbaud (100G PAM4) EML lanes are employed.

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Background

AI plays a vital role in deep learning, electric vehicles, robotics, healthcare, weather forecasting, and many other applications. Since the launch of ChatGPT in November 2022, AI has emerged as one of the most significant technological advancements [5]. ChatGPT helps users obtain answers, access useful references, and enhance productivity. Following the release of Nvidia's DGX H200 supercomputing systems in 2023, AI infrastructure and factories have been reshaping and revolutionizing various industries [6]. In early 2025, the introduction of DeepSeek language models further facilitated the integration of AI tools into household applications through their accessible platforms [7,8].

GPUs, AI servers, and high-speed optical links are all critical building blocks in enabling High-performance Computing (HPC) for AI models [9-11]. High-speed optical links, such as 400G and 800G optical transceivers, allow AI systems to rapidly exchange information and process data. These 400G/800G optics effectively support the fast data transmission required for HPC environments.

Table 1 shows the optical connectivity scenarios for 400G and 800G switches. Scenario 1 involves connectivity between servers and switches—for example, GPUs connecting to top-of-rack switches using 400G or 800G optical transceivers. Scenario 2 refers to intra-server connectivity, such as GPU-to-GPU communication. Scenario 3 addresses multi-server connectivity, which requires optical communication between AI servers.

400G optical transceivers are widely used in AI computing infrastructure to provide high-speed, low-latency connections among AI servers, GPUs, switches, and storage systems. Meanwhile, 800G transceivers are increasingly being deployed in high-end AI clusters. As of 2025, 400G transceivers remain a critical component due to their cost-effectiveness, compatibility, and widespread adoption in existing AI networks. AI workloads—particularly those powered by GPUs such as NVIDIA's H100 or AMD's MI300—require ultra-high-bandwidth, low-latency connectivity for efficient data exchange. Both 400G and 800G optical transceivers are essential to AI computing infrastructure, enabling the high-bandwidth, low-latency data transfer needed for large-scale AI model training and inference.

The demand for 400G and 800G optical transceivers is rising rapidly in response to the surge in AI computing. Each AI GPU typically uses 2 to 8 optical transceiver modules [12]. For example, an NVIDIA DGX H100 (8-GPU node) typically connects each GPU with 2–4 transceivers, depending on the NVLink configuration. In certain AI workloads, a system with eight H100 GPUs may require 12 × 800G and 18 × 400G optical transceivers to support high-speed interconnects. According to TrendForce [13] and Cignal AI [14], worldwide shipments of 400G and higher-speed optical transceivers are projected to grow from 20.4 million units in 2024 to 31.9 million units in 2025, representing an annual growth rate of 56.5%.

Table 2 summarizes the device speed, transmission format, and device type for each application. At present, 100G-per-lane or 53Gbaud lasers are still the mainstream components for high-speed optical transceivers. By using 100G/lane lasers, chip and transceiver suppliers can meet cost and performance targets for 400G and 800G optical switch applications.

Looking ahead, 1.6T and 3.2T systems will require higher-speed light sources. For example, 1.6T optics will likely require 8 × 200G lasers, enabling a transmission rate of 200 Gb/s per lane. Meanwhile, 3.2T optical switches will probably require 8 × 400G lasers, making 400G/lane operation essential to support such high-performance computing and data center demands. A 200 Gb/s per lane (200G PAM4) EML was reported in our previous work [15,16]. By extending the EML speed from 100G PAM4 to 200G PAM4 through fine-tuning the EA design, EML devices continue to be key technology enablers for 1.6 T. In the future, 400G PAM4 EMLs may further enable extensions to 3.2T optics [17,18].

For each technology node of optical switches (Table 2), several device options can meet performance requirements. For example, EML and Silicon Photonics (SiPh) are the two most common choices for 400G and 800G optical transmissions. EML offers high ER, low modulator drive voltage, and proven reliability, while SiPh is more scalable and cost-effective in high volumes [19]. For 1.6T and beyond, SiPh and Photonic Integrated Circuits (PICs) hold greater promise for integration with Co-Packaged Optics (CPO) and future roadmap extensions [20].

Materials and methods

Figure 1(a) shows the 3-dimensional schematic of a 100G PAM4 monolithic integrated EML structure designed for 400G

Table 1: Connectivity scenario of optical transceivers for AI servers.

