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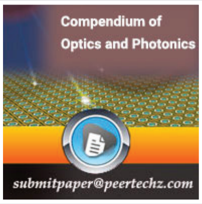

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Research Article

212Gbps high-power EML for 800G artificial intelligence optical transmissions

Jack Jia-Sheng Huang[1,2]*, Hsiang Szu Chang[2], Yi-Ching Hsu[2], Alex Chiu[2], ZiHan Fang[2], Chun-Yen Yu[2] and Sam Hsiang[2]

[1]Source Photonics, 8521 Fallbrook Avenue, Suite 200, West Hills, CA 91304, USA

[2]Source Photonics, No.46, Park Avenue 2nd Rd., Science Park, Hsinchu, Taiwan

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***Corresponding author:** Jack Jia-Sheng Huang, Source Photonics, 8521 Fallbrook Avenue, Suite 200, West Hills, CA 91304, USA,
E-mail: jack.huang@sourcephotonics.com

ORCiD: https://orcid.org/0000-0002-9991-5678

Keywords: Electro-absorption modulated laser; EML; Artificial intelligence; AI; Energy efficiency; Environmental; ESG; Reliability; 800G LR4 optical network

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Abstract

We present a high-power, high-speed 212Gbps four-level Pulse Amplitude Modulation (PAM4) Electro-absorption Modulated Laser (EML) designed for 800G LR4 optical transmission and Artificial Intelligence (AI) applications. The Lan wavelength division multiplexing (LWDM) EML channels, operating at wavelengths of 1295.56 nm, 1300.05 nm, 1304.58 nm, and 1309.14 nm in 800G LR4 optical transceivers, exhibit clear eye openings even after 10km of transmission. Our 212Gbps PAM4 LWDM EMLs demonstrate high bandwidth, high extinction ratio, high power, and high energy efficiency, making them suitable for 10km transmission and environmentally friendly connectivity.

Introduction

Optical communication is a key method of transmitting information in the modern age. It involves signal transmission using light waves through optical fibers or free space. These light signals carry information in the form of digital data, images, and video, over vast distances with minimal signal loss [1].

Electro-absorption Modulation Laser (EML) is a type of semiconductor laser used in optical communication systems [2]. It combines the functions of a laser diode and an electroabsorption modulator in a single device. EMLs are commonly employed in high-speed optical communication applications, such as fiber-optic communication networks, due to their ability to provide both modulation and light emission functions. For data transmission over long distances, EML chips can offer many performance advantages over other alternative technologies such as Directly Modulated Laser (DML) and silicon photonics (SiPh) [3,4].

In today's fiber optic applications, laser chips and optical modules are often required to meet a broad scope of stringent criteria as illustrated in Figure 1. Firstly, high performance and high reliability are essential. Secondly, component suppliers need to have the capability for high-volume manufacturing and low-cost solutions. Thirdly, the source lasers need to meet the transmission requirements of the 400G/800G/1.6T Artificial Intelligence (AI) applications. The final key metric is compliance with Environmental, Social, and Governance (ESG)

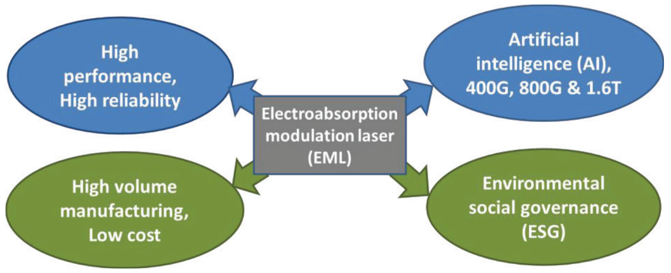

Figure 1: Key metrics of modern fiber optic products. EML chip is the technology enabler to meet all criteria in the applications of 400G/800G/1.6T AI.

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to reduce carbon emissions and address the imminent crisis of climate change.

