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High Power and Stable High Coupling Efficiency (66%) Superluminescent Light Emitting Diodes by Using Active Multi-Mode Interferometer

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SUMMARY The fabricated 1.55 μm high power superluminescent light emitting diodes (SLEDs) with 115 mW maximum output power and 3 dB bandwidth of 50 nm, using active multi-mode interferometer (MMI), showed high coupling efficiency of 66% into single-mode fiber, which resulted in maximum fiber-coupled power of 77 mW.

key words: *active multi-mode interferometer (MMI), high coupling efficiency, superluminescent light-emitting diodes (SLEDs), single-mode fiber*

1. Introduction

Superluminescent light-emitting diodes (SLEDs) are attractive for wavelength division multiplexing [1], optical gyro sensors [2], and optical coherence tomography [3], because of high output power and broad bandwidth. One of the factors that restrict high power SLEDs might be the thermal heat produced at the active region. In order to improve the power saturation level, we have exploited active multi-mode interferometer (MMI) [4]–[6] to SLEDs (Active-MMI SLEDs) [7], which emitted at a wavelength of 1.55 μm with 115 mW output power and a wide 3 dB bandwidth of 50 nm. Wide active area of active-MMI SLEDs, compared with regular single-stripe SLEDs, contributed to obtain a high output power with regular single transverse-mode output. However, one remaining issue is the feasibility of a stable optical field up to the maximum output power, which is important for fiber coupling. This is because, generally speaking, SLEDs emits in non-oscillation condition, and thus the injected carrier density is not clamped like in laser diodes; therefore, the optical field profile in MMI region might change as the injection current increases due to refractive index change. Thus, it is essential to investigate the fiber coupling efficiency of active-MMI SLEDs to confirm the stable optical field.

In this paper, we investigated the fiber coupled power of active-MMI SLEDs into single-mode fiber for the first time. As a result, stable output power coupling into the single-mode fiber, as well as high coupling efficiency of 66%, was successfully confirmed.

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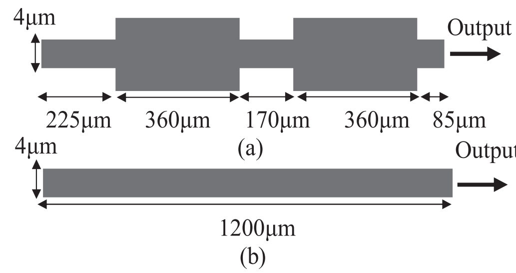

Fig. 1 Schematics of the fabricated SLEDs. (a) Active-MMI SLEDs. (b) Regular SLEDs.

2. Device Structure

The implemented active-MMI SLEDs consist of two 1 × 1 multi-mode interference couplers, which are connected to regular single-mode waveguides, to cover almost all of the length with active MMI region, as described schematically in Fig. 1(a). The main peculiar feature of this structure, i.e., wide active area, compared with regular single stripe SLEDs, contributed to obtaining a high power in addition to regular single transverse-mode output, which can be coupled into regular single mode fiber without using an additional output mode trimming device [8].

For the actual implementations, we used multiple quantum wells (λ = 1.55 μm) as the active layer. The waveguide structure was ridge one. In addition of antireflection coating, the waveguide structure was tilted to suppress facets reflectivity. The width of the single-mode waveguide was 4 μm, while the MMI region was designed to have a width of W_{MMI} = 10 μm and a length of L_{MMI} = 360 μm. For comparison, regular single-stripe SLEDs of 4 μm width were also fabricated simultaneously on the same wafer. The cavity length for both structures was 1200 μm. Both of them were mounted p-side down on artificial diamond heat-sinks to obtain better heat dissipation.

3. Results and Discussion

Coupling with hemispherical lens fiber is one of the ways to confirm the stability of the output optical field, as the coupling efficiency is sensitive to the far-field angle devia-

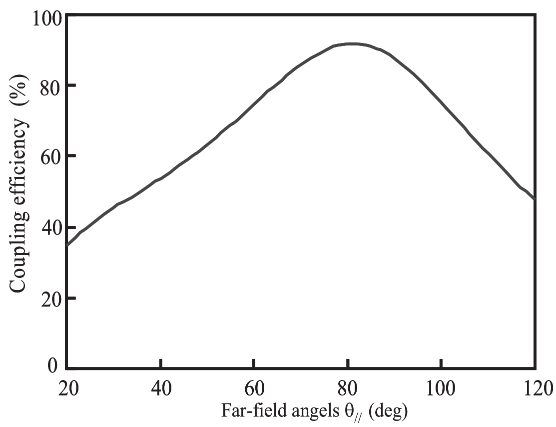

Fig. 2 Calculated coupling efficiency as a function of far-field angles $\theta_{//}$.

