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An Ultra-Compact VCSEL-based Transceiver for Co-Packaged Optics and Testing Station Employing a High-Density Electrically Pluggable Interface

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ABSTRACT This paper describes design and characteristics of a Vertical Cavity Surface Emitting Laser (VCSEL)-based transceiver for Co-Packaged Optics under the National Institute of Information and Communications Technology (NICT) Beyond 5G BRIGHTEN project. To decrease the mechanical size, we adopt the record narrowest 0.3-mm pitch Land Grid Array (LGA) for the electrical interface of the transceiver. Consequently, a footprint is as narrow as 7.7 mm × 15.9 mm. We also design and fabricate an electrical pluggable interface for 0.3-mm pitch LGA. To characterize the electrical pluggable interface, we design and fabricate a testing station which is employing the electrical pluggable interface. A 3-dB bandwidth of the testing station is as wide as ≧ 14 GHz, which is equivalent to the Nyquist frequency of 28-Gbaud operation. We attach the VCSEL transceiver to the testing station and evaluate the optical link characteristics. When operating 8 channel simultaneously with 56-Gb/s PAM4 signals, a sufficiently low bit error rate is obtained to build a 400-Gb/s optical link.

1. INTRODUCTION

As the Social Networking Services (SNS) and high-definition video streaming services become widespread, data traffic is significantly increasing in recent years. To process a large amount of data traffic in a data center, there is a strong demand for wide-bandwidth and low-power optical links among network switch devices. Conventional network switch devices employ pluggable optical transceivers that adopt a Small Form Factor (SFF) and are mounted on the front panel. However, such network switch devices adopt long-length electrical transmission lines between the switch Application Specific Integrated Circuit (ASIC) and the pluggable optical transceivers. Therefore, it requires high-power Digital Signal Processors (DSPs) on the electrical transmission lines, to ensure the electrical signal quality.

Co-Packaged Optics (CPO) is a promising solution to realize wide bandwidth and low power consumption, where a switch ASIC is mounted on the center of a daughter board and optical transceivers are densely mounted surrounding the ASIC[1]. The electrical transmission loss of the CPO is significantly less than the conventional system because the optical transceivers are located near the ASIC for the CPO. Several research institutes have been demonstrating two types of optical transceivers for CPO, which are silicon photonics-based and VCSEL-based transceivers.

The international standardization organization Optical Internetworking Forum (OIF) has issued an Implementation Agreement (IA) for optical transceivers using silicon photonics devices[2]. This IA defines two types of CPO transceivers. The one type integrates the light source into the optical transceivers, while the other employs an external light source (ELS). The ELS is placed on the front panel and supplies a Continuous Wave (CW) light using Polarization-Maintaining Fibers (PMF). The ELS IA classifies the optical output of external light source into six types, and we demonstrated an external light source that uses Quad Small Form-factor Pluggable (QSFP), which corresponds to a Very High Power (VHP) class[1].

On the other hand, VCSEL-based transceivers are very attractive in terms of saving power consumption with the aid of their low current drive characteristics. Additionally, VCSEL has a significant advantage in increasing the number of optical channels because VCSEL is easy to fabricate into an array. The Advanced Research Project Agency-Energy Multi-Wavelength Optical Transceivers Integrated on Node (ARPA-EMOTION) project demonstrates a VCSEL transceiver using Multi-Mode (MM) VCSEL[3]. When modulation speed is 50-Gb/s Non-Return

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to Zero (NRZ) per channel, the project reported a power consumption of 4 pJ/bit. However, the transmission distance is limited within 30 m since the optical link uses MM VCSEL and MM fiber.

We propose an ultra-compact CPO transceiver using a coupled-cavity 1060-nm Single-Mode (SM) InGaAs/GaAs VCSEL in the BRIGHTEN project, a commissioned research project of the Beyond 5G Research and Development Promotion Program of the National Institute of Information and Communications Technology[4]. The transmission speed per channel starts from 25 Gb/s NRZ, and it will be upgraded to 50 Gb/s NRZ and 100 Gb/s Pulse-Amplitude-Modulation 4-level (PAM4). 16 cores of a 19-core Multi-Core Fiber (MCF) are used for the optical interface, which realizes wide bandwidth signal transmission by Spatial Division Multiplexing (SDM). In addition, an extremely small footprint of 7.7 mm × 15.9 mm is achieved by using the record narrowest 0.3-mm pitch LGA for the electrical interface. To realize a reliable electrical connection, we designed and fabricated a high-density electrical pluggable interface to mount the VCSEL transceiver to a CPO daughter board. We also designed and fabricated a testing station with the electrical pluggable interface to evaluate the VCSEL transceiver. To characterize the testing station, we designed and fabricated a 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver using a commercially available 4-channel 850-nm MM-VCSEL array. The footprint and electrical interface are compatible with the 16-channel VCSEL transceiver. To achieve interoperability with other optical transceivers, we employ a standard 24-MT ferrule-terminated MMF cable for an optical interface.

