Highly efficient active optical interconnect incorporating a partially chlorinated ribbon POF in conjunction with a visible VCSEL

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Abstract: A low-loss 4-ch active optical interconnect (AOI) enabling passive alignment was proposed and built resorting to a transmitter (Tx) incorporating a red 680-nm VCSEL, which is linked to a receiver (Rx) module via a partially chlorinated ribbon POF. The POF was observed to exhibit an extremely low loss of ~0.24 dB/m at λ = 680 nm, in comparison to ~1.29 dB/m at λ = 850 nm, and a large numerical aperture of ~0.42. Both the Tx and Rx, which taps into a beam router based on collimated beam optics involving a pair of spherical lenses, were meant to be substantially alignment tolerant and compact. The achieved tolerance for the constructed modules was beyond 40 μm in terms of the positioning of VCSEL and photodetector. The proposed AOI was completed by linking the Tx with the Rx via a 3-m long ribbon POF, incurring a transmission loss of as small as 3.2 dB. The AOI was practically assessed in terms of a high-speed data transmission over a wide range of temperatures and then exploited to convey full HD video signals.

OCIS codes: (060.2340) Fiber optics components; (250.7260) Vertical cavity surface emitting lasers; (080.3630) Lenses; (230.3990) Micro-optical devices; (350.4600) Optical engineering.

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#208765 - $15.00 USD Received 24 Mar 2014; revised 2 May 2014; accepted 5 May 2014; published 7 May 2014

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1. Introduction

Optical interconnects have been widely regarded as an outstanding solution to efficiently deliver copious amounts of data due to their low power consumption, light weight, immunity to electromagnetic interference, and short signal delay [1,2]. A short-reach active optical interconnect (AOI) plays an integral role in diverse fields, including data processing centers, consumer electronics products, data storage systems, etc [3–5]. A variety of modules relying on a plastic optical fiber (POF) were created by means of passive assembly [4–8], taking into consideration that a transmitter (Tx) and receiver (Rx) module that allows for volume production at an affordable cost are essential to such interconnects [4,5,9–11]. Previously, a perfluorinated graded index POF has been principally developed to achieve relatively low-loss characteristics in the infrared band, which makes it suitable for 850-nm VCSELs [8,12]. In this paper, a highly efficient multi-channel AOI is demonstrated tapping into a Tx module based on a 680-nm VCSEL, which is attached to the Rx module via a partially chlorinated ribbon POF exhibiting conspicuously low-loss characteristics [13,14]. The proposed solution drawing upon a red VCSEL is anticipated to be definitively superior to the conventional counterparts exploiting an infrared light source. The Tx and Rx modules, taking advantage of a beam router based on collimated beam optics that is established by a pair of spherical micro-lenses, are attractive in terms of compact size and their high alignment tolerance. The transfer characteristics of the red VCSEL as well as the transmission loss and numerical aperture (NA) of the partially chlorinated POF are keenly scrutinized. Through a series of rigorous ray-optic simulations, the compact modules are robustly designed so as to bear a relaxed alignment tolerance for their constituents. The Tx and Rx comprising the AOI are first inspected with respect to the alignment tolerance by observing optical coupling characteristics. The proposed AOI, where the Tx is interfaced with the Rx via the POF, is evaluated for a high-speed data transmission at different ambient temperatures. Finally, full HD video signals have been successfully conveyed through the AOI.

2. Proposed multi-channel AOI and its design

Figure 1(a) shows the configuration of the proposed 4-ch Tx and Rx modules. For each of the four channels (Ch1 through Ch4), the Tx involves a red VCSEL operating at λ = 680 nm and a beam router, which consists of a prism connected to both the collimating and focusing spherical lenses, while the Rx includes a photodetector (PD) and a similar beam router. The Tx is linked to the Rx via a partially chlorinated ribbon POF. The beam routers used for the Tx and Rx play the role of conveying light from the VCSEL to the POF and from the POF to the PD, respectively. As described in Fig. 1(b), the light beam emitted by the VCSEL is collimated, steered by the prism towards the horizontal direction, and converged on the POF. The beam exiting the fiber is collimated, reflected by the prism along the vertical direction, and finally accepted by the PD. By virtue of the collimated beam optics adopted for the Tx and Rx, the loss caused by incomplete total internal reflection at the prism was satisfactorily mitigated. Moreover, the alignment tolerance primarily pertaining to the VCSEL and PD was drastically relaxed.