Optical transceiver connectivity scenario	400G	800G
Server to switch (Scenario-1)	AI servers with multiple GPUs (e.g., NVIDIA H100, A100) Connect to top-of-rack switches using 400G QSFP-DD transceivers	AI servers with multiple GPUs (e.g., NVIDIA H100, A100) Connect to top-of-rack switches via 800G OSFP/QSFP-DD transceivers
Intra-server (Scenario-2)	GPU-to-GPU communication within an AI server rack	GPU-to-GPU communication within an AI server rack
Multi-server (Scenario-3)	Communication among multiple racks of AI servers	Communication among multiple racks of AI servers

Table 2: High-speed lasers and optical transceivers during the evolution of 400G to 3.2T.

Optical transceiver	400G	800G	1.6T	3.2T
Date rate/lane	100G	100G (dominant) 200G (alternative)	200G	400G
Device speed	53Gbd	53Gbd 106Gbd	106Gbd	212Gbd
Transmission	4x100G PAM4	8x100G PAM4 or 4x200G PAM4	8x200G PAM4	8x400G PAM4
Device type	EML SiPh	EML SiPh	EML SiPh PIC	EML SiPh PIC

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and 800G optical transceivers. The front section of the EML device serves as the modulator for RF modulation, while the rear section consists of a Distributed Feedback (DFB) laser acting as the light source. The LD and EAM are monolithically integrated using Butt-joint (BJ) technology [21,22], in which the EAM is regrown adjacent to the LD. These two sections are separated by an isolation region. For both the LD and EAM, quaternary InGaAsP Multi-quantum Well (MQW) and separate confinement heterostructure (SCH) layers were grown using metal-organic chemical vapor deposition. (MOCVD). A SiO_2 dielectric layer was deposited for passivation. Contact openings were formed in the dielectric layers to establish Ohmic contact with Ti/Pt/Au p-metal [15,16].

By implementing Coarse Wavelength Division Multiplexing (CWDM), the 100G PAM4 EML chips can support 4 lanes and 8 lanes for 400G FR4 and 800G 2×FR4 modules, respectively, as illustrated in Figure 1(b). The CWDM wavelengths are achieved by adjusting the DFB wavelength of the laser section.

After wafer processing, laser bars were cleaved from the wafers and coated with Ion Beam Sputtering (IBS) films. To minimize optical reflection, the front facet of each EML was coated with an ultra-low Antireflective (AR) coating, while the rear facet was coated with a Highly Reflective (HR) coating. Finally, chips were scribed from the laser bars and tested for light versus current (LI), current versus voltage (IV), and optical spectrum.

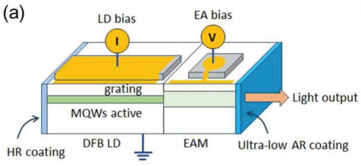
Burn-in and reliability aging data were measured on Chip-on-submount (CoS) samples. The chip was electrically connected to the submount using wire bonding. The aging condition was set at a stress current of 120 mA at a case temperature of 85 °C. 100% of the EML devices were screened for burn-in, and 32 samples were selected from the wafer for the reliability aging test.

Results

Figures 2(a)–(d) show the LI curves of 100G PAM4 EML devices across CWDM lanes (L0, L1, L2, and L3). All four lanes exhibited low threshold current (Ith~15 mA) and high output power (Po>30mW at 120 mA). The LI curves also demonstrated good linearity with minimal rollover. To quantify device energy efficiency, we measured the wall-plug efficiency in terms of thermal dissipation [23,24]. Wall-plug efficiency was defined as the ratio of total optical output power to input electrical power, representing the energy conversion efficiency of the laser chip. At a bias current of 60 mA, the output power was 15 mW, and the forward voltage was approximately 1.3 V. The wall-plug efficiency was estimated to be around 22%, indicating high energy efficiency for the EML. For comparison, the typical wall-plug efficiency of a Directly Modulated Laser (DML) ranges from 13% to 18% [25].

Figure 3(a) shows the typical optical spectra of 100G PAM4 CWDM EMLs. Each EML channel exhibited excellent single-mode DFB performance, achieving a Side-mode Suppression Ratio (SMSR) of over 50 dB. Figure 3(b) illustrates fiber dispersion as a function of wavelength. Different wavelengths experience varying levels of attenuation and dispersion in optical fibers, which can impact signal quality and overall optical performance. At 1310 nm, the fiber reaches zero dispersion. In contrast, dispersion worsens at 1270 nm due to higher fiber loss and chromatic dispersion.