This paper describes the detailed design of the electrical pluggable interface, the testing station, and the 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver. Furthermore, we also report the optical link characteristics of the 8-channel VCSEL-based transceiver by using the testing station. Consequently, a measured Bit Error Rate (BER) was below the KP4-Forward Error Correction (FEC) threshold and we successfully realize building a 400-Gb/s PAM4 optical link under 8-channel simultaneous operation.

2. ELECTRICAL PLUGGABLE INTERFACE

To minimize the footprint of an optical transceiver, a solder reflow mounting is preferable. However, to ensure whole system reliability by making the optical transceiver replaceable, an electrical pluggable interface is required. To minimize the mounting area, we designed and fabricated an electrical pluggable interface employing a spring contact probe with an outer diameter of 0.1 mm for the 0.3-mm pitch LGA. The LGA size is determined by the number, arrangement, and pitch of the lands.

Figure 1 shows a schematic illustration of a staggered arrangement (Figure 1 (a)) and in a grid arrangement (Figure 1 (b)) for the LGA. The total number of lands can be reduced by using a staggered arrangement, but it raises a concern about the degradation of the signal integrity by crosstalk. Therefore, we performed an electromagnetic simulations for the electrical contact probe units in both arrangements. The simulation results are shown in Figure 2. In the frequency range of 0 to 40 GHz, we measured sufficient characteristics for 25-Gb/s signal transmission, with a return loss of less than 14 dB, a transmission loss of less than 0.4 dB, and a crosstalk characteristic of less than 50 dB. Since there is no significant difference in the characteristics between the grid arrangement and the staggered arrangement, we adopted the staggered arrangement, which can reduce the number of lands.

Figure 3 shows a photograph of the fabricated electrical pluggable interface. Figure 3 (a) shows a photograph of the inside and the lid of the electrical pluggable interface. The electrical pluggable interface consists of a contact-probe unit and a guide frame to align the position of the VCSEL-based transceiver. The lid provides appropriate force to reliable electrical connection. Figure 3 (b) shows an enlarged photograph of the contact probe unit. As can be seen from the photograph, the spring electrical contact probes are inserted with staggered arrangement at a pitch of 0.3 mm.

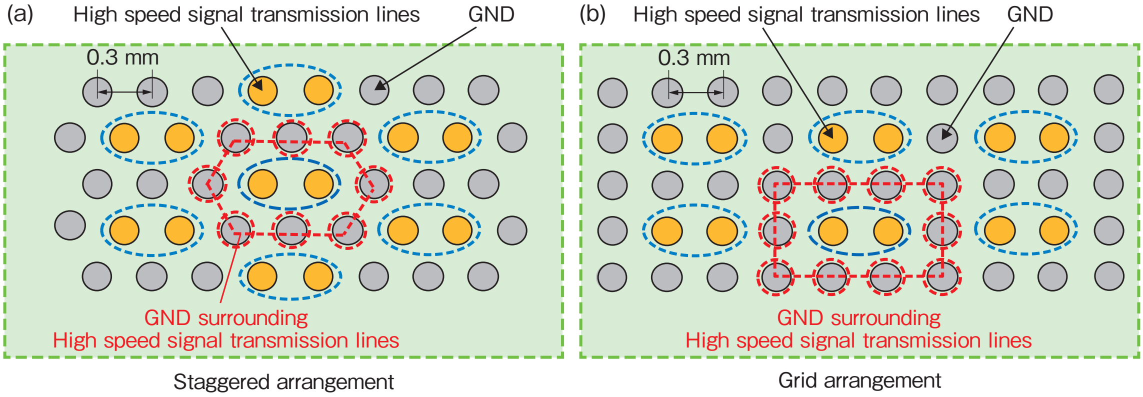

Figure 1 Schematic illustrations of 0.3-mm pitch LGA arrangement. (a) Staggered arrangement. (b) Grid arrangement.