#208765 - $15.00 USD Received 24 Mar 2014; revised 2 May 2014; accepted 5 May 2014; published 7 May 2014

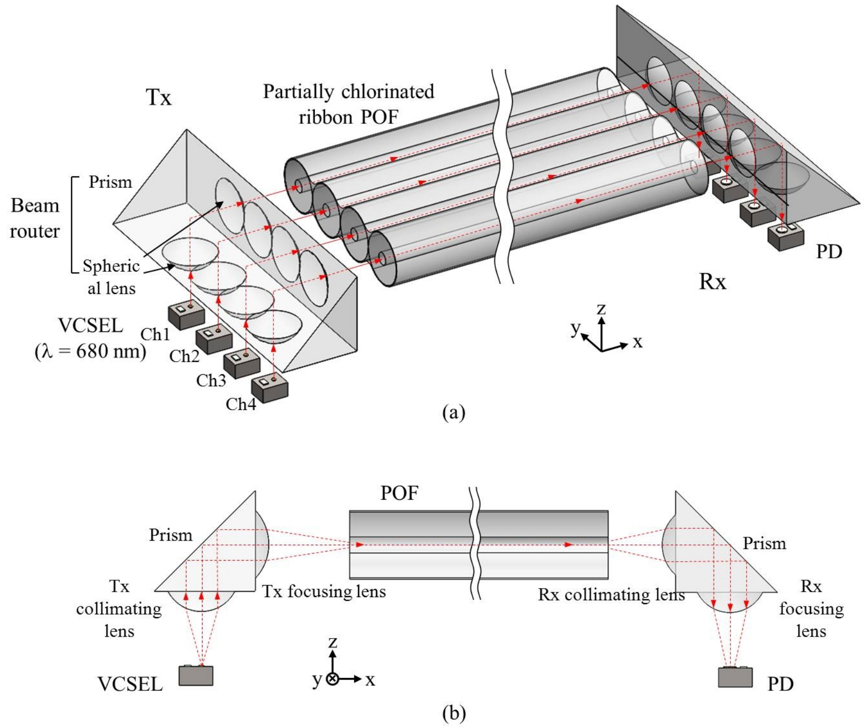

Fig. 1. (a) Configuration of the proposed low-loss 4-ch AOI based on a 680-nm VCSEL in conjunction with a partially chlorinated ribbon POF (b) Beam propagation for the AOI.

The proposed Tx/Rx module can be constructed through a truly passive assembly procedure based on a pick-and-place scheme, as described in Fig. 2. A reference guide has been introduced to a printed circuit board (PCB) containing drive circuits, by matching the column of the former to the hole of the latter. The VCSELs or PDs can be precisely mounted by referring to the line extended by the two holes embedded in the reference guide, so that the alignment of the components is not subject to the accuracy pertaining to the size of the holes prepared in the PCB substrate. The holes created in the PCB are just required to efficiently accept the columns belonging to the reference guide. Actually the tolerance will be determined by the accuracy for the elements to be made through the injection molding, which is approximately 10 µm. A fiber guide is utilized to securely align the ribbon POF with the beam router, which is subsequently attached to the reference guide. The proposed fiber guide involves a rectangular hole corresponding to the size of the POF, which is longitudinally tapered so as to facilitate the installation of fiber. The POF can be securely held by the fiber guide via an epoxy. Finally a cover is used to protect the prepared module. Noting that an infrared VCSEL operating at 850-nm wavelength has been prevalently exploited to develop a POF based AOI despite its relatively large optical loss, we attempted to embody a highly efficient multi-channel AOI, taking advantage of a 680-nm VCSEL in tandem with a partially chlorinated POF. In order to design the Tx and Rx modules associated with the AOI, we first probed into the transfer characteristics of the suggested VCSEL and the transmission loss and NA of the POF. As for a 680-nm multi-mode VCSEL available from Vixar, which has a modulation bandwidth of 3.5 GHz, the optical output with the drive current at room temperature is plotted in Fig. 3. The observed peak power was ~3.6 mW for a current of 10 mA. In regard to the POF, the core was first observed to have a dimension of 120 µm in diameter. As indicated in Fig. 4(a), the optical propagation loss was checked using the cutback method to provide as low as ~0.24 dB/m at λ = 680 nm, as desired, in comparison to

~1.29 dB/m at λ = 850 nm. As plotted in Fig. 4(b), the NA of the POF was examined by monitoring the optical output with respect to the angle of incidence. The estimated NA was about 0.42, equivalent to an angle of 25°.

