Passively Aligned Transmit Optical Subassembly Module Based on a WDM Incorporating VCSELs

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***Abstract*—A short-reach transmit optical subassembly module enabled by a passive alignment has been proposed and manufactured which takes advantage of a filter free coarse wavelength-division multiplexer (WDM). A four-channel data transmission was accomplished by employing only two plastic optical fibers and four vertical-cavity surface-emitting lasers (VCSELs). A multiaxis beam combination was introduced to overcome the use of WDM filters. The proposed module was constructed via a passive alignment; the overall alignment tolerance was examined by assessing the optical coupling efficiency in terms of the VCSEL displacement. The achieved tolerance was ~20 and ~150 μm in the horizontal and vertical direction respectively, while the demonstrated peak coupling was ~41%. Finally, a high-speed 2.5-Gb/s signal was successfully delivered via the demonstrated module.**

***Index Terms*—Optical interconnect, optical subassembly, plastic optical fiber, vertical-cavity surface-emitting laser (VCSEL), wavelength-division multiplexing (WDM).**

I. Introduction

AN OPTICAL interconnect technology using an optical subassembly (OSA) has attracted enormous interest as a viable alternative to the conventional copper cable-based electrical counterparts [1], [2]. It renders prominent benefits such as a wide bandwidth, a light weight, a low cost, a flexible structure, and immunity to electromagnetic interference. It may be suitable to a high-capacity data transmission, like from a video source to a display device or from a data storage center to a terminal. Such a short-reach optical interconnect is one of the most prominent Green IT technologies, enabling a drastic energy saving entailing a negligibly small heating.

Conventional optical transceiver modules employ a low-efficiency diode laser, which mainly resorts to an active alignment-based packaging, a ferrule in between the fiber and the OSA module, and a hermetic sealing. They have suffered from several issues, including a complicated manufacturing process leading to a low cost effectiveness, and poor miniaturization. Since a short-distance optical link needs to be compact and simple, a vertical-cavity surface-emitting laser (VCSEL) is a viable candidate as a light source. It features such advantages as a low cost, a circular beam profile, and a low power-consumption [3]–[5]. Previously, several approaches were proposed for creating a short-reach optical interconnect module [6]–[8]. In this letter, we have proposed and built a transmit OSA (TOSA) module linked to a plastic optical fiber (POF) as a short-reach optical interconnect vehicle. A coarse wavelength-division-multiplexing (WDM) scheme with two types of VCSELs at different wavelengths, requiring no expensive wavelength filters, was adopted that cuts down the fiber count by half. The constituent elements, including a lens, a prism, and cases, were manufactured through an injection molding technique and put together by means of a passive alignment so as to complete the module.

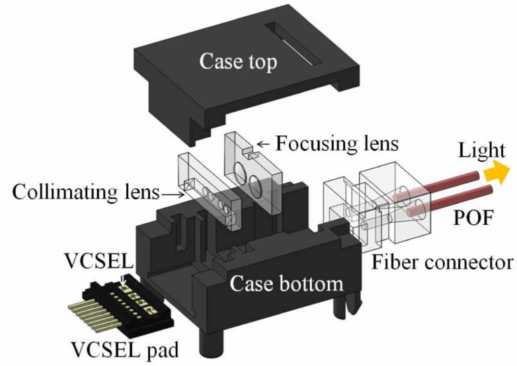

Fig. 1. Schematic configuration of the proposed TOSA module.

II. Proposed TOSA Module

The configuration of the proposed TOSA module is depicted in Fig. 1. A module case consisting of a case-bottom with built-in grooves and a case-top plays the role of accommodating the constituent parts which encompass a metal pad, a fiber connector, a collimating lens combined with a 45° prism, and a focusing lens. A set of four VCSELs are mounted onto the metal pad, which contains pins connected to a printed circuit board, while a pair of POFs are put into the fiber connector.