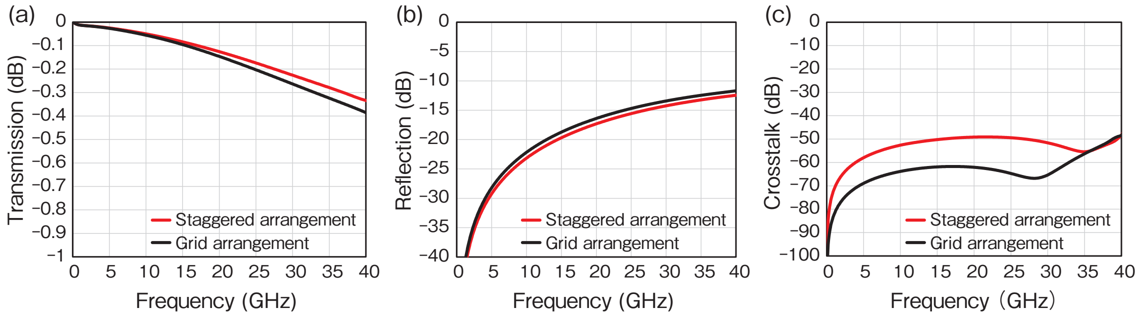

Figure 2 Calculated transmission and crosstalk characteristics of contact probe units employed a staggered arrangement and a grid arrangement.
(a)Transmission characteristics. (b)Reflection characteristics. (c)Crosstalk characteristics.

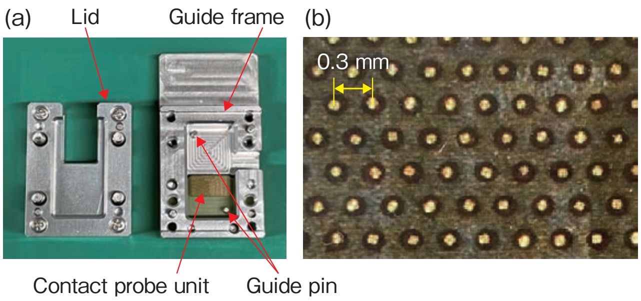

Figure 3 Photograph of the electrical pluggable interface.
(a) A top view of the inside of guide frame and lid.
(b) A contact probe unit.

3. TESTING STATION

Figure 4 shows a photograph of the testing station employing the electrical pluggable interface. Sub-miniature Push-on Micro (SMPM) connectors are mounted surrounding the electrical pluggable interface for high-frequency electrical signal inputs and outputs. The wiring of PCB are shaped for power, signal, ground, and differential transmission lines to transmit and receive high-speed signals between the VCSEL transceiver and the SMPM connectors. To achieve wider bandwidth, we adopt a core-less building-up organic substrate having a fine design rule[5], because this substrate does not have thicker via-holes passing through the core layer, it enables impedance matching structure while maintaining the via-pitch of differential transmission lines as narrow as 0.3 mm from LGA to any layers. The length of the transmission lines is designed to be 30 mm or less between the SMPM connector and the center of the electrical pluggable interface to suppress an electrical loss. An Alternative Current (AC) coupling capacitor is mounted near the SMPM connector. In addition, a temperature control unit is also attached to the back side of the PCB to precisely control the case temperature of the VCSEL transceiver.

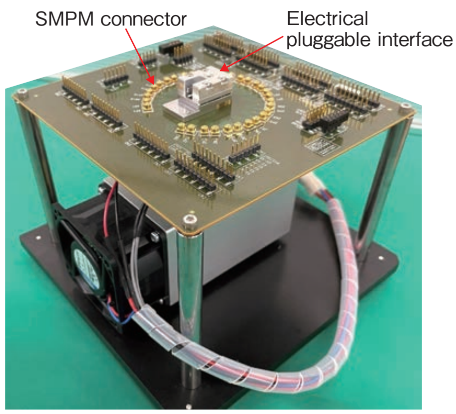

Figure 4 Photograph of the testing station.

Figure 5 shows a schematic cross-sectional illustration of the testing station attached with a loopback module that directly connects high-speed signal input pads and output pads with short transmission lines on an electrical pluggable interface. The signal transmitted to the input differential transmission line is connected to the output differential transmission line via the electrical pluggable interface and the loopback module. There are three types of high-speed signal paths that have different routing of the differential transmission lines inside of the PCB. As shown in the illustration, we use the surface layer, 5th layer, 7th layer, 12th layer, and bottom layer for high-speed signal transmission lines.

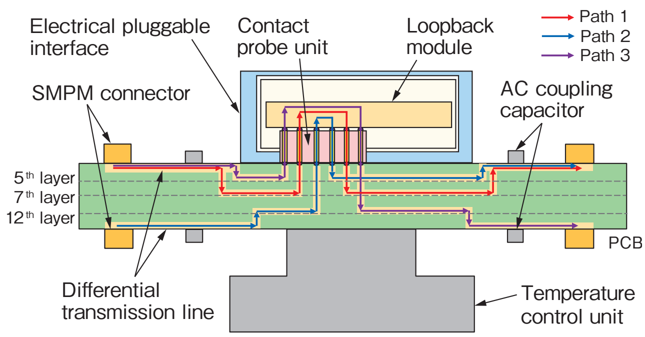

Figure 5 Schematic cross-sectional illustration for the electrical transmission line arrangement of the testing station with the electrical pluggable interface and the loopback module.

