10-km Transmission of 106-Gb/s PAM4 with Directly Modulated DFB Lasers in the CWDM Range

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Abstract: The 106-Gb/s PAM4 operation of four DMLs in the 1.3-μm CWDM range demonstrated < 2.0 dB TDECQ after 5-km transmission. Clear eye openings and BER below KP4-FEC limit (2.2×10^{-4}) were achieved even after 10-km transmission.

1. Introduction

High-speed optical interconnection is desired due to the continuous explosion of network traffic stemming from improvements to intra-datacenter traffic and the 5G wireless network. To meet this demand, 400-Gb/s Ethernet (400GbE) based on 53-Gbaud (106-Gb/s) four-level pulse amplitude modulation (PAM4) in the 1.3-μm coarse wavelength division multiplexing (CWDM) range is starting to be deployed for a 2-km reach [1]–[2]. Also, the application of 400GbE beyond the 5-km reach standardized as 400G-LR4-10 [1] and 400GBASE-LR4-6 [2] is under discussion. Currently, an electro-absorption modulator integrated DFB laser (EA-DFB) and silicon photonics platform are utilized as components of optical transceivers to achieve 400GbE. At the same time, the directly modulated DFB laser (DML) has attracted attention as an alternative candidate for a 106-Gb/s light source thanks to its low cost, low power consumption, and reduced footprint. PAM4 operation using DML has been reported in several studies [3]–[8], including our own demonstration of the 106-Gb/s PAM4 operation of ridge-waveguide (RWG) DMLs for 2-km single-mode fiber (SMF) transmission in the 1.3-μm CWDM range [3]. Since RWG-DML has a simple structure favorable to mass production, this result suggests the feasibility of a commercial DML for 400GbE. Further, investigation of 10-km transmission should prove fruitful for potential of 106-Gb/s PAM4 application such as 400G-LR4-10 and 400GBASE-LR4-6. In this study, we demonstrated 10-km transmission of 106-Gb/s PAM4 using newly developed RWG-DMLs with four wavelengths in the 1.3-μm CWDM range (lanes 0 to 3). The four DMLs exhibited clear eye openings even after 10-km SMF transmission. We also evaluated the transmission dispersion eye closure quaternary (TDECQ) values and bit error rate (BER) characteristics in a back-to-back (BTB) configuration and after 5-km and 10-km SMF transmission, along with a calculation of the dispersion penalty of the four DMLs.

2. Device structure

We developed DMLs with four different wavelengths using our previous work [3] as a basis. Specifically, we modified the epitaxial layers of the devices including InGaAlAs multi-quantum-well (MQW) layers, separate confinement heterostructure (SCH) layers, and a grating layer, all of which were grown on an n-type InP substrate with metal-organic chemical-vapor deposition, to suppress carrier overflow and to optimize coupling coefficient κL and the Zn doping design. The optimal Zn profile at the p-doped region is effective to obtain a large differential gain dg/dn, resulting in high bandwidth characterized by relaxation oscillation frequency fr. Photoluminescence wavelengths corresponding to four lanes for CWDM were designed to obtain optimal wavelength detuning. An asymmetric corrugation pitch modulated (ACPM) grating structure was utilized to suppress longitudinal spatial hole-burning [9]. The cavity length was set to 150 μm. We also reduced the size of the top electrode pad formed on an organic insulator structure to eliminate parasitic capacitance.

3. Laser characteristics

All characteristics of the fabricated DMLs were evaluated in a chip-on-carrier (COC) configuration based on a ceramic carrier with a resistor for 50-Ω impedance matching. DML temperature (T_{LD}) was controlled with a thermo electric controller (TEC).

Figure 1(a) shows light-current (L-I) and voltage-current (V-I) characteristics of the four fabricated DMLs operated at 25 °C. The threshold currents ranged from 8.4 to 9.2 mA, showing similar performances with each CWDM wavelength. Figure 1(b) shows lasing spectra of the DMLs with the bias current (I_b) of 33 mA. A side-mode suppression ratio over 40 dB was obtained at each lane corresponding to the CWDM range.

E/O responses of the four DMLs were measured at the T_{LD} of 25 °C with the I_b of 60 mA. The 3-dB bandwidth f_{3dB} values of these DMLs were almost 36 GHz, indicating preferable characteristics for 106-Gb/s PAM4 operation.