Fig. 2 illustrates the formation and propagation of the light beam in a top- and cross-sectional structure of the module. To accomplish a four-channel transmission a total of four VCSELs, two at $\lambda_1 = 850$ nm and two at $\lambda_2 = 780$ nm, were employed. The four channels are composed of an upper pair, Ch1 (λ_1) and Ch2 (λ_2), and a lower pair, Ch3 (λ_2) and Ch4 (λ_1). The operating principle of the module is first elucidated for the upper pair. Each of the two beams emanating from the Ch1 and Ch2 VCSELs is vertically steered into the horizontal direction via a 45° prism, which is supposed to provide a total internal reflection, and collimated by the corresponding collimating lens.

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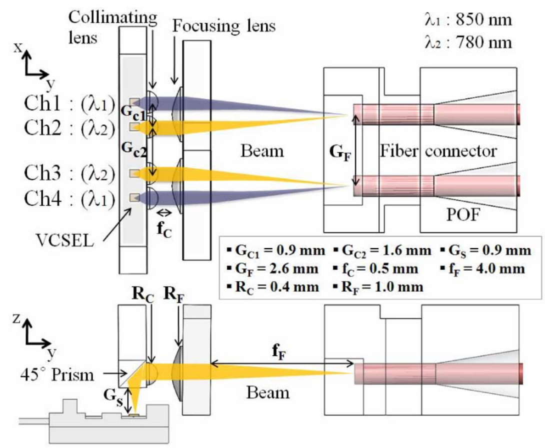
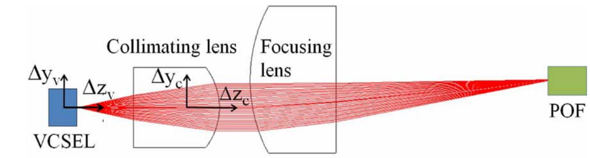


Fig. 2. Beam propagation in the proposed TOSA module.

The two beams impinge upon a single common focusing lens at the off-axis to be focused and coupled to a POF; as a result, the demand for a WDM filter, which is indispensable in the conventional schemes, could be overcome. It is noted that the fiber count was reduced by half thanks to the salient configuration of the designed module.

The design parameters used for the module are summarized: the POF core was 120 μm in diameter, having a graded index profile with a numerical aperture of ~0.185. The focusing/collimating lens and the prism were made of polycarbonate with $n = 1.569$ at $\lambda_1 = 850$ nm and $n = 1.571$ at $\lambda_2 = 780$ nm. The divergence angle of the VCSEL was 25°. It is remarked that the VCSEL pad and the cases are all made of plastic, polyamided (PA) 66, having a melting temperature at ~260 °C, and hence the module is scarcely subject to any deformation resulting in an alignment error during the VCSEL operation. The distance between the Ch1 and Ch2 collimating lenses is $G_{C1} = 0.9$ mm, the gap between the Ch2 and Ch3 lenses is $G_{C2} = 1.6$ mm, and the two focusing lenses are separated by $G_F = 2.6$ mm. The distance from the VCSEL to the collimating lens is determined to be $G_S = 0.9$ mm considering its beam divergence; the focal length of the focusing lens is $f_F = 4.0$ mm to achieve an alignment tolerance of ~20 μm. The diameter of the collimating lens and the focusing lens is $R_C = 0.4$ mm and $R_F = 4.0$ mm, respectively, and the distance between the two is $f_C = 0.5$ mm. The designed module was theoretically proven to cause no remarkable difference between the two wavelengths λ_1 and λ_2.

The proposed module is to exhibit an affordable alignment tolerance leading to a decent coupling efficiency, which is critically determined by the whole alignment of its constituent parts. In order to assess the general alignment tolerance of the module, however, we were primarily concerned about the position of the VCSEL relative to the collimating optics. It has been assumed that the alignment between the collimating lens and the focusing aspheric lens has been relaxed due to an architecture based on beam collimation, while the POF has a sufficiently large core. And the mechanical tolerance of the collimating and focusing part can be controlled below ±10 μm thanks to a high precision injection molding technique. And the VCSEL is placed with a precision custom-made die mounter featuring an accuracy of 5 μm. Therefore, the alignment tolerance between the collimating lens and the VCSEL is practically estimated to be about ±10 μm.