Figure 6 shows the measured transmission loss characteristics of a typical channel for the testing station with the loopback module. The measurements were performed by a four-port network analyzer. Since these characteristics include the transmitting and receiving lines, a 3-dB bandwidth is equivalent to a 6-dB bandwidth in this figure. The measured 6-dB bandwidth was 17 GHz or more, which is well above 12.5 GHz equivalent to the

Nyquist frequency of 25-Gbaud operation and 14 GHz equivalent to the Nyquist frequency of a 28-Gbaud operation.

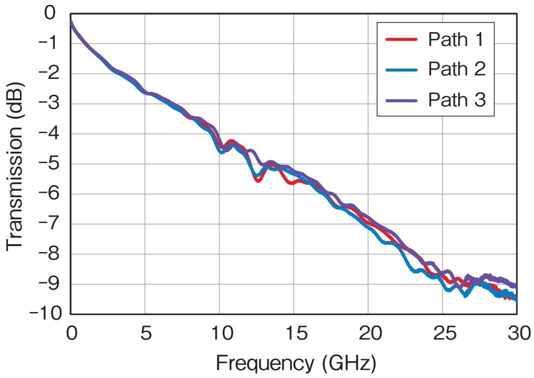

Figure 6 **Measured transmission characteristics of the testing station with the electrical pluggable interface and the loopback module.**

Figure 7 shows the measured far-end crosstalk (FEXT) and near-end crosstalk (NEXT) characteristics of the testing station with the loopback module. Channel 11 was used as a monitor channel. This channel was expected to be the most affected by the crosstalk since the transmitter (TX) and receiver (RX) are located in the center of the LGA. The other 15 channels were used as aggressors. FEXT and NEXT are shown in blue and red solid curves, respectively. The crosstalk amplitudes were sufficiently suppressed to -40 dB at 12.5 GHz and 14 GHz in both cases.

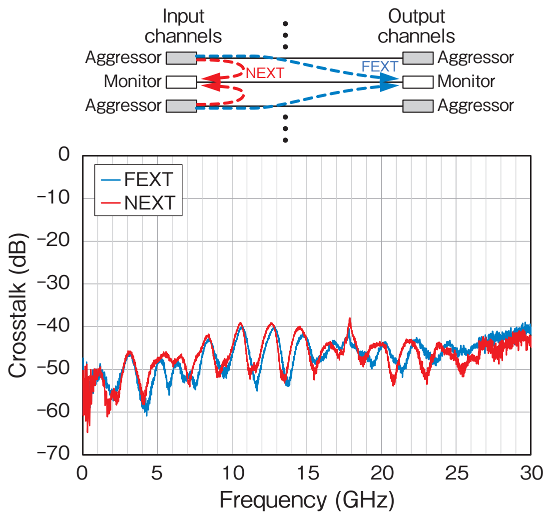

Figure 7 **Measured crosstalk characteristics of the testing station with the electrical pluggable interface and the loopback module.**

4. 8-CHANNEL VCSEL-BASED TRANSCEIVER FOR ULTRA-COMPACT CPO

Figure 8 shows a photograph of an ultra-compact 28-Gbaud NRZ/PAM4 × 8-channel 850-nm VCSEL-based transceiver for CPO. A US 10-cent coin is placed next to it for size comparison. A 24-core MMF ribbon cable terminated by a Mechanical Transfer (MT) ferrule is used for input and output of optical signals. The mechanical size is as small as 7.7 mm × 15.9 mm × 7.95 mm which is the same size as the 16-channel transceiver.

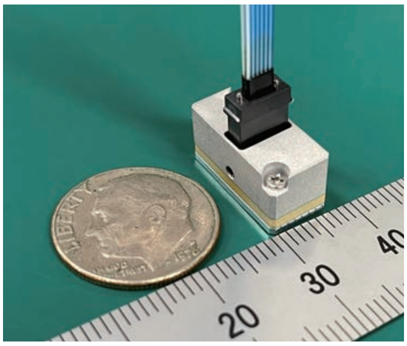

Figure 8 **Photograph of the 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver.**

Figure 9 (a) shows a schematic perspective view of an electrical subassembly of the 28-Gbaud NRZ/PAM4 × 8-channel 850-nm VCSEL-based transceiver. Two pairs of 4-channel 850-nm VCSEL/ Photo Diode (PD) and VCSEL Driver (VD)/ Trans-Impedance Amplifier (TIA) are mounted on a PCB. The VD and TIA are integrated Clock Data Recovery (CDR) circuits that can recover degraded signals by differential transmission lines and optical fiber transmission. The VCSEL and PD arrays have a channel pitch of 250 μm that is complaint with Quad Small Form Factor Double-Density (QSFP-DD) as shown in Figure 9 (b). The VCSEL/PD and VD/TIA, VD/TIA and the gold pads of the PCB are electrically connected using gold wires of a 20 μm diameter. To suppress transmission loss and channel-to-channel crosstalk, the length of the gold wires is controlled to be 350 μm or less. Positioning holes are shaped on the corners of the PCB, which realizes precise positioning and stable electrical connection to the electrical pluggable interface.