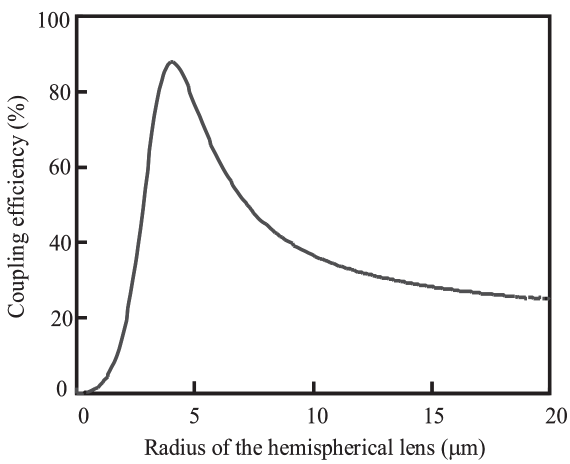

Fig. 3 Calculated coupling efficiency as a fuction of lens radius.

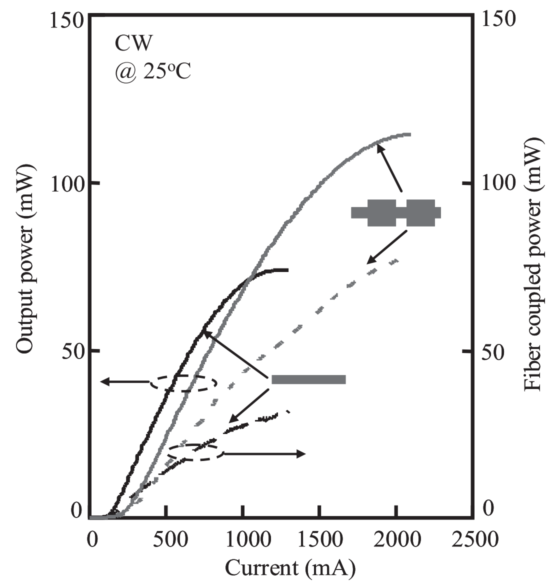

Fig. 4 Light output power and Fiber coupled power.

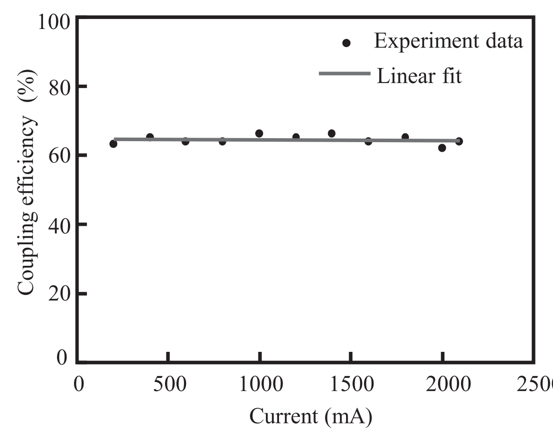

Fig. 5 Coupling efficiency as a function of injection current.

tion, as shown in Fig. 2. Figure 2 shows the calculated coupling efficiency as a function of $\theta_{//}$ (here, $\theta_{//}$ is the far-field angle parallel to the junction plane and is defined as full angels at $1/e^2$ of the maximum power of the far-field pattern). The far-field angle of $\theta_{\perp}$ perpendicular to the junction planes, which was the value evaluated on the devices explained later. It can be clearly seen that the maximum coupling efficiency is strongly sensitive to the deviation of the far-filed angels. It implies that stable output field is needed, otherwise abrupt coupling efficiency change may occur as the injection current increase. In the calculation, the fiber core refractive index, radius of hemispherical lens, and fiber spot size was 1.4682, 4 μm, and 5.2 μm, respectively.

Figure 3 shows the calculated coupling efficiency as a function of the radius R of the hemispherical lens fiber. In the calculation, the far-field angles perpendicular ($\theta_{\perp}$) and parallel ($\theta_{//}$) to the junction planes were 69° and 81°, which were evaluated from the far field patterns of the fabricated devices. From the calculated results, it can be concluded that $R = 4\,\mu$m is the radius for the highest coupling efficiency. The output power and the fiber coupled power as a function of current under CW operation at 25°C are shown in Fig. 4. The active-MMI SLEDs attained the maximum output power of 115 mW, corresponding to a significant power improvement of 40 mW, i.e., 54%, compared with the maximum output power (75 mW) of the regular SLEDs. By utilizing the active-MMI configuration, high output power is achieved due to the wider actively pumped area, which contributes to improving the power saturation level. Moreover, high coupling efficiency of 66% and a maximum output power of 77 mW were achieved for active-MMI SLEDs.