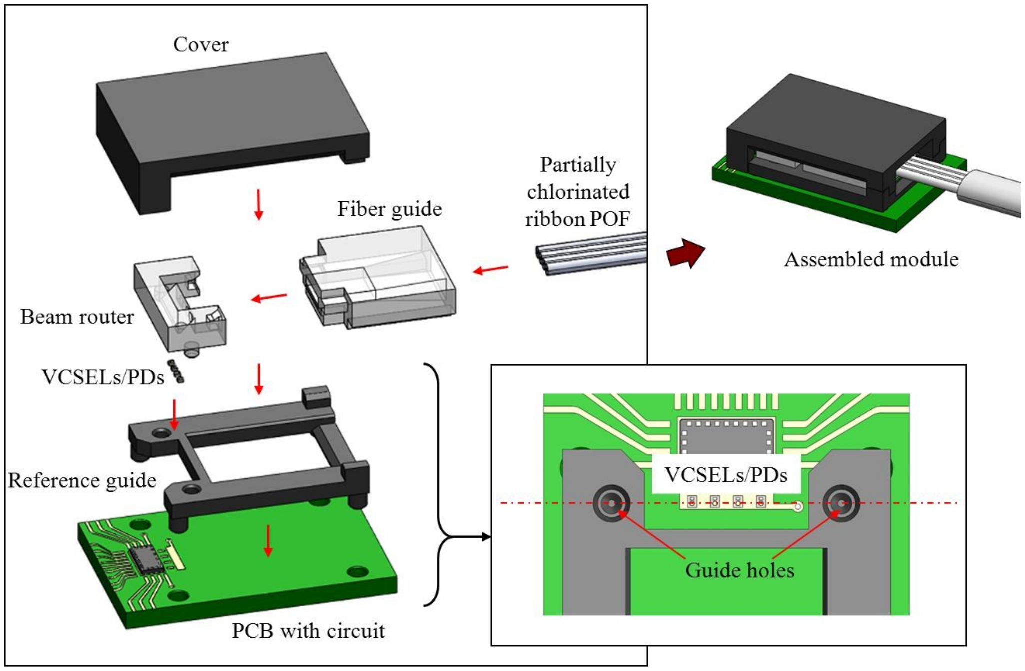

Fig. 2. Passive alignment of constituent elements assisted by a reference guide.

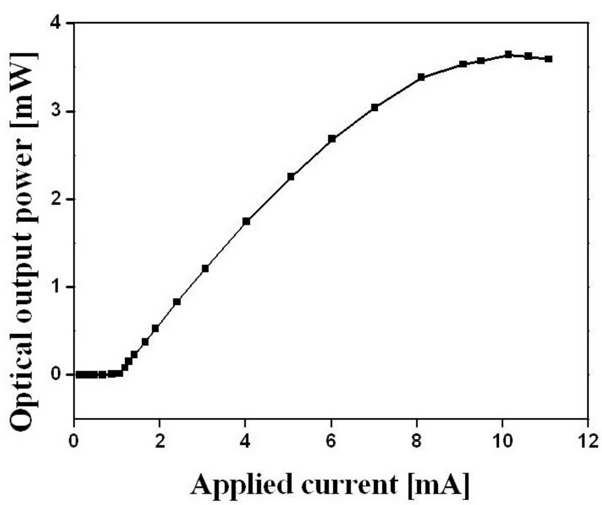

Fig. 3. Transfer curve for the 680-nm VCSEL observed at room temperature.