High performance & high reliability

To enable 800G AI transmission, semiconductor lasers are required to meet high-performance aspects, including low threshold current, high power, and high Extinction Ratio (ER). The threshold current is the level of bias current above which lasing occurs due to stimulated emission. The lower the threshold current, the higher the energy efficiency. Optical power is the key factor determining the transmission distance. The greater the power coupled into the fiber, the longer the transmission distance. ER is critical for the quality of optical communication, as it is based on the difference between the ON state and the OFF state. The greater the ER ratio is, the wider the separation, and thus the better quality of optical transmission [5].

Modern fiber optic links also demand high reliability from optical transceiver modules. To meet the overall reliability requirement of optical modules, each component needs to be robust. For example, the "Parts Count" method in Telcordia SR-332 calculates the failure rate of the optical transceiver unit as the sum of all device types, weighted by the quantity of each device [6]. In the case of an 800G optical transceiver, each laser chip would likely need to be ≤ 15 FITs to limit the total failure rate to ≤ 200 FITs at the module level.

$$\lambda_{\text{total}} = \sum_{i=0}^{n} N_i L_i \tag{1}$$

Where λ_{total} is the total failure rate of the optical transceiver for all n device types, N_i is the number of each component, and L_i is the failure rate of each device type.

High volume manufacturing & low cost

The global landscape of semiconductor chip manufacturing has undergone a major shift in the last few decades [7]. The United States has moved chip manufacturing offshore, particularly to Asia, since the mid-1990s. Despite recent efforts by the US to bring chip production back to its home soil through initiatives like the CHIPs and Science Act bill, tangible progress may not be evident until a longer time horizon [8,9]. European countries such as the United Kingdom, Germany, and France have experienced decreased market share for decades. Japan is also losing its chip manufacturing prowess. On the other hand, Taiwan and Korea have emerged as manufacturing leaders, while China and Southeast Asia are catching up with government subsidies.

Artificial intelligence & 400G/800G/1.6T

AI plays an important role in manufacturing, electric vehicles, robotics, healthcare, and other sectors. Recently, AI applications have been accelerated by companies such as Nvidia and OpenAI. The launch of ChatGPT software in November 2022 has resulted in widespread user adoption and contributed to AI business growth [10]. On the AI hardware side, Nvidia recently released the DGX H200 supercomputer, which has reshaped industry demand, leading to significant growth in orders for 800G optical transceivers since the second half of 2023 [11]. The Magnificent Seven big tech companies, including Microsoft, Alphabet, Meta, and Amazon, are integrating AI servers into their operations [12]. In the realm of 800G & 1.6T AI, 106Gbaud high-speed EML serves as the key building block for 212 Gbps four-level pulse amplitude modulation PAM4 (106Gbaud) transmission [13,14].

Environmental, social and governance

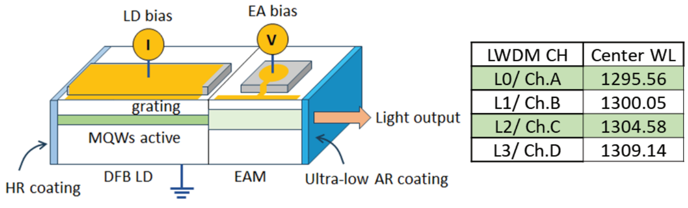
The 2023 United Nations Climate Change Conference (COP28, Dubai) once again highlighted the urgent need to combat global temperature rise caused by fossil fuels [15,16]. Carbon emission reduction requires a concerted effort between governments and across all industry sectors. ESG, or Environmental, Social, and Governance practices, is an environmentally sustainable practice undertaken by companies in order to mitigate their negative environmental impact while staying profitable.

Energy efficiency, to comply with environmental regulations and reduce carbon emissions, has become an increasingly important aspect of optoelectronic products [17]. In 800G networks, the power consumption can be drastically reduced by incorporation of 200Gbps EML [18-20], as the use of the 200G/lane optics can reduce the number of lasers by half compared to 100Gbps EML [13].

In this paper, we report high-power 212Gbps PAM4 (106GBaud) EMLs for 800G LR4 and AI optical transceivers. Our 212G EMLs show high power, high bandwidth, high ER, and low threshold current that can make 800G optics cost-effective and environmentally friendly. The 212G EML also demonstrates extremely high reliability at the device level, resulting in a low overall failure rate prediction at the transceiver module level.