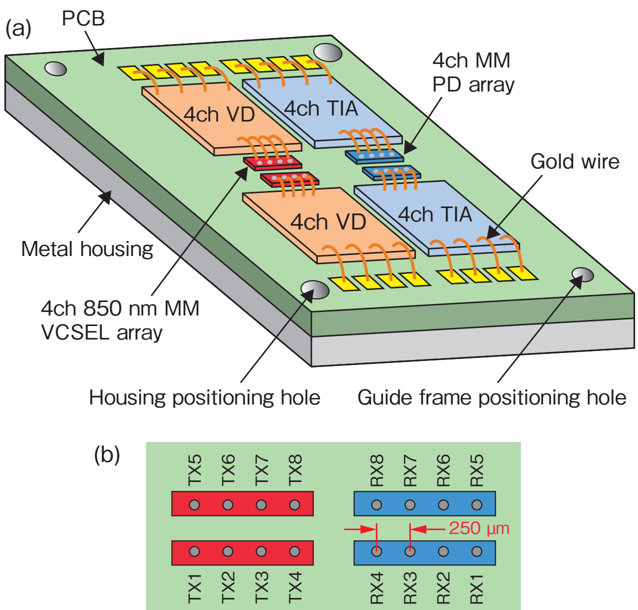

Figure 9 **Schematic perspective view of the electrical subassembly for the 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver (a) and layout of VCSEL/PD arrays (b).**

Figure 10 shows a schematic cross-sectional view of the VCSEL transceiver. For optical coupling between the VCSEL/PD and the MT ferrule, we employed a plastic microlens array for a standard MT ferrule with 12-channels × 2 rows. The VD and TIA are the most heat-generating components and need efficient cooling to below the operating temperature. Therefore, the VD and TIA are thermally connected to the metal case through a thermally conductive material[6]. Next, we designed the differential transmission line of the PCB. In order to minimize the size of the CPO daughter board, the LGA is placed on the left side of the center of the VCSEL transceiver as shown in Figure 10[7]. Therefore, the differential transmission line of a right-side VD/TIA path is longer (for example, TX2/RX2 channels), and the left-side VD/TIA path is shorter (for example, TX6/RX6 channels).

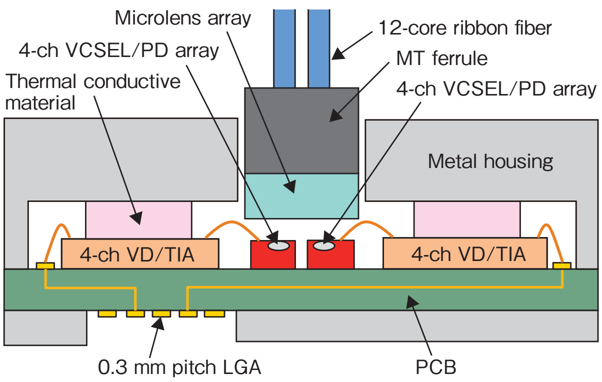

Figure 10 Schematic cross-sectional view for the 28-Gbaud × 8-channel VCSEL-based transceiver.

Figure 11 shows calculated transmission loss and crosstalk characteristics of the differential transmission lines by an electromagnetic simulation. The transmission loss characteristics and the crosstalk characteristics are shown with solid and dashed lines, respectively. The crosstalk characteristics were calculated when operating 4 channels including the monitor channel simultaneously. For all four channels, a 3-dB bandwidth was 28 GHz or wider, which was sufficient for a 28-Gbaud operation. In addition, the crosstalk was less than -30 dB in a frequency range from 0 to 30 GHz. These results indicate that the

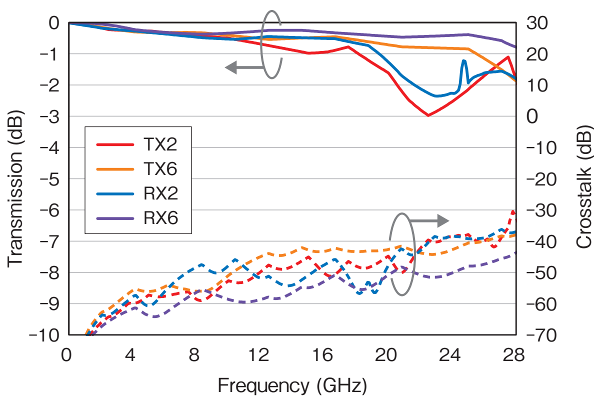

Figure 11 Calculated transmission and crosstalk characteristics of the designed differential transmission lines of the PCB for VCSEL-based transceiver.

designed inner wiring has sufficient characteristics for a 28-Gbaud modulation.