#208765 - $15.00 USD Received 24 Mar 2014; revised 2 May 2014; accepted 5 May 2014; published 7 May 2014

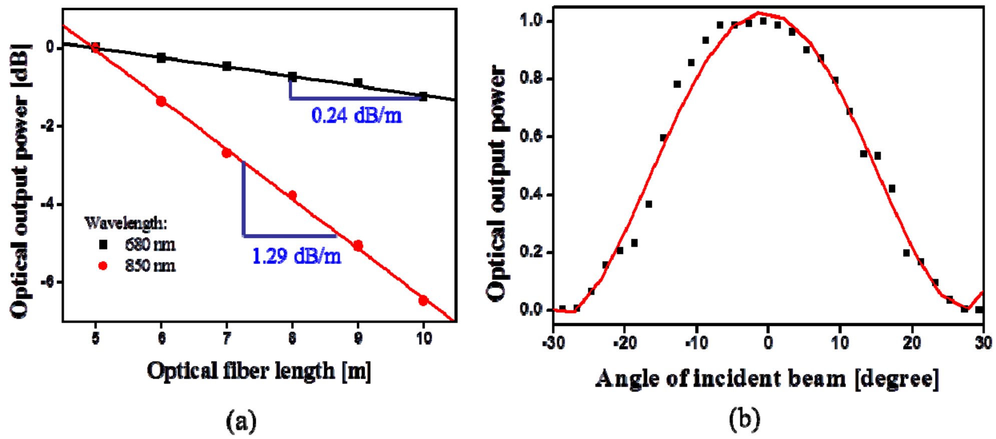

Fig. 4. Observed characteristics of the partially chlorinated POF (a) Losses at λ = 680 and 850 nm (b) Estimation of the NA from the relation between the optical output power and the angle of incidence.

We designed the proposed Tx and Rx modules with the help of ray-optic simulations, as shown in Fig. 5, taking into account practically observed characteristics of the VCSEL and POF. The red VCSEL and the PD were supposed to have a divergence of 30° in full angle and an aperture of 100 μm in diameter, respectively. The VCSEL was assumed to exhibit a uniform beam profile. The prism made of polycarbonate was chosen to have a height of 0.7 mm and a wedge angle of 45°. The lenses to be integrated with the prism were spherical, in light of their flexible formation of arrayed structures, facilitated fabrication and miniaturization. The distance between the VCSEL/PD and lens was set at 0.4 mm in view of the thickness of the reference guide. The gap between the lens and POF was determined to be 0.6 mm, thereby maximizing the optical coupling for the Tx. In case of the Rx, the corresponding gap was fixed at 0.4 mm due to the NA of the POF. As a result, the beam focused towards the POF had a divergence of ~9° and a spot of ~52 μm for the Tx. The focused beam impinging on the PD had a spot of 150 μm for the Rx.

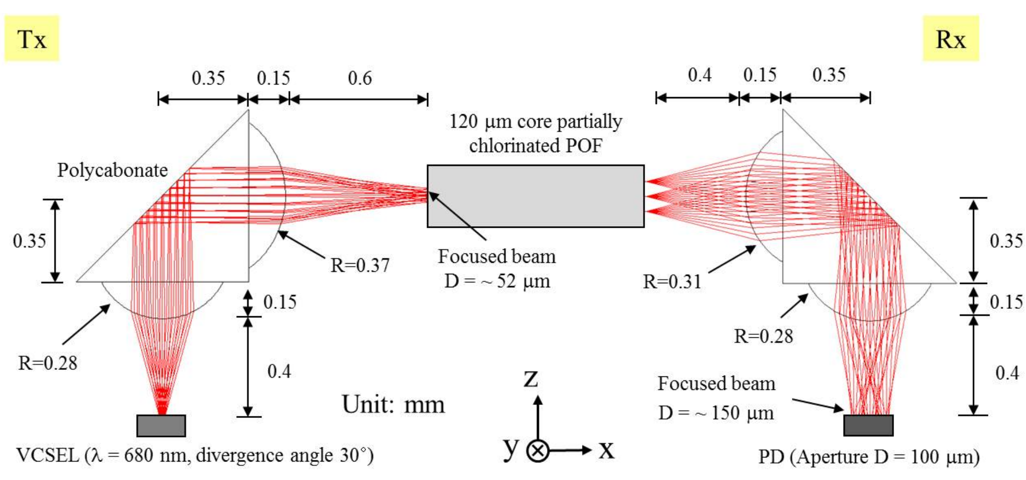

Fig. 5. Arrangement of the Tx and Rx modules, with the beam propagation indicated.