Materials and methods

Figure 2 shows the 3-D schematic of a 212Gbps EML device structure with an LWDM wavelength scheme to support 800G LR4. The front section of the EML device consisted of the Electro-Absorption Modulator (EAM) for RF modulation, while the rear section was comprised of the distributed feedback laser diode (DFB-LD) for DC bias [13]. The DFB-LD structure was optimally designed to achieve high output power and single-mode DFB lasing. The four LWDM lasers were fabricated in the same process except that the grating angle was adjusted to hit each LWDM target. The LD and EAM were joined by using Metal-Organic Chemical Vapor Deposition (MOCVD) Butt-Joint (BJ) technology [21]. Ti/Pt/Au metallization was deposited



LWDM CH	Center WL
L0/ Ch.A	1295.56
L1/ Ch.B	1300.05
L2/ Ch.C	1304.58
L3/ Ch.D	1309.14

Figure 2: 3-D schematic device structure of 212Gbps LWDM EML where the front EAM pad is for RF modulation, and the rear DFB laser is for DC bias.

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to form the p-contact to achieve low contact resistance and robust reliability [22].

To minimize optical reflection, the front facet of EML was coated with ultra-low Anti-Reflective coating (AR) using Ion Beam Sputtering (IBS). The LD section was biased with a DC current ranging from 0 to 150mA. With a constant LD bias, the EAM section was tested with a reverse voltage ranging from 0 to -3V. The Extinction Ratio (ER) was extracted based on the plot of fiber-coupled power versus EAM voltage, with the peak-to-peak voltage swing between the ON and OFF states being 1V.

The optical spectrum and DFB wavelength of the EML were measured using an Optical Spectrum Analyzer (OSA), a precision instrument designed to display the intensity distribution of an EML over a specified wavelength span (1285-1320nm). The bandwidth was determined from the Optical-Electrical (O-E) frequency response curve measured by an Anritsu Network Analyzer. The 3dB bandwidth was determined by locating the cutoff frequency at -3dB on the response curve.

Reliability aging data was measured on the Chip-on-Submount (CoS) loaded on the carrier. The chip was electrically connected to the submount using a wirebond. The aging condition was set at a stress current of 85 mA at a case temperature of 85 °C.

Results

Figure 3 shows the Optical Modulation Amplitude (OMA) power specification of different 400G & 800G AI optical transceivers where DR4, FR4, and LR4 denote the transmission modes of 500m, 2km, and 10km according to IEEE802.3 specifications [14,23]. The specification of the power at the chip level is based on the correlation between chip and transceiver levels, considering coupling efficiency and optical losses in the transceiver. The power requirement of the source laser increases with increasing transmission distance. The power specification is the most stringent for 800G LR4.

Figure 4 shows the light versus current (LI) curves of 212Gbps EML devices of LWDM channels (L0, L1, L2, and L3). All four channels showed low threshold current (~15 mA) and high power (> 30 mW at 120 mA). The LI also showed good linearity with a small rollover. To quantify the device's energy efficiency, we measured the wall-plug efficiency in terms of thermal dissipation [24,25]. The wall-plug efficiency was defined as the ratio of the total optical output power to the input electrical power, representing the energy conversion efficiency of the laser chip. At a bias current of 60mA, the power was 15mW and the forward voltage was about 1.3V. The wall-plug efficiency was estimated to be approximately 22%, suggesting a high energy efficiency for EML. The typical wall-plug efficiency of DML is in the range of 13% - 18% [17].

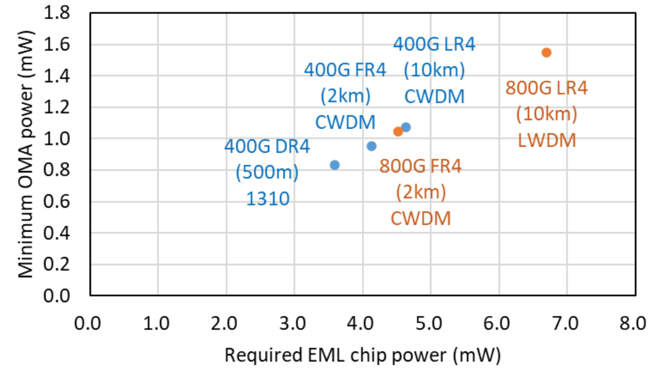

Figure 3: The transmitter power specifications of 400G DR4/FR4/LR4 & 800G FR4/LR4. The EML chip power versus transceiver OMA power is shown.