The experimentally evaluated coupling efficiency of the active-MMI SLEDs was almost constant up to the maximum output power, as shown in Fig. 5. With respect to stable and high coupling efficiency with hemispherical lens single-mode fiber, we could successfully confirm that active-MMI SLEDs can emit with stable output profile up to the maximum output power.

In addition, actually evaluated coupling efficiency was higher with the active-MMI SLEDs (66%) rather than the regular SLEDs (43%). To verify this difference of the fiber-coupling efficiency between the active-MMI and the regular SLEDs, we have experimentally evaluated the coupling efficiencies with four different radius (R = 4, 6, 8, and 13 μm)

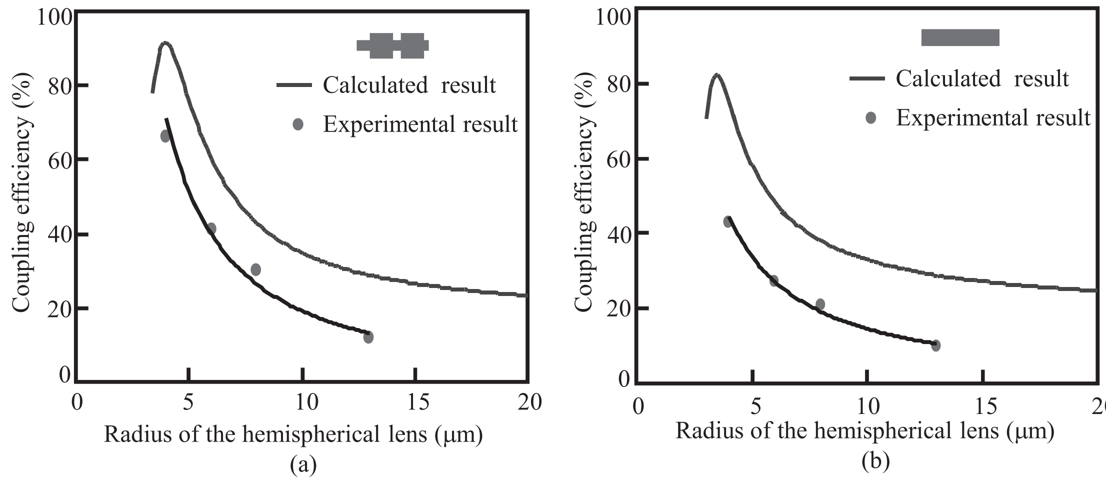

Fig. 6 Calculated and experimental results about coupling efficiency as a function of lens radius.

hemispherical lens fiber. Figures 6(a) and (b) shows the results. On set of the figure, the calculated coupling efficiencies are also shown for the comparison. For the calculation of fiber coupling efficiency in Fig. 6(b), $\theta_{//}$ = 83° and $\theta_{\perp}$ = 57° were used. The difference between the theoretical value and experimental value seems to be caused by reflection loss and spherical aberration from the lens surface, since we assumed that the lens behaves as an ideal transformer in the theoretical calculations. In addition, the tilted waveguide structure was also responsible for this difference. As is shown here, the coupling efficiency was higher with active-MMI SLEDs rather than regular SLEDs in both experiment and calculation at any radius. This coupling efficiency difference was brought by the difference in the far-field angle of, not lateral, transverse direction between the active-MMI SLEDs and the regular SLEDs, which might be caused by active-MMI phenomenon in the active-MMI SLEDs. We consider this phenomenon which caused the difference in the perpendicular angle is as follows. The layer structure of the active-MMI one is exactly the same as with the regular one. However in the active-MMI, the light does not simply propagate along the single-stripe waveguide. Instead, especially in the region of MMI, the light is diffracted once at the MMI-input, and then re-focused at the MMI-output. This procedure may cause "un-sharp focus" toward the MMI-output at the all of the spectral range that results in more circular far-field-profile. Presently this is just the assumption, therefore, we will do further analysis about this matter in the future. The evaluated far-field angles of the active-MMI SLEDs $\theta_{\perp}$ (69° was relatively close to the $\theta_{//}$ (81°), while for regular SLEDs, $\theta_{\perp}$ was 57° and $\theta_{//}$ was 83°. ($\theta_{\perp}$ and $\theta_{//}$ are the full angles at $1/e^2$ of the maximum power of the SLEDs far-field pattern). Much circular output field profile in the active-MMI SLEDs contributed to the higher coupling efficiency compared to regular SLEDs.

4. Conclusion

We have successfully demonstrated the stable and high coupling efficiency of the active-MMI SLEDs using hemispherical lens single-mode fiber for the first time. Active-MMI SLEDs showed a fiber coupled power of 77 mW, with a stable and high coupling efficiency of 66% up to the maximum output power. In addition, the coupling efficiency was much higher in the active MMI-SLEDs (66%) due to their circular output beam profile compared to regular SLEDs (43%).

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