This dispersion, combined with laser chirp, can cause the spectral width of the laser to broaden, affecting the



(b)

400G optical module	
Channel	Wavelength (nm)
L0	1271
L1	1291
L2	1311
L3	1331

800G optical module	
Channel	Wavelength (nm)
L0	1271
L1	1291
L2	1311
L3	1331
L4	1271
L5	1291
L6	1311
L7	1331

Figure 1: (a) 3D schematic of the 100G PAM4 EML device structure. Signal modulation is applied at the front EAM section, while the rear LD operates under Continuous-wave (CW) conditions. (b) Wavelength scheme.

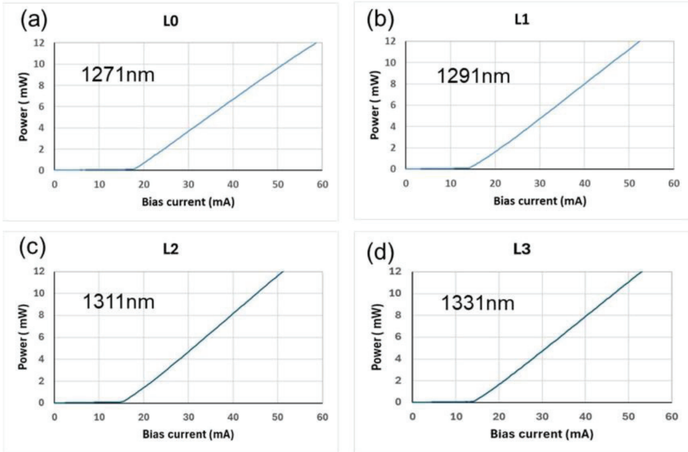


Figure 2: LI curves of the 100G PAM4 CWDM EML devices with the EAM section in the OFF state (no bias) at 53 °C.

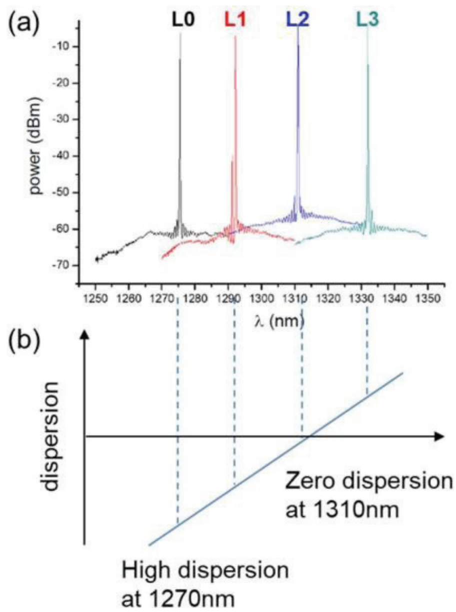


Figure 3: (a) Optical spectra and (b) corresponding fiber dispersion of 100G PAM4 CWDM EML devices. The dispersion is zero at a wavelength of 1310 nm and becomes more severe at 1270 nm.

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transmission characteristics of the optical signal. Laser chirp can also introduce additional dispersion in the optical fiber, leading to pulse broadening and inter-symbol interference, thereby increasing the likelihood of bit errors.

To mitigate dispersion issues at 1270 nm, we have optimized our 1270 nm EML chip to improve its performance in 400G FR4 and 800G 2×FR4 transceivers. The active region of the laser chip has been re-engineered to enhance ER, Optical Modulation Amplitude (OMA), and Bandwidth (BW).

Figures 4(a)–(d) show the optical power curves of the 100G EML CWDM devices with the EAM voltage varying from 0 to −2.5 V at 53 °C. The LD bias was fixed at 50 mA. The variation in power with EAM voltage was due to light absorption in the EAM section. As the reverse voltage increased, absorption in the modulator also increased, resulting in lower optical power output. The ER was proportional to the slope shown in the boxed region during the voltage swing. For a peak-to-peak voltage swing of 1.0 V (Vpp = 1.0V) centered at an EAM bias of −1.0 V, the ER can be determined from the ON and OFF states indicated in the dashed box, where VON = −0.5V and VOFF = −1.5V, respectively.