Figure 12 shows a schematic bottom view of the VCSEL-based transceiver. The LGA has a matrix of the of 21 rows and 11 columns with 0.3-mm pitch, which is the same as the electrical pluggable interface. In addition, to suppress channel-to-channel crosstalk, signal lands are surrounded by the ground land. The ultra-compact VCSEL-based transceiver can be also mounted as an optical engine of a pluggable optical transceiver using SFF. Figure 13 shows a 3D model of the QSFP-DD type 1 Active Optical Cable (AOC) where the 28-Gbaud NRZ/PAM4 × 8-channel 850-nm VCSEL-based transceiver is built in the QSFP-DD housing. A DSP is mounted to a PCB assembly in the housing. The electrical interface of the VCSEL transceiver is arranged vertically to the PCB assembly in the housing so that a flexible printed circuit board is used for the electrical connection.

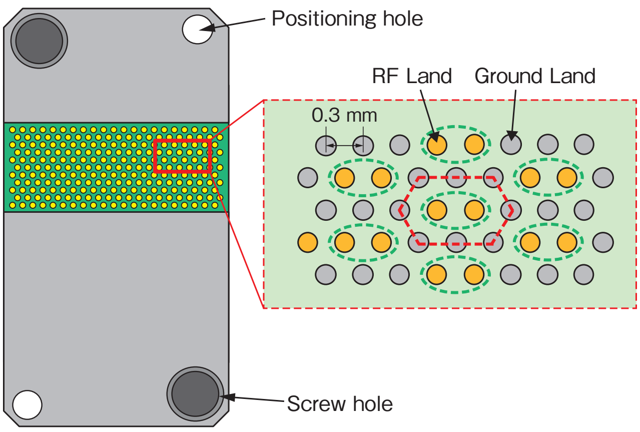

Figure 12 Schematic bottom view for the 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver.

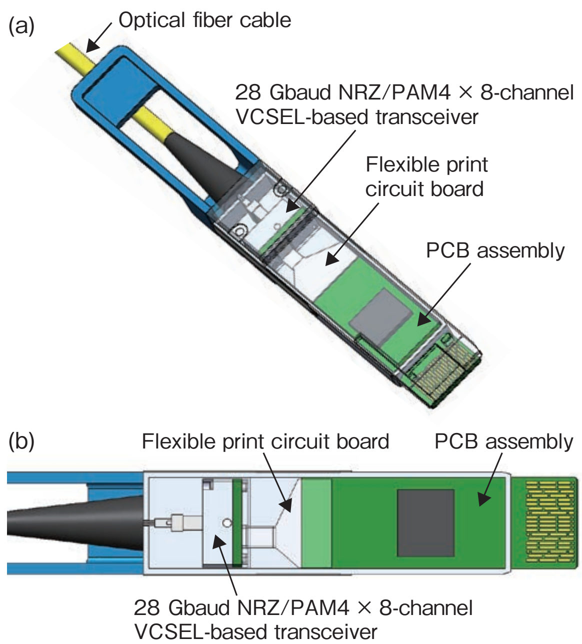

Figure 13 3D model of the QSFP-DD type-1 AOC where the 56-GB/s PAM4 × 8-channel VCSEL-based transceiver in built in the housing.
(a) Upper right view. (b) Top view.

5. EVALUATION OF OPTICAL LINK CHARACTERISTICS

5.1 Serial Optical Link

To evaluate optical link characteristics, we attached the 8-channel VCSEL-based transceiver to the testing station. A Pulse Pattern Generator (PPG), an Error Detector (ED) with integrated a 1-tap Decision Feedback Equalizer (DFE), and a Digital Communication Analyzer (DCA) were used for the optical link test. To build a loopback optical link, we operated monitor channel under a 28-Gbaud NRZ Pseudo-Random Binary Sequence (PRBS) 2^{13}-1 signal (28-Gbaud NRZ signal) and a 28-Gbaud PAM4 Pseudo-Random Binary Sequence Quaternary (PRBSQ) 2^{13}-1 signal (28-Gbaud PAM4 signal).