The Tx and Rx modules were designed to achieve a 3-dB alignment tolerance over 40 μm for a PD with a sensitivity of −10 dBm and a speed of 4 Gbps. The PD is available from Cosemi Technologies. In a bid to verify the feasibility of passively prepared Tx and Rx modules, the alignment tolerance for the PD and VCSEL was scrutinized regarding the

#208765 - $15.00 USD Received 24 Mar 2014; revised 2 May 2014; accepted 5 May 2014; published 7 May 2014

optical coupling characteristics, as shown in Fig. 6. A 3-dB tolerance was obtained by identifying the power captured by the POF or PD, when the VCSEL or PD was displaced in steps of 10 and 50 μm along the x/y and z axes, respectively. The observed VCSEL tolerance for the Tx was ~40 μm and over 100 μm along the x/y and z axes, respectively. The PD tolerance for the Rx was estimated to be ~50 μm and beyond 100 μm along the x/y and z axes, respectively. For the Tx an optical loss of 0.65 dB was accounted for by the Fresnel reflection. For the Rx, a loss of 1.9 dB was ascribed to the beam mismatch of 1.25 dB in addition to a Fresnel reflection also with a loss of 0.65 dB. Assuming that all of the elements are aligned perfectly, the VCSEL-to-PD coupling loss would be 3.27 dB for the case of a 3-m long POF. However, for the worst situation causing a misalignment of 40 μm, the VCSEL-to-PD loss is estimated to reach 8.92 dB, which is accounted for by the Tx coupling loss of 4.1 dB, the Rx coupling loss of 4.1 dB, and the propagation loss for the 3-m long POF of 0.72 dB. With the VCSEL driven to supply an optical power of ~1.76 dBm with a current of 4 mA, the optical power reaching the PD was observed to be −7.16 dBm, safely meeting the target of −10 dBm. The above theoretical study supported the idea that the proposed Tx and Rx modules are remarkably alignment tolerant. Noting that the channel crosstalk is of prime concern in relation to the design of the proposed 4-ch interconnect, we explored the influence of individual channels on their contiguous channels. As predicted, a 490-μm pitch related to the ribbon POF was discovered to ensure a negligibly small channel crosstalk.

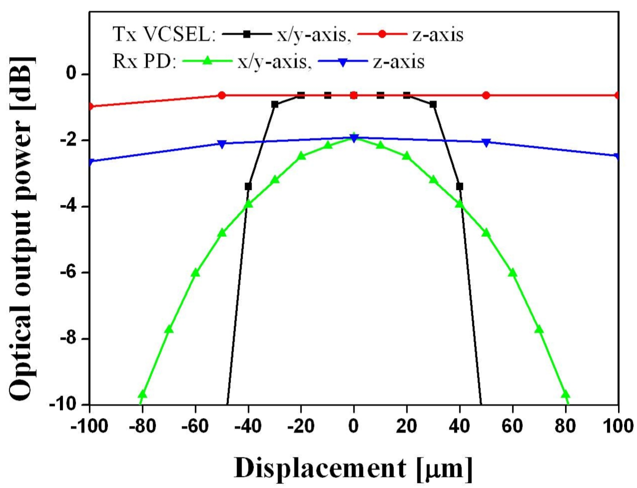

Fig. 6. Estimated optical coupling with the VCSEL and PD displacement for the Tx and Rx, respectively.

3. Realization of the highly efficient AOI and its characterization

A plastic injection molding technique, which is capable of guaranteeing a processing accuracy of 10 μm, was utilized in common to produce an alignment guide and cover in polyimide, in addition to a beam shaper and fiber guide in polycarbonate. Details on manufactured Tx and Rx modules, which are basically of the same configuration except for the presence of either the VCSEL or PD, are shown in Fig. 7(a). The Tx and Rx were inspected to have the same dimensions of 8.6x7.0x1.9 mm^3, where the constituent spherical lenses were all arranged in accordance with a pitch of 490 μm as intended. The partially chlorinated ribbon POF, having the same pitch of 490 μm, was stably installed on the fiber guide with an epoxy, with the facet adequately polished with a milling machine. The VCSELs and PDs were passively mounted along the holes imbedded in the reference guide, by use of a pick-up tool equipped with a vision camera. The VCSELs and PDs were positioned with an

#208765 - $15.00 USD Received 24 Mar 2014; revised 2 May 2014; accepted 5 May 2014; published 7 May 2014

accuracy of ~10 μm, as observed in Fig. 7(b). Figure 7(c) reveals the completed AOI, where the Tx and Rx are mediated via a ribbon POF.