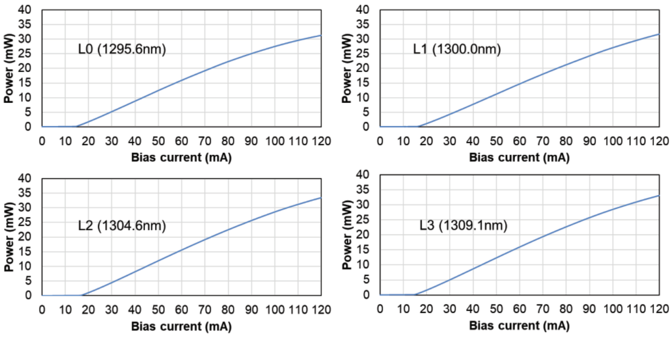

Figure 4: LI curves of the 212Gbps LWDM EML devices at 53 ^{0}C. The output power was measured with no voltage bias to the EAM section (V_{EA}=0V).

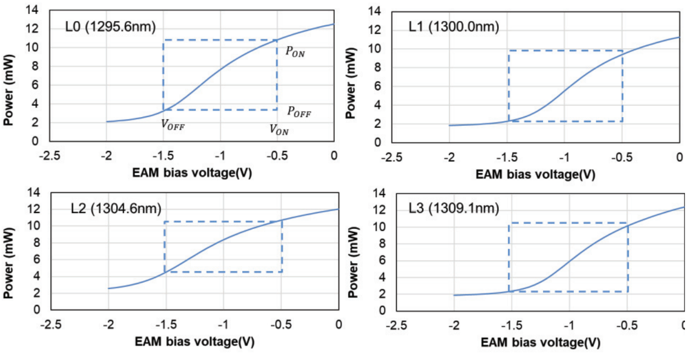

Figure 5: Optical power curves of the 212Gbps LWDM EML devices as a function of the EAM reverse voltage where the LD section was biased at 53 ^{0}C, 50mA. The ER can be extracted from the EA absorption curve. The voltage swings between the ON and OFF states are indicated.

Figure 5 shows the optical power curves of the 212Gbps EML LWDM devices with EAM voltage varying from 0 to -2.5V at 53 °C. The LD bias was fixed at 50mA. The power change with the EAM voltage was caused by light absorption from the EAM section. Light absorption from the modulator increased at higher reverse voltage, resulting in lower power output. The ER was proportional to the slope shown in the box during the voltage swing. For a peak-to-peak swing of 1.0V (V_{pp}=1.0V) at an EAM voltage of -1.0V, the ER value can be determined by the ON and OFF states shown in the dashed lined box, where V_{ON}=-0.5V and V_{OFF}=-1.5V, respectively.

Figure 6 shows the typical optical spectra of 212Gbps PAM4 LWDM EMLs. Each EML channel exhibited excellent single-mode DFB performance, achieving a side-mode-suppression-ratio (SMSR) of over 50dB. Figure 7 displays the electrical-optical frequency response plot of 212Gbps LWDM EML devices,

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with the 3dB bandwidth reaching about 65 GHz, exceeding the specification of 60 GHz.

Table 1 presents the extinction ratio (ER) and transmitter dispersion eye closure quaternary (TDECQ) values of the 212Gbps PAM4 EMLs in the 800G LR4 optical transceivers. The 212G EML can meet both TDECQ and ER targets for 800G FR4 optical transceivers. The typical target for TDECQ is ≤ 3.9dB [26,27]. For 1.6T and beyond, ultra-high speed (> 212Gbps PAM4) lasers would be necessary to maintain the quality of modulated optical signals, and achieving such ultra-high speeds with EMLs would pose significant challenges in terms of bandwidth and reliability.

