Monolithically integrated 4 ch × 25.8 Gbps lens-integrated surface- emitting DFB laser array directly coupled to SMF

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Abstract: Direct optical coupling and a 4 × 25.8-Gbps 2-km optical link were demonstrated simultaneously by using a lens-integrated surface-emitting DFB laser (LISEL) array for a low-cost multi-lane optical module. The integrated lens was optimized so that the LISEL had a focused beam, resulting in high-efficiency (−3.5 dB) direct optical coupling to a SMF. Thanks to its short DFB cavity with high-gain InGaAlAs active layer, the LISEL array demonstrated 4 × 25.8-Gbps 2-km error-free transmission. Moreover, it achieved error-free transmission up to 70 °C.

Keywords: DFB, lens, SMF, optical coupling

Classification: Integrated optoelectronics

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1 Introduction

The amount of data traffic in data centres (DCs) is increasing at an explosive rate and utilization of 100-Gbps base optical interconnects in DCs is being actively discussed. Parallel Single-Mode 4-lane (PSM4) is one of promising solutions for interconnect in DCs [1]. The intrinsic feature of PSM4 is a very simple configuration; namely, a 25.8-Gbps $\times$ 4-lane parallel interface connecting a single-mode-fiber (SMF) array with a minimum support distance of 500 m. Additionally, to satisfy the demand for low-power consumption, uncooled operation of the light source is assumed. One approach to realize an optical module compliant with PSM4 is to use a 1.3- μ m direct-modulation-laser (DML) array [2], which can reduce the size and number of components in a module as compared to using multiple single lasers. Some DMLs operating at 25.8 Gbps at high-temperatures were reported [3, 4, 5]. However, one of the key issues concerning a DML array is optical coupling to a SMF array. A conventional DML needs some external lenses to assure sufficient optical coupling to a SMF. As a result, the process for aligning multiple beams with external lenses is much more complex than that for a single laser. The assembly cost thus increases drastically.

To address this issue, a new surface-emitting laser, named a “lens-integrated surface-emitting laser” (LISEL), was previously developed by monolithically integrating a 45° total-reflection mirror and a micro lens to a DFB laser. A feasibility of direct optical coupling between the LISEL and SMF, which makes alignment much simpler than that for a conventional DML with external lenses, was demonstrated [6]. Moreover, clear eye openings for several data rate of up to 40 Gbps due to a short-DFB cavity were also reported [7].

In this study, a LISEL array for an optical module compliant with PSM4 was demonstrated. An integrated lens was optimized so that the LISEL array had a focused beam, achieving high-efficiency (−3.5 dB) direct optical coupling to a SMF. Due to the short DFB cavity, a 4 $\times$ 25.8-Gbps optical link using a 4-ch LISEL array was demonstrated. Moreover, error-free transmission up to 70 °C was achieved. These results indicate that the optimized LISEL array is a promising light-source for a very low-cost PSM4 optical module.

2 Device design and fabrication process

Conceptual images of an optical module using a LISEL array are shown in Fig. 1. A LISEL array, a photodiode (PD) array, and ICs are mounted on the same substrate as shown in Fig. 1(a), providing a very small footprint compared to that of a conventional module using several discrete packages. A cross-sectional view of the optical configuration is shown in Fig. 1(b). Since a lens is integrated to the LISEL, an optical connector can be located just above the LISEL without any

Fig. 1. Schematic image of low-cost module with LISEL: (a) bird's-eye view, and (b) cross section

external lens. This simple configuration can reduce both alignment complexity and total number of components.

The far-field pattern (FFP) of the LISEL can be controlled by changing the distance from the emission edge of the DFB cavity to the lens surface (L) and radius of curvature (R) of the lens. Consequently, by optimizing R and L , high-efficiency direct coupling is possible. Maximum coupling efficiency between the LISEL and a SMF with respect to R and L calculated on the basis of Gaussian optics is shown in Fig. 2. According to this calculation, the LISEL with a focused beam can supply higher coupling efficiency than one with a divergent beam.

Fig. 2. Calculated coupling efficiency between LISEL and SMF.

This is because the mode-field size at the focused point (i.e., beam waist) can be adjusted to that of the SMF. To obtain a high coupling efficiency of around -3 dB, R and L were respectively chosen as $60\ \mu\text{m}$ and $135\ \mu\text{m}$.