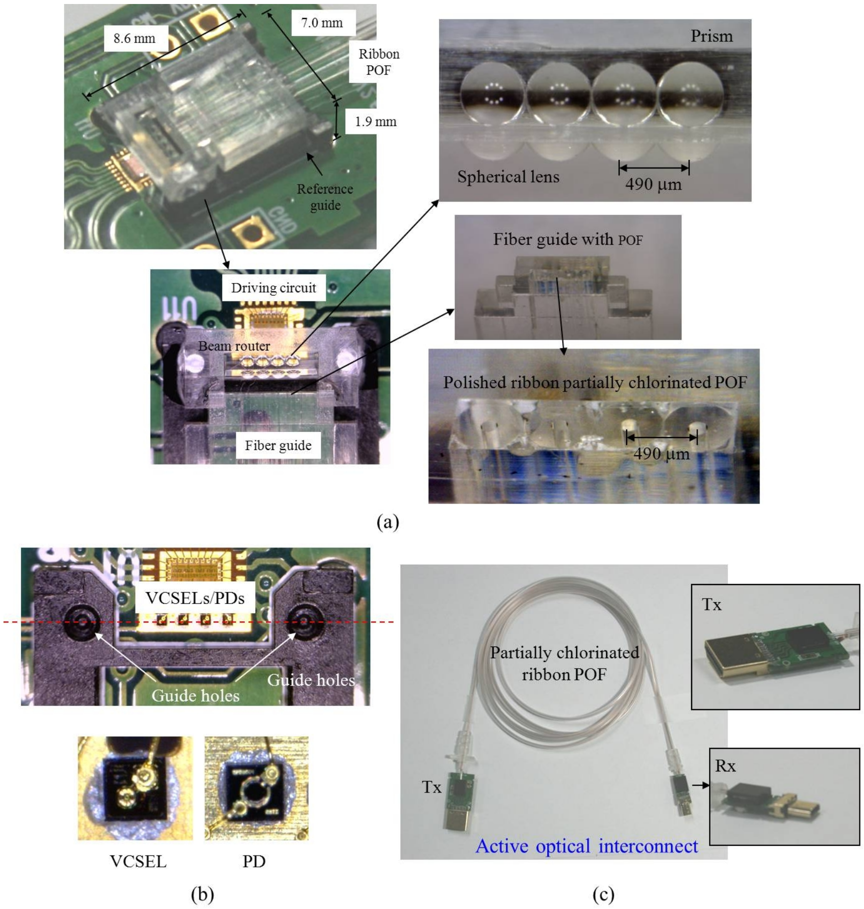

Fig. 7. (a) Completed Tx/Rx modules (b) Passively positioned VCSLEs/PDs (c) Completed AOI encompassing the Tx, Rx and POF.

The manufactured Tx and Rx modules were evaluated in terms of the alignment tolerance and high-speed data transmission. In order to examine the alignment tolerance, as plotted in Fig. 8, the optical output was recorded when either of the VCSEL or PD was displaced in the transverse and longitudinal directions with increments of 10 and 50 μm, respectively. For the Tx, the obtained 3-dB tolerance was ~45 μm and over 100 μm along transverse (x/y) and longitudinal (z) directions, respectively, while the VCSEL-to-fiber coupling loss was about 1.0 dB. For the Rx, the obtained tolerance was ~45 μm and over 100 μm for the transverse and longitudinal directions, respectively, while the fiber-to-PD coupling loss was ~1.5 dB. The total optical loss corresponding to a 40-μm structural tolerance was found to be 8.7 dB for the case of a 3-m long POF. There was good agreement between the theoretical and experimental results. On the whole, the demonstrated tolerance surpassing 20 μm was believed to make possible practical passive alignment. The prepared Tx and Rx modules were connected to each other via a 3-m long ribbon POF so as to build the proposed AOI. The optical output for the AOI was obtained from the PD belonging to the Rx. The observed insertion loss was 4.0, 4.7, 3.9, and 4.3 dB for Ch1, 2, 3, and 4, respectively. As a result, all of the four channels were confirmed to operate properly, exhibit a variation of 0.8 dB in the throughput.