Figure 5 shows the manufacturing process flow for 400G/800G optical transceivers. First, the EML chip is tested for LIV, ER, and SMSR, as shown in Figures 2-4. The LIV test includes measurements of Ith, Po, and series resistance (Rs). Next, the chip is assembled onto a silicon submount. After Die Bonding (DB) and Wire Bonding (WB), the Chip-on-submount (CoS) is tested again for LIV, ER, and SMSR, followed by burn-in screening to eliminate weak parts. Third, the Optical Sub-assembly (OSA) process includes Fiber Array (FA) attachment, lens alignment, and OSA testing. Finally, the 400G or 800G transceiver module is tested for Transmitter Dispersion Eye Closure Quaternary (TDECQ), OMA, ER, and fiber link Bit Error Rate (BER).

During wafer qualification, 48 devices were tested per lane. Once the wafer was deemed qualified, the remaining devices were screened for production. The sample size for each wafer is typically around 3,000.

OMA is the difference between the maximum and minimum optical power levels in a modulated optical signal [26]. It serves as a critical metric for evaluating modulation depth, reflecting how much the optical signal's intensity fluctuates during modulation. OMA is essential for assessing modulation quality and determining a signal's effectiveness in data transmission. Figures 6(a) and 6(b) show the OMA box plots for 400G FR4 and 800G 2xFR4, respectively. OMA is the difference between the optical power when the laser source is ON versus OFF; it represents the peak-to-peak power of the modulated optical signal. A higher OMA generally indicates a stronger optical signal and a better signal-to-noise ratio. The OMA performance of both 400G and 800G optics is excellent, well above the specification of > -0.2 dBm for FR4 with 2 km transmission and LR4 with 10 km transmission.

Figures 7(a) and 7(b) show the TDECQ box plots for 400G FR4 and 800G 2xFR4, respectively. TDECQ evaluates the

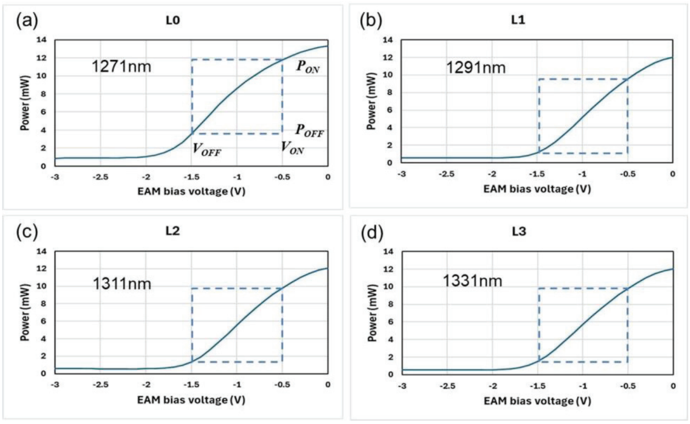

Figure 4: Typical fiber-coupled power curves of the 100G PAM4 CWDM EML device, where the EAM section is subjected to a reverse voltage of up to -3 V at 53 °C. The ER can be extracted from the EA absorption curve, with the voltage swing between the ON and OFF states indicated.

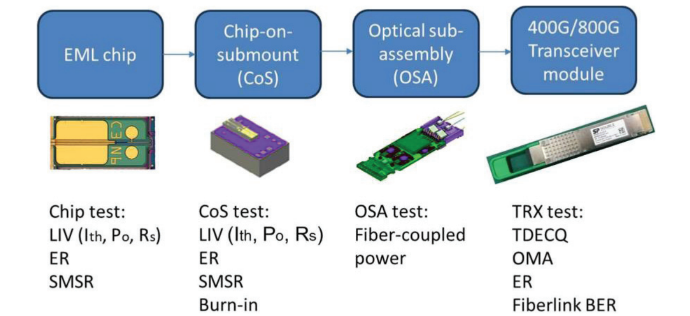

Figure 5: 400G/800G optical module manufacturing process flow.