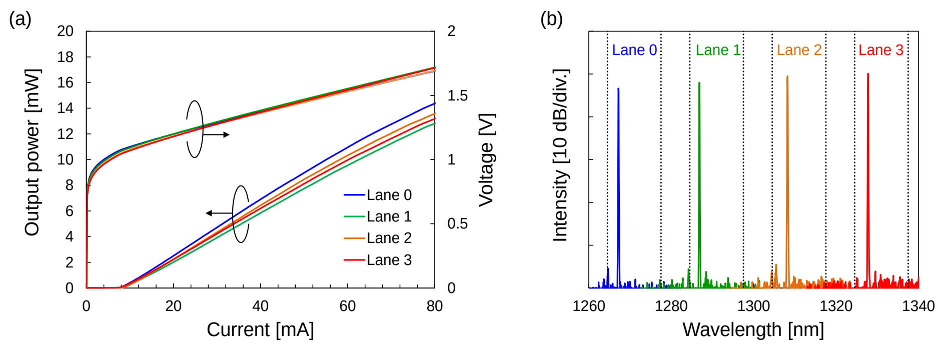

Fig. 1. (a) L-I, V-I characteristics and (b) lasing spectra of four DMLs at 25 °C.

4. Evaluation of 106-Gb/s PAM4

BTB, 5-km, and 10-km transmission of 106-Gb/s PAM4 signals were performed with the measurement setup shown in Fig. 2. The T_{LD} and I_b of the DMLs were set to 25 °C and 60 mA, respectively. A Keysight M8045A pattern generator and an RF amplifier were used to generate the 106-Gb/s PAM4 electrical signal up to 2.7 Vpp. The electrical signal was adjusted with a 5-tap feed-forward equalizer (FFE). We used 5-km and 10-km SMFs compliant with SMF-28, which has zero dispersion at 1310 nm, for evaluation of the transmission performance.

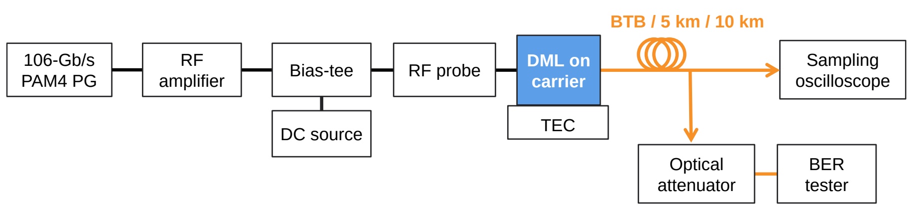

Fig. 2. Measurement setup for 106-Gb/s PAM4 transmission.

First, we observed the 106-Gb/s PAM4 eye diagrams of the four DMLs from lanes 0 to 3 across the CWDM range. A short stress pattern random quaternary (SSPRQ) was used to obtain the eye pattern. The outer extinction ratio (ER) of the optical signal measured with a Keysight N1092C sampling oscilloscope was adjusted to 3.0 dB. Figure 3 shows 106-Gb/s PAM4 diagrams after equalization. In the BTB configuration and after 5-km transmission, clear eye openings were obtained with TDECQ values of less than 2.0 dB. Also, recognizable eye diagrams were obtained even after 10-km transmission.

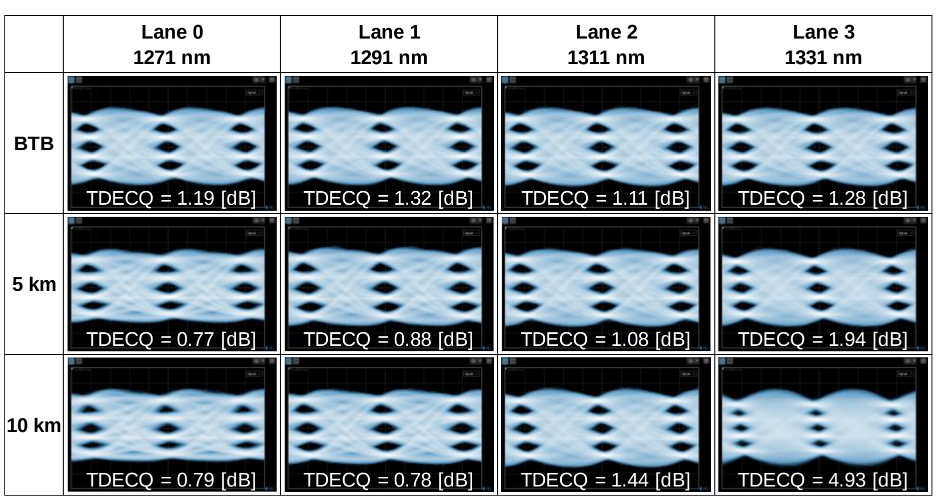

Fig. 3. 106-Gb/s PAM4 eye diagrams of four DMLs in BTB, 5-km, and 10-km transmission.