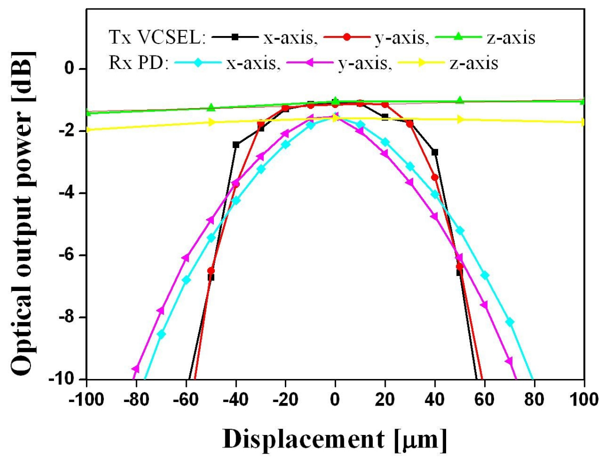

Fig. 8. Measured optical coupling efficiency with respect to the VCSEL displacement for the Tx and the PD displacement for the Rx.

Lastly, the created Tx and Rx modules were tested to conduct a high speed data transmission over a 3-m long POF using a 2^{31}-1 pseudorandom bit sequence signal at 3.4 Gbps. The optical eye pattern for the Tx was attained by detecting the POF output. For the Rx, the electrical eye pattern was acquired similarly, while the bit error ratio (BER) was measured with a BER tester. For each of the four channels, an optical eye diagram was measured from the output of a 3-m long POF that is linked to the Tx, as plotted in Fig. 9(a). An electrical eye diagram was also observed at the output of a trans-impedance amplifier (TIA) appended to the Rx, which has been connected to the Tx via the POF, as shown in Fig. 9(b). It was supported that all of the four channels, including Ch1 through Ch4, could efficiently deliver a digital signal at 3.4 Gbps. If the proposed AOI is constructed by utilizing an advanced red VCSEL with a modulation bandwidth over 10 GHz, which is currently being developed by Vixar [13], and a high performance PD with a speed over 10 Gbps, it is expected to readily achieve a data rate of around 10 Gbps. The temperature dependence for the Tx and Rx was scrutinized over the range from −20 to 70 °C. The observed optical eye pattern for the Tx for Ch4 is presented in Fig. 10(a). And Fig. 10(b) shows the measured electrical eye pattern for the Rx for Ch4, signifying a BER of below 10^{-10}. The embodied AOI proved to successfully deliver a full HD video clip over a 3-m long partially chlorinated ribbon POF, as shown in Fig. 11. It was categorically confirmed from the above experimental results that the proposed AOI utilizing a red VCSEL in tandem with a partially chlorinated ribbon POF could act as an outstanding low-loss short-reach optical conduit, rendering a relaxed alignment.

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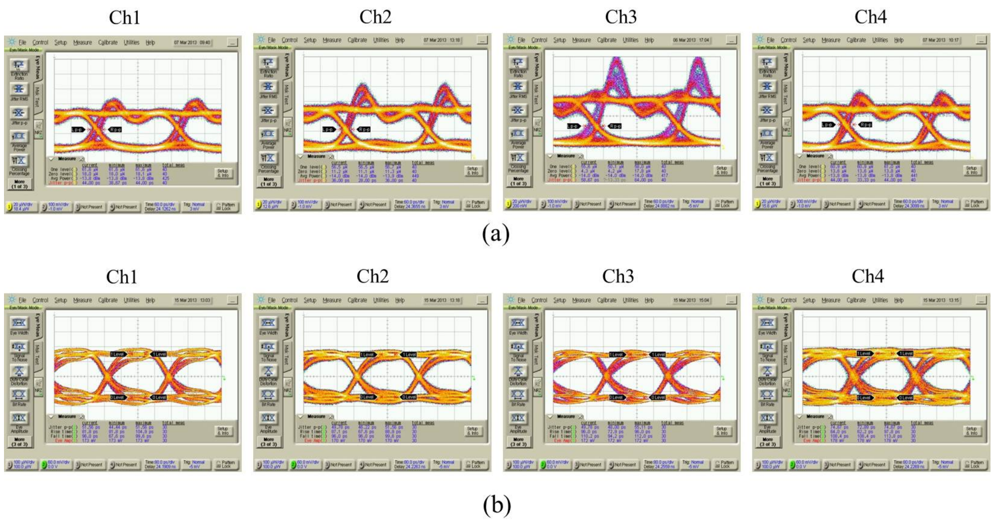

