Asymmetric Output Characteristics in 1.3-μm Spot-Size Converted Laser Diodes

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Abstract—A spot-size converted laser diode (SSC-LD) with a vertically tapered passive waveguide structure was fabricated by Butt–joint-built-in (BJB) coupling and selective area metal organic chemical vapor deposition growth. A high coupling efficiency exceeding 50% and 1-dB alignment tolerance of ±2.5 μm were obtained at a distance of 20 μm between a flat-end single-mode fiber and the SSC-LD. Experimental results show that the asymmetric output property can be described by the radiation mode added to the guide mode and spatial hole-burning in the active region.

Index Terms—Asymmetric property, laser diode, optical waveguide, spatial hole-burning, spot-size converter.

I. INTRODUCTION

OPTICAL access systems have been used to a limited extent due to the high cost of optoelectronic components which are caused mainly by packaging related problems. The development of low-cost and highly functional optical modules has been a major concern [1], [2]. The narrow beam of the laser diode is considered to be essential to the passive alignment between a laser and flat-end single-mode fiber (SMF) or planar lightwave circuit (PLC) in a hybrid integration scheme which reduces the packaging cost [3], [4]. The SSC-LD can provide not only high optical coupling but also a large alignment tolerance in passive alignment assemblies. The narrow beam of the laser diode can be realized by integrating a mode-size converter at the front facet [5]–[8]. Several studies for enhancing the lasing performance of SSC-LDs have been reported [5]–[8]. However, there remain several problems associated with SSC-LDs, such as the asymmetric optical output power, the increase of threshold current, poor thermal characteristics, and saturation of the full-width at half-maximum (FWHM) of the far-field pattern. In this paper, we fabricate a 1.3-μm SSC-LD with a vertically tapered waveguide grown by a butt–joint selective MOVPE growth technique and demonstrate its lasing and coupling performance. The asymmetric output power property of the SSC-LD is also analyzed by considering the radiation modes in addition to the guide mode in the SSC region and the spatial hole burning in the active region. In Section II, the fabrication procedures and device characteristics are given.
structure was formed by reactive ion etching, followed by wet etching with a SiN	extsubscript{x} mask to reduce surface roughness. The p–n blocking layer, p-InP cladding, and GaInAs contact layers were grown successively. The stripe width of the mesa was maintained between 1.0 and 1.2 μm for high coupling efficiency. All epitaxial crystal layers were grown by metal organic chemical vapor deposition (MOVPE) technology.

The optical output power and far field pattern (FFP) were measured under CW conditions with the as-cleaved facets. The average threshold current and slope efficiency at 25 °C were 13 mA and 0.32 mW/mA, respectively. The dependencies of slope efficiency \( \eta_{dr} \) and the front-to-rear optical power ratio \( \frac{P_{out,r}}{P_{out,t}} \) on the waveguide thickness \( t_{ssc} \) at the end of the SSC region are plotted in Fig. 2. A value of \( P_{out,r} \) greater than 3.5 and \( \eta_{dr} \) higher than 0.3 mW/mA were achieved for a passive waveguide thickness \( t_{ssc} \) between 600–900 Å. The dependence of both \( P_{out,r} \) and \( \eta_{dr} \) on \( t_{ssc} \) shows approximately the same tendency. The FFP was measured by rotating a GaInAs detector with 100-mm rotating arms and a diameter of 2 mm. Fig. 3 shows the FFP angles along the directions vertical and parallel to the junction plane defined by \( t_{ssc} \). As the passive waveguide thickness \( t_{av} \) increases, the FWHM of the FFPs also increases in the vertical direction. However, the FWHM of the FFPs shows the opposite tendency in the parallel direction. The FWHM of the FFP from the facet of the active side was as large as 30° and asymmetric. A nearly circular FFP from the facet of the SSC region was obtained. The FWHM values for the parallel and perpendicular directions for the device having a \( t_{ssc} \) of 700 Å were 10.8° and 10.3°, respectively. The narrow and circular FFPs were maintained at an output power exceeding 25 mW.

The coupling loss was measured by an SSC-LD with a \( t_{ssc} \) value of 700 Å and a single-mode fiber with a core diameter of 10 μm. The distance between the SSC-LD and single-mode fiber was fixed at 20 μm. A maximum coupling efficiency exceeding 50% was obtained as shown in Fig. 4. The coupling loss tolerances within the additional coupling loss of 1 dB were ±2.5 μm for the parallel direction and ±2.3 μm for the perpendicular direction. The alignment tolerance was increased to more than ±4 μm at a working distance of 100 μm while maintaining a coupling loss of −7.2 dB.