The process for fabricating the integrated lens is the same as that previously reported [8]. After dry etching (Fig. 3(a)), wet chemical etching was used (Fig. 3(b)) [9]. Here, R can be controlled by changing both the diameter of the lens (D) and etching time. Measured R with respect to wet-etching time at D of $70\ \mu\text{m}$ is shown in Fig. 3(c). R is infinite before the wet etching (Fig. 3(a)), and it is also infinite when the lens is over etched (In both cases, the lens is close to a flat plain.). As a result, R varies as parabolic curve with respect to the etching time with

Fig. 3. (a) and (b) Fabrication process for lens, (c) etching depth vs radius (R), and (d) diameter (D) vs minimum radius (R).

a local minimum. This local minimum changes with respect to D, and almost the same R values for V and H directions were obtained, as shown in Fig. 3(d).

The rest of the basic device structure was almost the same as a previously reported high-speed design [10]. For achieving high-speed (25.8 Gbps/ch) operation, a short cavity (150-μm length) with high gain AlGaInAs active layer was adopted.

3 Measured characteristics

A photograph of fabricated 4-ch LISEL array and measured lens shape of each channel were shown in Fig. 4(a), (b), and (c). Average values of R for V and H direction were 58.6 and 59.6 μm, and the deviation (3σ) in the array was under 4.0 μm in both directions. Uniform lenses were successfully obtained over all four channels. Moreover, we previously confirmed that lasing characteristics of the LISEL were almost the same as those of the conventional DFB laser, indicating the optical losses at both the lens and the 45° mirror were negligible [9]. Then, it is expected that the chip yield of the LISEL is almost the same as that for the conventional DFB laser.

Fig. 4. (a) Top view of fabricated 4-ch LISEL array, (b) lens shape (V direction), and (c) lens shape (H direction).

Measured coupling efficiency between a SMF and a fabricated LISEL is plotted in Fig. 5. The result for a device with divergent beam (R of 90 μm) was also plotted for comparison. The coupling efficiency at R of 60 μm shows a peak, while that at R of 90 μm monotonically decreases with respect to distance between the LISEL and SMF. Here, the spot size of the focused beam at the beam waist was designed to match that of the SMF. Accordingly, coupling efficiency reaches maximum at the

beam-waist position. The peak of Fig. 5 thus indicates that a beam with R of $60\ \mu\text{m}$ is surely focused. Moreover, maximum coupling efficiencies for R of $60\ \mu\text{m}$ and $90\ \mu\text{m}$ were $-3.5\ \text{dB}$ and $-8\ \text{dB}$, respectively, showing a good agreement with the calculated efficiencies.

Fig. 5. Experimentally measured direct optical coupling between LISEL and SMF.

A $4 \times 25.8\text{-Gbps}$ optical link using the 4-ch LISEL array was demonstrated. A $2^9 - 1$ pseudo-random-bit-sequence (PRBS) with a 25.8-Gbps non-return-to-zero (NRZ) electrical signal was directly applied from a pulse-pattern generator to each channel of the LISEL array. Here, any termination resistances were not used. Applied bias and modulation currents over all four channels are $60\ \text{mA}$ and $65\ \text{mA}$, and extinction ratio (ER) of the output optical signal ranged from 6.0 to $6.3\ \text{dB}$. Measured bit error rate (BER) after 2-km SMF transmission is plotted in Fig. 6(a). Received optical-modulation amplitudes (OMAs) at BER of 10^{-12} are around $-10\ \text{dBm}$. Note that variations between channels were mainly caused by experimental setup, and this indicates all four channels have almost the same performances. These results confirm $4 \times 25.8\text{-Gbps}$ 2-km error-free transmission. Transmission capability at high temperature (up to $70\ ^\circ\text{C}$) was experimentally evaluated using ch. 4 of the LISEL array. In this experiment, the laser-driving condition was adjusted to optimize fiber output power and ER. A bias of $70\ \text{mA}$ was applied to

Fig. 6. Data transmission result: (a) $4 \times 25.8\text{-Gbps}$ optical link with 4-ch LISEL array, and (b) measured bit error rate.

that channel, and ER was measured as around 5.5 dB. As shown in Fig. 6(b), error-free 2-km transmission up to 70°C with the power penalty of less than 1 dB was confirmed.

4 Conclusion

High-efficiency direct optical coupling and a 4×25.8 -Gbps 2-km optical link using a lens-integrated surface-emitting DFB laser (LISEL) array were simultaneously demonstrated for the first time. A process for fabricating a lens for a focused beam was developed, providing a good uniformity of the lens shape. The LISEL with focused beam demonstrated high-efficiency (−3.5 dB) direct optical coupling to a SMF. Due to its short-DFB cavity with a high-gain InGaAlAs active layer, the LISEL array demonstrated 4×25.8 -Gbps 2-km error-free transmission. Moreover, it achieved error-free transmission up to 70 °C using one of four channels. These results indicate that the optimized LISEL array is a promising light source for low-cost PSM4 optical modules.