Case	Displacement (μm)				Coupling efficiency (%)
	VCSEL		Collimating lens		
	Δy_v	Δz_v	Δy_c	Δz_c	
Ideal	0	0	0	0	41
I	+10	+10	-10	-10	32
II	+20	+20	0	0	33
III	+20	+200	0	0	20

Fig. 3. Ray-tracing-based analysis on the coupling efficiency depending on the alignment of the VCSEL relative to the collimating lens for the Ch2.

As illustrated in Fig. 3, a ray tracing has been conducted for the Ch2 to observe the influence of the alignment of the VCSEL and the collimating lens upon the optical coupling to the POF. This coupling is determined by the incidence angle, the spot size, and the position of the focused beam in front of the POF. For the ideal case accompanying no displacement, the maximum coupling efficiency was 41%. The worst situation is then simulated in Case I, where the two components were extremely shifted in opposite directions along the y- and z-axis; and, for Case II, the lens displacement was equivalently reflected to the VCSEL displacement. The fact that the coupling efficiency for the two cases is approximately the same as noted in Fig. 3 indicates that Case I may be mimicked by Case II. Moreover, for Case III, the coupling declined only by half compared to the ideal case, even when the VCSEL was further displaced by up to 200 μm in the light propagation direction. As a consequence, taking into account the above theoretical results, we have decided to take a simple but efficient simulation approach solely based on the VCSEL displacement in order to address the alignment characteristics of the TOSA module.

The alignment tolerance of the designed module was numerically examined by observing the optical coupling efficiency when the VCSEL is only deviated in one of the three axes from a reference position: x and y for the transverse direction and z for the longitudinal. The coupling reached a peak of ~41% at the center, and the corresponding loss of ~59% (or 3.9 dB) is accounted for by a Fresnel reflection of 1.4 dB, an incomplete total internal reflection of 1.1 dB by the prism, and a POF coupling loss of 1.4 dB. The coupling declined gradually along the x- and y-axes, but remained nearly constant along the z-axis. The VCSEL alignment tolerance was defined as the magnitude of the displacement that lowers the efficiency by half as compared to the peak value. It was calculated to be ~20 μm in the horizontal x- and y-direction and ~150 μm in the longitudinal z-direction.

III. Module Implementation and Its Characterization

The proposed TOSA module shown in Fig. 1 was constructed by employing the parts prepared by using the injection molding method. The relevant implementation procedure is described here: the collimating and focusing lenses, the VCSEL pad, and the fiber connector were appropriately inserted onto the case-bottom, and the case-top was subsequently combined with the case-bottom to mechanically fix and align them in a secure

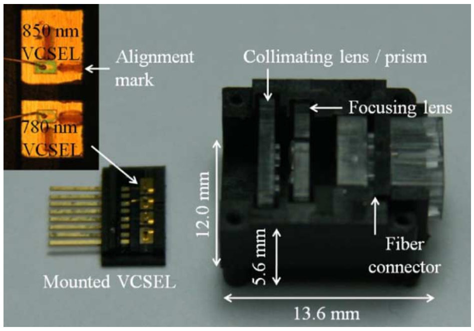


Fig. 4. Completed TOSA module.

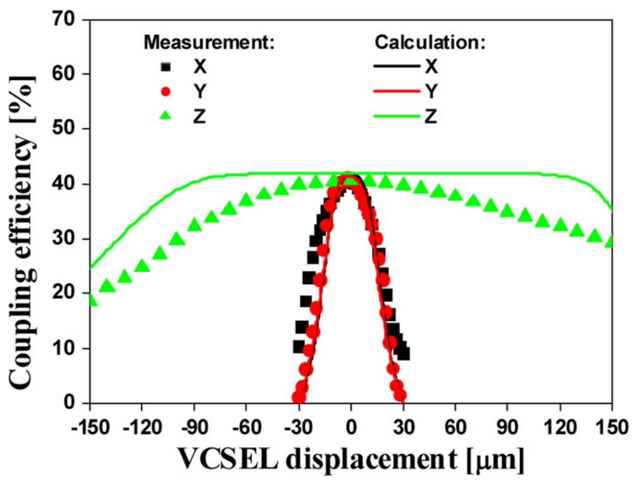


Fig. 5. Optical coupling with the VCSEL displacement for the Ch2.