Fig. 9. Demonstrated results of the digital data transmission at 3.4 Gbps for each of the four channels (a) Optical eye pattern for the Tx (b) Electrical eye pattern for the Rx.

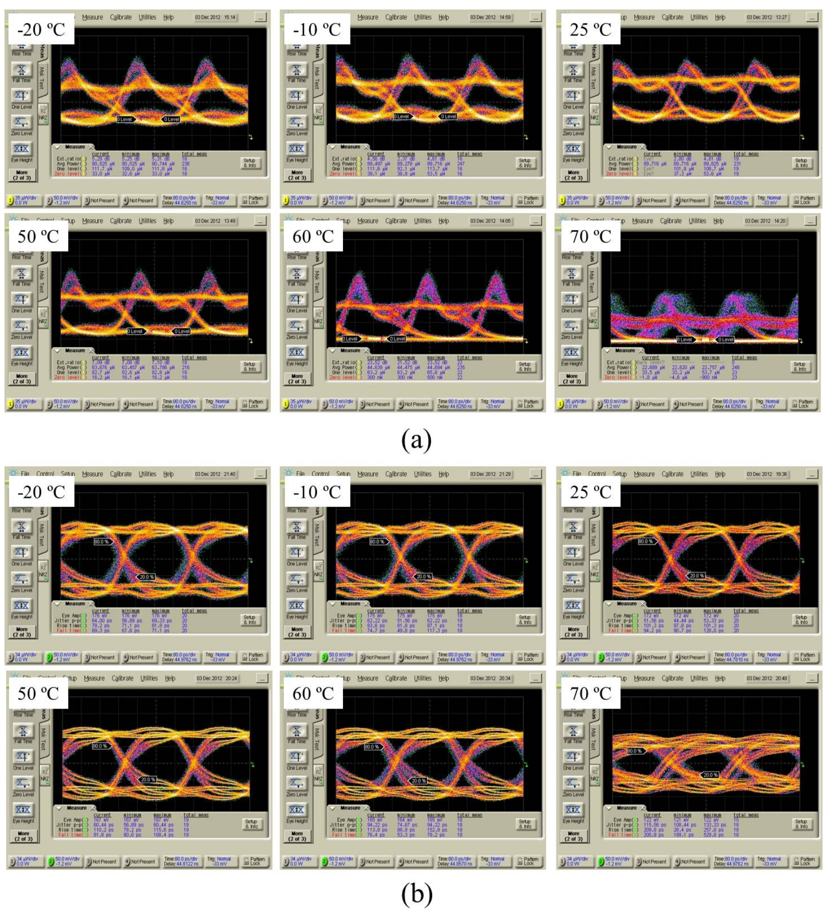

Fig. 10. Demonstrated results of the digital data transmission at 3.4 Gbps for different temperatures (a) Optical eye pattern for the Ch4 Tx (b) Electrical eye pattern for the Ch4 Rx.

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Fig. 11. Demonstration of full HD video data delivery via the manufactured AOI.

4. Conclusion

A low-loss multi-channel short-reach AOI was presented tapping into a Tx adopting a red VCSEL, linked to a Rx module through a partially chlorinated ribbon POF. The Tx and Rx modules, relying on a beam router based on collimated beam optics leading, were passively embodied thanks to their relaxed alignment tolerance. The prepared AOI having a 3-m long POF was thoroughly assessed in terms of a high speed data transmission over a range of temperatures. Ultimately, it was readily applied to convey full HD grade video data.

Acknowledgments

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2013-008672), and a research grant from Kwangwoon University in 2014.