Figure 8 shows the long-term reliability aging plot of 212Gbps LWDM EML chips, where the aging condition was set at a stress current of 85mA at 85 °C. Both threshold current and optical power showed little change after 3000 hours of aging. Since no failures occurred, we projected the device lifetimes using a sublinear fit on the aging curves [28]. Using the end-of-life criterion of a 20% change in power, the mean-time-to-failure (MTTF) of the 212Gbps EML devices was estimated to be approximately 2748 years at 53 °C operating condition. This represents a significant reliability margin for the 20-year guaranteed life per Telcordia standards. The wear-out failure rate was projected to be approximately 3 FITs. This ultralow FIT rate at the chip level ensures a high confidence level of reliability at the transceiver module level. According to the "Parts Count" method in Telcordia SR-332, the FIT rate of the 800G transceiver can still be maintained at < 150 FITs (spec. < 200 FITs) even under worst-case estimation, resulting from the sum of 4 EML chips and over 40 other active and passive components.

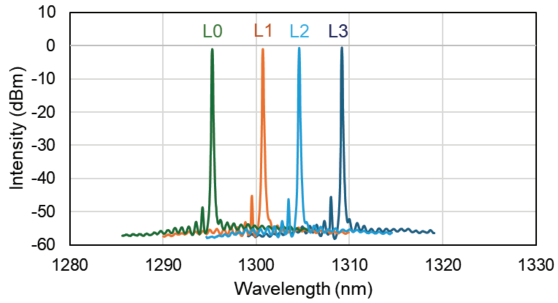

Figure 6: The optical spectra of 212Gbps LWDM EML devices for 800G LR4 transmission. All channels show excellent single-mode DFB performance with SMSR over 50 dB.

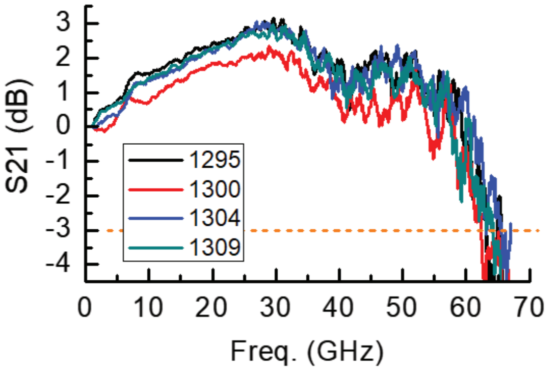

Figure 7: Frequency response curves of the 212Gbps PAM4 LWDM EML devices showing high 3dB bandwidth.

Table 1: ER and TDECQ performance summary of the 212Gbps LWDM EMLs in 800G LR4 & AI optical transceivers.

Modulation speed	ER (target ≥ 3.5dB)	TDECQ (target ≤ 3.9dB)
212 Gbps PAM4 (106GBaud)	4.5dB	2.0dB

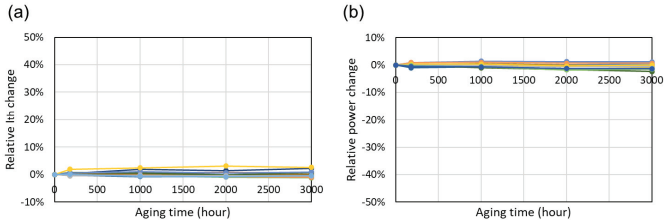

Figure 8: Aging plots of 212Gbps LWDM EMLs based on the stress condition of 85 ^{0}C, 85 mA. The relative changes of (a) threshold current and (b) optical power are small after 3000hr aging.

Conclusion

We have manufactured high-speed 212Gbps PAM4 (106GBaud) LWDM EMLs for 800G LR4 optical transmission, achieving an extinction ratio of ≥4.5dB and a TDECQ of ≤ 2.0dB. The ultra-low failure rate at the EML device level (≤ 3 FITs) ensures a low failure rate for the overall 800G transceiver module. The high-speed, high-power 212Gbps LWDM EMLs meet the stringent criteria of modern 800G LR4 connectivity, including (1) high performance and high reliability, (2) low cost, (3) high-speed AI computing, and (4) environmental and energy efficiency.

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