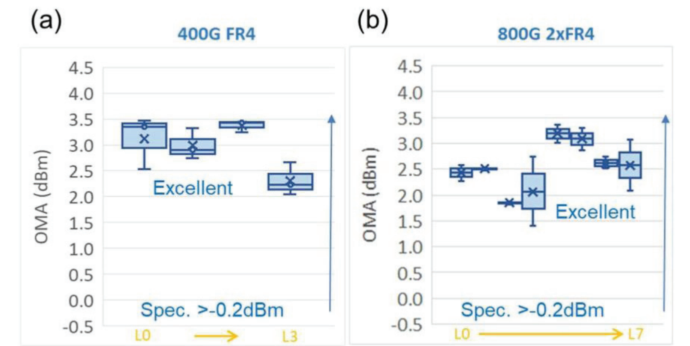

Figure 6: OMA data of (a) 400G FR4 and (b) 800G 2×FR4 optical transceivers. The OMA performance of both 400G and 800G transceivers was excellent, well above the specification of >−0.2 dBm for FR4 (2 km) transmission.

transmitter's ability to deliver a high-quality PAM4 signal to the receiver. A lower TDECQ value indicates better signal quality and improved receiver sensitivity. The TDECQ performance of both 400G and 800G optics is excellent, well below the specification of < 3.4 dB.

BER is a key performance metric in 400G and 800G optical transceivers, measuring the ratio of incorrectly received bits to the total transmitted bits. It directly impacts signal integrity, link reliability, and overall system performance in high-speed optical networks. The BER test setup is illustrated in Figure 8. The fiber link BER data, shown in Figure 9, indicates a BER in the range of 1×10^10 to 1×10-11 for 800G transceiver modules.

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Such a low BER meets the most stringent requirements of 800G InfiniBand (IB) switches.

Figure 10 shows the correlation between ER and BER. The higher the ER, the better the BER. A higher ER means a clearer distinction between the two transmitted logic levels, "1" and "0." This clearer distinction makes it easier for the optical receiver to differentiate between the ON and OFF levels, resulting in a lower BER. The ER value depends on the peak-to-peak voltage (Vpp) swing. For example, the ER at Vpp 0.5 is roughly half that at Vpp 1.0. Our 100G EML can achieve an ER of approximately 4 dB at Vpp = 0.5 V, resulting in an ultra-low BER of 1×10^{-11}.

For 400G optical transceivers, an ER ≥ 2.8 dB at Vpp 0.5V typically enables excellent optical transmission for FR4 (2 km). For 800G optics, the ER requirement is more stringent. In today's most demanding 800G IB applications, the ER needs to be above 3.5 dB at Vpp 0.5V to ensure a BER below 1×10^{-9}. We have achieved tight distributions of ER from wafer to wafer. For a sample size of 3,000 taken from a wafer, the median CoS ER at Vpp = 0.5 V is around 3.8 dB, with a standard deviation of only 0.2 dB. This small variation enables cost-effective, high-volume manufacturing. Our in-house device design and fabrication processes are scalable for mass production. Owing to this scalable production yield, EML chip production reached 11.3 million units in 2024 and is projected to grow to over 32.0 million in 2025.

Figure 11 shows the reliability aging plot of 100G PAM4 EML chips, where the lasers were subjected to stress conditions of 85 °C and 120 mA. Both threshold current and optical power showed no failure after 5,000 hours of aging. Since the degradation was minimal compared to the end-of-life criterion (20% change), we extrapolated the device lifetimes using a sublinear fit of the aging curves [19,22]. The mean time to failure (MTTF) of the 100G PAM4 devices is estimated to be approximately 1,716 years under operating conditions (53 °C).

Conclusion

We demonstrate high-extinction-ratio, high-speed 100G PAM4 EML lasers suitable for 800G AI data center applications. The 100G EML also exhibits a low threshold current (~15 mA) and high power (>9 mW) at an operating temperature of 53 °C. The high lasing efficiency meets the low power consumption requirements. The ER can reach ≥ 8 dB at Vpp = 1V and ≥ 3.5 dB at Vpp = 0.5V, making the 100G EML feasible for achieving low fiber link BER (< 1×10^9) at the transceiver level.

Based on the high-ER EML performance at both chip and transceiver levels, we can realize high-volume, high-yield manufacturing for 400G & 800G AI optics.