manner. A VCSEL was precisely placed and fixed on top of an alignment mark formed on the silver epoxy coated metal pad. Next, the POF was inserted to the fiber connector up to the position defined by a guide pin and attached with a UV epoxy. The fiber connector has a guide pin, which is used to make the focal point of the focusing lens fall on the front facet of the POF. In this way, the proposed TOSA module has been completed via a passive alignment involving no active power monitoring. Fig. 4 displays the completed TOSA module with a footprint of $13.6 \times 12.0 \times 5.6$ mm^3. An enlarged view of the two VCSELs mounted on the metal pad is also included.

For the purpose of investigating the alignment tolerance of the completed module as a function of the VCSEL position, the optical coupling efficiency was first measured for the Ch2 by shifting the VCSEL from a reference position with a 2-μm step in the x- and y-direction and a 10-μm step in the z-direction. As shown in Fig. 5, the transmission efficiency decreased gradually with the VCSEL displacement in the horizontal direction along the x- and y-axis, whereas it remained nearly constant in the longitudinal direction along the z-axis. The average tolerance along the x- and y-axis was about $\sim$22 and $\sim$18 μm, respectively, and that along the z-axis was $\sim$150 μm as predicted. As anticipated from the geometrical asymmetry along the x-axis of the proposed module shown in Fig. 2, a slight asymmetry was observed along the x-axis. It was hence confirmed that the alignment tolerance offered a good correlation between the simulation and the experiment.

Finally, the performance of the prepared module as a TOSA was evaluated in terms of the optical coupling efficiency and

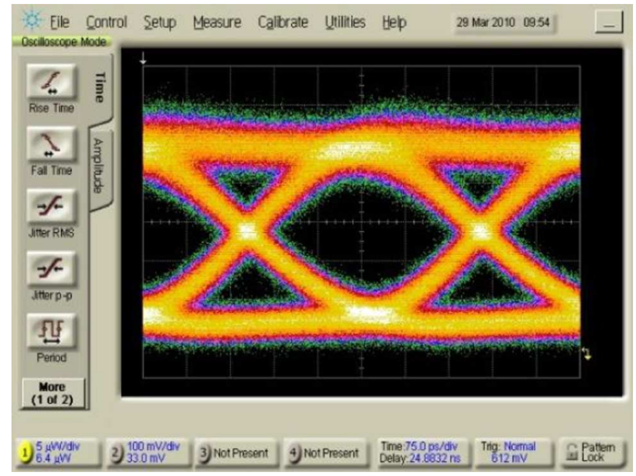


Fig. 6. Observed optical eye pattern for the Ch2 for a 2.5-Gb/s data transmission.

the high-speed signal transmission. The optical output from the POF of the module was first measured with an optical power meter to find that the achieved coupling efficiency was up to $\sim$41% and $\sim$39% for Ch1 and Ch2, respectively, supporting that the proposed passive alignment scheme is highly feasible. The module was then tested to transmit a 2.5-Gb/s $2^{31} - 1$ pseudorandom bit sequence signal generated by a pattern generator from Anritsu. As is displayed in Fig. 6, a decent optical eye pattern for the Ch2 was obtained by monitoring the optical output from the POF with an Agilent 86100 DCA, when the average optical power was -2.4 dBm and the extinction ratio 9 dB.

IV. Conclusion

In summary, a coarse WDM-based TOSA module was presented. An optical coupling scheme based on a multiaxis beam combination was adopted engaging no WDM filters. The module components were produced by means of an injection molding technique and assembled exploiting a passive alignment. A receive OSA module incorporating a WDM filter is being developed to complete a transceiver.

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