Figure 14 shows optical eye diagram (a) for TX2 (longest line) and TX6 (shortest line) and the electrical eye diagram (b) for RX2 (longest line) and RX6 (shortest line) operated with a 28-Gbaud NRZ signal. Both the optical and electrical eye diagrams are clearly opened regardless of the length of the differential transmission line. Figure 15 shows the optical eye diagram (a) for channels TX2 and TX6 and the electrical eye diagram (b) for channels RX2 and RX6 with a 28-Gbaud PAM4 signal. Even when using a PAM4 signal, eye diagrams are opened for measured 4 channels.

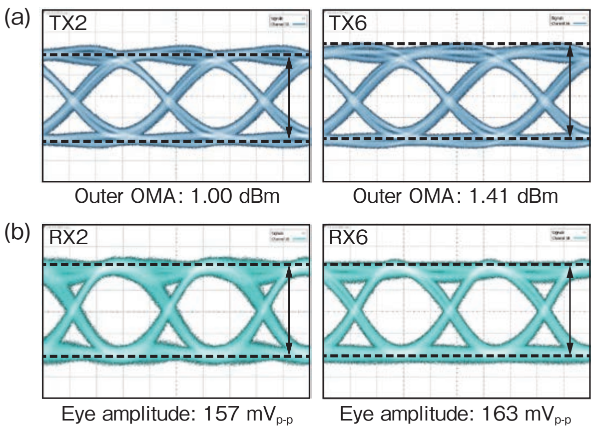

Figure 14 Eye diagrams under 28-Gbaud NRZ operation. (a) Optical eye diagrams. (b) Electrical eye diagrams.

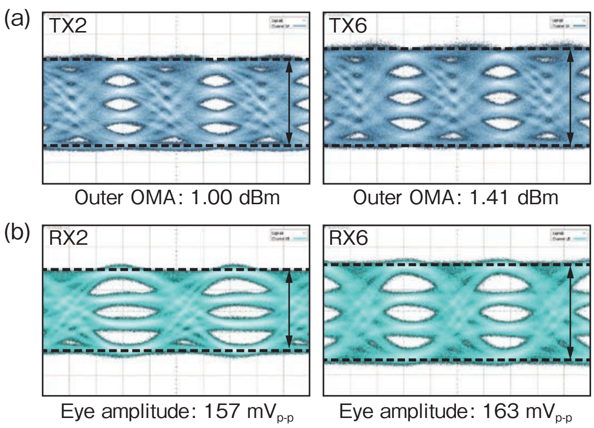

Figure 15 Eye diagrams under 28-Gbaud PAM4 operation. (a) Optical eye diagrams. (b) Electrical eye diagrams.

Figure 16 shows BER characteristics when operating optical links of TX2-RX2 (purple square) and TX6-RX6 (blue triangle) with a 28-Gbaud NRZ signal. Measured BER of <1.0×10^{-12} was obtained at the received optical power of -10 dBm. In addition, when a PAM4 signal was used (orange circle and red diamond), measured BER of <2.4×10^{-4} was obtained, which value is sufficiently below the KP4-FEC threshold. In addition, the BER was also achieved less than 1.0×10^{-12} thanks to the built-in CDR into VD and TIA. The minimum sensitivity at the KP4-FEC threshold for the longest path (orange circle) and the shortest path (red diamond) was -6.9 dBm and -7.8 dBm, respectively. The maximum optical output of the TX was 1.2 dBm. Hence, power budget is calculated as wide as 8.1 dB, which value meets the specified value of 6.5 dB in IEEE802.3cm[8].

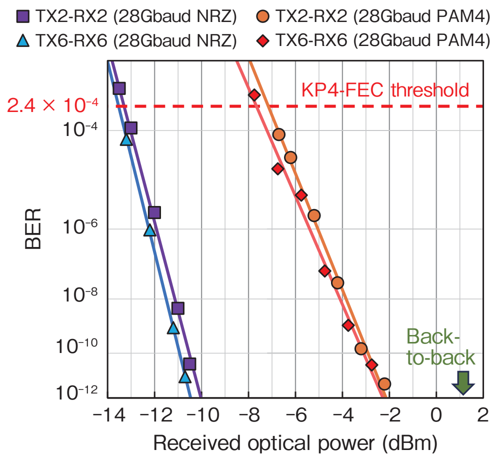

Figure 16 Measured BER characteristics for loopback optical link under 28-Gbaud NRZ and PAM4 operations.

5.2 8-channel Parallel Optical Link

To build an 8-channel parallel optical link using 28-Gbaud PAM4 signals, the 28-Gbaud × 8-channel VCSEL-based transceivers were attached to the two testing stations. TX3 and RX3 were used as monitor channels during the test. A single-channel PPG and ED were used for the optical link test. The other TX channels and RX channels were connected to another multi-channel PPG and a terminator, respectively. The optical eye diagram was filtered by DCA using a 5-tap Feed-Forward Equalizer (FFE) filter specified in IEEE802.3cm.