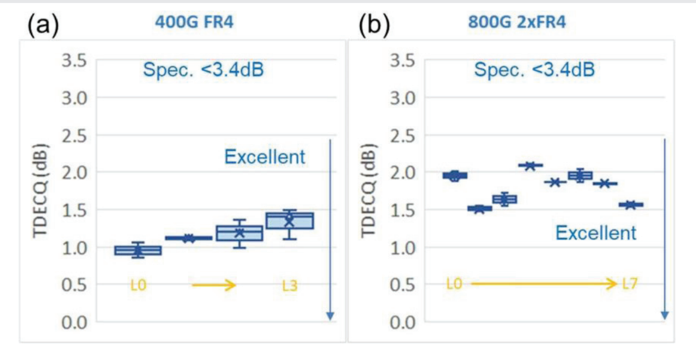

Figure 7: TDECQ data of (a) 400G FR4 and (b) 800G 2×FR4 optical transceivers. The TDECQ performance of both 400G and 800G transceivers was excellent, well below the specification of < 3.4 dB.

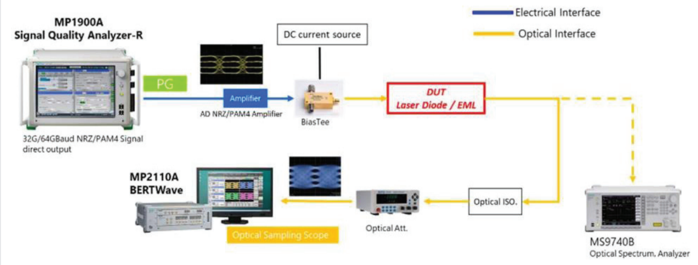

Figure 8: Bit error rate (BER) test schematic.

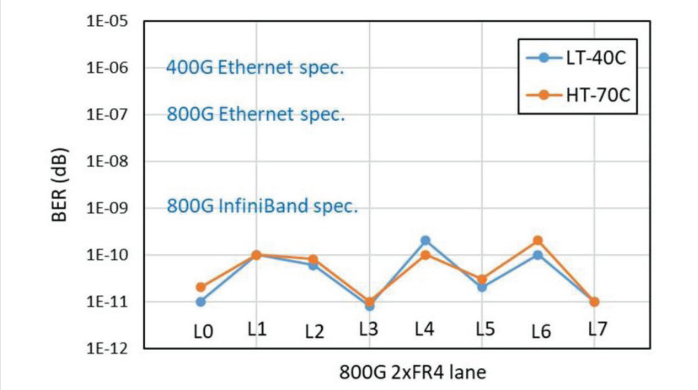

Figure 9: Bit error rate of 100G PAM4 CWDM EML devices in 800G 2xFR4, measured at 40 °C and 70 °C. All 8 lanes showed excellent BER performance, exceeding the specifications for the 800G Infiniband (IB) requirement.

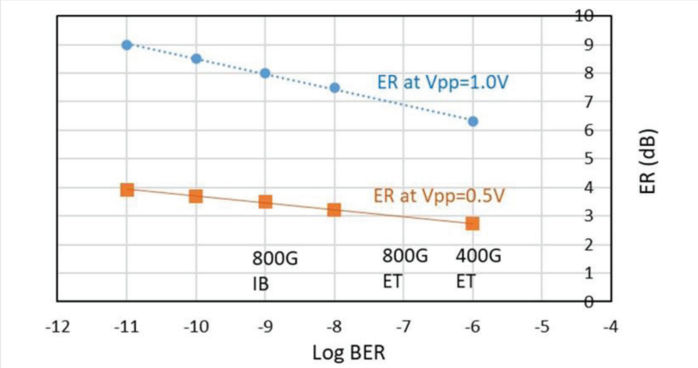

Figure 10: Correlation between bit error rate and extinction ratio of 100G PAM4 EML devices.

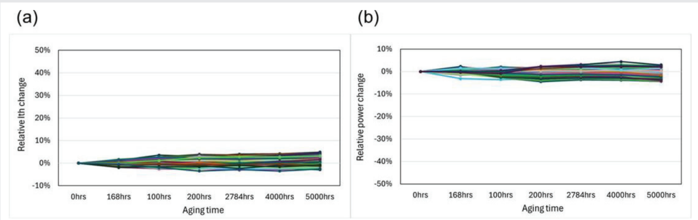

Figure 11: Aging plots of 100G PAM4 EMLs based on the stress condition of 85 °C, 120mA. The relative changes of (a) threshold current and (b) optical power are small after 5000 hours of aging.

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