Next, we evaluated the BER with an electrical signal consisting of a gray-coded pseudo-random binary sequence (PRBS) $2^{31}-1$ pattern using the same measurement setup. A commercially available QSFP28 transceiver compatible with 100GBASE-FR1 was used as the BER tester. Figure 4 shows BER characteristics versus optical modulated amplitude (OMA) for lanes 0 to 3 in the BTB setup and after 10-km SMF transmission. BER values below the KP4-FEC limit (2.2×10^{-4}) were achieved with all conditions, though the received sensitivity defined as the OMA at the KP4-FEC threshold differed among the four DMLs after 10-km transmission due to chromatic dispersion. In particular, the BER of lane 3 was degraded since a significant positive chromatic dispersion affected the transmission performance.

We then used the results of the BER test to clarify the relationships between the fiber dispersion and dispersion penalty of the 5-km and 10-km transmission, as shown in Fig. 5. Four plots in each fiber length correspond to lanes 0 to 3. Even after 10-km transmission, the worst dispersion penalty caused by lane 3 for 10-km transmission was approximately 2.2 dB. Since the developed DMLs showed feasible characteristics for 10-km transmission, they have potential for beyond 5-km transmission of 106-Gb/s PAM4 in the CWDM range.

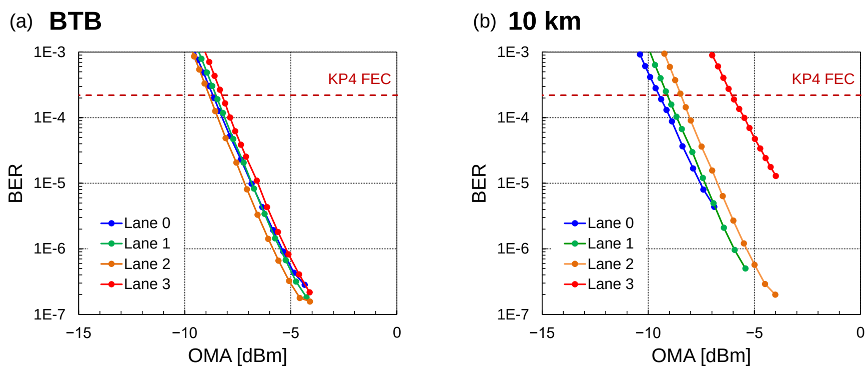

Fig. 4. BER characteristics of 106-Gb/s PAM4 against received optical power in (a) BTB and (b) 10-km transmission.

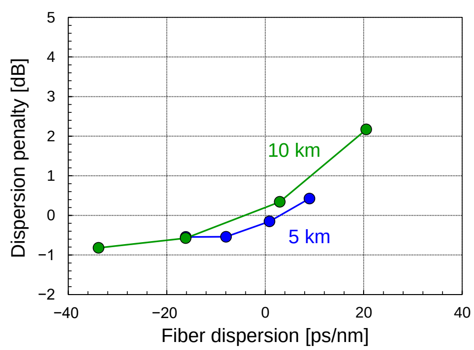

Fig. 5. Relationship between fiber dispersion and dispersion penalty.

5. Conclusions

We demonstrated 106-Gb/s PAM4 operation using newly developed RWG-DMLs in the CWDM range. The four DMLs obtained clear eye opening even after 10-km transmission, and TDECQ values were lower than 2.0 dB after 5-km SMF transmission. BER below 2.2×10^{-4} and a superior dispersion penalty after 10-km transmission were also confirmed. These results indicate that the developed DMLs are attractive candidates to establish a cost-effective and energy-efficient commercial light source for 106-Gb/s PAM4 application that reaches up to 10 km.

Reference

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