Figure 17 shows the optical eye diagram (a) and electrical eye diagram (b) operated under single and 8-channel simultaneous operation using 28-Gbaud PAM4 signals. As shown in Figure 17 (a), both optical eye diagrams are opened for single and 8-channel operations. In addition, the Transmitter and Dispersion Eye Closure Quaternary (TDECQ) values were 1.93 dB and 2.04 dB for single and 8-channel simultaneous operation, which values were sufficiently lower than 4.5 dB which is specified in IEEE802.3cm[8]. The TDECQ penalty was as small as 0.11 dB. As shown in Figure 17 (b), the electrical signal for RX also showed good eye-opening regardless of the number of operating channels.

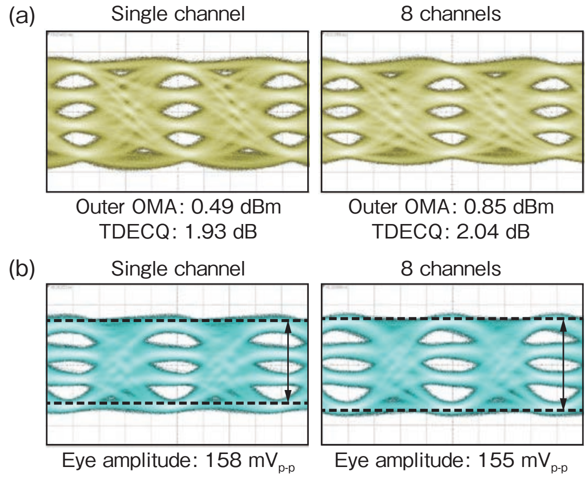

Figure 17 Optical (a) and electrical (b) eye diagrams using 28-Gbaud PAM4 signal under single and simultaneous 8-channel operations.

Figure 18 shows measured BER bathtub curves for single and 8-channel operations. The measured BER were below the KP4-FEC threshold both single and 8-channel operations. The error floor is observed around BER of 2.6×10^{-7} for the 8-channel operation, but it is still lower than the KP4-FEC threshold. On the other hand, a jitter margin at the KP4-FEC threshold was about 0.40 Unit Interval (UI) for both serial and 8-channel operation because the degraded signal was sufficiently recovered by the CDR.

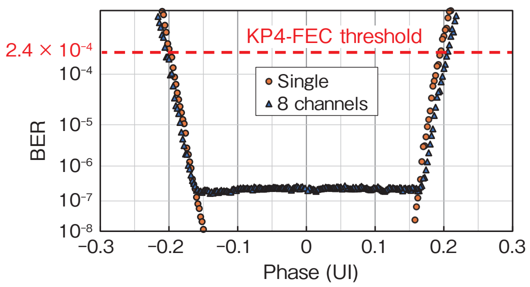

Figure 18 BER burst curve measurement value when driving single-channel and 8-channel simultaneously.

6. CONCLUSION

We designed and fabricated an ultra-compact 28-Gbaud NRZ/PAM4 × 8-channel VCSEL-based transceiver and a testing station employing a high-density electrical pluggable interface. To achieve a compact size of 7.7 mm × 15.9 mm × 7.95 mm, the VCSEL-based transceiver adopts the record narrowest 0.3-mm pitch LGA for electrical interface. The electrical pluggable interface employs electrical contact spring probes which has a staggered arrangement with a 0.3-mm pitch. It contributes to reduces the area of the electrical connections. We verified high-frequency characteristics for the electrical pluggable interface based on electromagnetic simulations. The simulated results show a reflection loss of less than -14 dB, a transmission loss of less than -0.4 dB, and crosstalk of less than -50 dB at a frequency range of 0 to 40 GHz. As a result of evaluating the testing station employing the electrical pluggable interface using a loopback module, a 3-dB bandwidth of 17.3 GHz was obtained. In addition, 8-channel VCSEL-based transceivers were attached to two testing stations and modulated by 28-Gbaud PAM4 signals to build an 8-channel parallel optical link. Clear optical and electrical eye diagrams were obtained in both single and 8-channel simultaneous operations. BER exhibited below the KP4-FEC threshold even under the 8-channel operation. Since the transmission speed per channel was 56-Gb/s, we demonstrated a 400-Gb/s optical link. In this project, we intended to increase the transmission speed per channel to 100 Gb/s (50-Gbaud PAM4)[9), 10)]. As the final target, we will demonstrate a 1.6-Tb/s ultra-compact VCSEL-based transceiver for CPO.

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