III. ANALYSIS MODEL AND METHOD

In Section II, the asymmetry of the optical output power ratio \( \frac{P_{out,r}}{P_{out,t}} \) and the saturation of the FWHM values of the FFPs were described in the fabricated SSC-LDs. Such abnormal properties are often observed, even in SSC-LDs grown by selective area growth. The SSC-LDs are usually expected to have almost perfect optical coupling between the active and passive regions. This large asymmetric property cannot be explained simply by the difference of the effective facet reflectivity resulting from the beam size difference. In order to explain this effect, we construct the model shown in Fig. 5. The subscripts \( \text{guide} \) and \( \text{rad} \) represent the guide mode and radiation mode, respectively. The parameters \( l \) and \( r \) denote the propagation directions to the active and passive regions, respectively. A quasi-TE guide mode was assumed by taking the optical gain and the
waveguide structure into account. The electric field $E_x$ can be expressed by

$$
E_x(x, y, z, \omega) = \sum_{q=1}^{N_{\text{max}}} D_q G_q(x, y) e^{-j\beta_q z} + \sum_{\omega}^{k_{\text{c}}} D(\beta) G_q(x, y, \beta) e^{-j\beta \beta} d\beta + \sum_{j=-\infty}^{k_{\text{c}}} D(\beta) G_q(x, y, \beta) e^{-j\beta \beta} d\beta
$$

where

- $\beta$, $\omega$ propagation constant and angular frequency, respectively [11];
- $k_{\text{c}}$ vacuum wavenumber;
- $n_{\text{c}}$ refractive index of the cladding;
- $N_{\text{max}}$ total number of propagation modes.

The first, second, and third terms in (1) represent the guide modes, radiation modes, and decay modes, respectively. The decay modes are disregarded in the following analysis since their effect on the optical output is negligible. $D_q$ and $D(\beta)$ denote the expansion coefficients which are obtained by using the orthogonal property among the modes. The $\Sigma$ represents the summation for the degenerated modes.

The fundamental guide mode of the active section (i.e., $-L_{\text{act}} \leq z < 0$) is assumed to be the lasing mode in order for $N_{\text{max}}$ to become one. If the optical coupling at the butt–joint portion is almost perfect and the beam is adiabatically changed within the SSC section (i.e., $0 < z \leq L_{\text{sec}}$), the second term in (1) may be negligible. In this case, the output beam from the SSC facet can be designed by the waveguide structure around the SSC facet. Since the optical loss of the guide mode may be considered to be negligible in the SSC region, the lasing properties of the SSC-LD, such as threshold current, temperature characteristics, and output power from the facets are almost the same as those without the SSC region. However, the actual devices are not ideal in that there could exist scattering at both the butt–joint interface and the SSC region. The degree of scattering may differ depending on the field propagating directions. In such a case, the second term in (1) must be included in the analysis.

We assume that the radiation modes are generated at the butt–joint interface, as well as at the SSC region. These radiation modes are supposed to make the different optical output powers from the facets. Furthermore, the radiation modes are expected to contribute only to the optical output power at the facet of the SSC region. As a result, the output beam at the facet of the SSC region (i.e., $z = L_{\text{sec}}$) consists of the radiation modes and the guide mode, whereas the output beam from the active region facet ($z = -L_{\text{act}}$) consists of only the guide mode of the active region. These results are due to the following reasons. It is well known that the field reflectivity of the guiding mode propagating from the narrow waveguide to the wide waveguide is much smaller than that of the opposite propagating case. In fabricated SSC-LDs, the waveguide thickness of the active region is almost four times thinner than that of the SSC region at the butt–joint interface. Thus, the field reflectivity from the active to the passive regions is smaller than the opposite case. In addition, only a limited number of the components radiated from the butt–joint interface to the active region facet contributes to the output since the active region is too long for the radiation modes to reach the facet. However, the situation is different in the SSC region. The gradual change of the waveguide structure reduces the radiation of the optical field to a negligible degree so that the total field profile is similar to the guide mode at a particular propagation position. The radiated field is likely to arrive at the SSC facet without optical loss. Furthermore, the reflectivity of the field propagating from the SSC region to the active region at the butt–joint interface is large, as mentioned before.

In order to quantitatively interpret the radiation mode effects, we developed a simple model as shown in Fig. 5. We assume that all radiation modes result from the butt–joint interface and that the modes affect only the optical output power from the SSC facet. We also assume that the SSC waveguide is uniform within the SSC region. The uniform waveguide structure was modeled after the end SSC facet of the fabricated device. The thickness of the selectively grown layer changes gradually within a 100–150-μm range near the butt–joint interface. The total length of the SSC region is 300 μm. Thus, the length of the uniform region should be 150–200 μm, which is long enough for the field to be converted into a stable guiding mode of the uniform waveguide. As a result, the output beam at the SSC facet is the sum of the...
guide mode of the uniform waveguide and the radiation modes produced in the nonuniform section.

Our analysis begins by calculating the lasing properties of the modeled SSC-LD which consists of two uniform sections (see Fig. 5). Nonuniform photon and carrier distributions along the cavity in the active region are included in this analysis [12]. It is essential to include the nonuniform photon and carrier distribution effects, namely the spatial-hole burning effect (SHB), since SHB is able to easily modify the optical output property. Since the active layers consist of compressively strained quantum wells, only the fundamental quasi-TE mode is taken into account in this analysis. The electric field is approximated by

\[
\bar{E}(x, y, z) = G(x, y)e^{i\beta(x, y, z)/2 - j\beta(x, y, z)z} \approx F(x)K(y)e^{i\gamma(x, y, z)/2 - j\gamma(x, y, z)z}
\]

(2)

where \(g(x, y, z)\) and \(\beta(x, y, z)\) are the net power gain and propagation constant, respectively. The field profiles \(F(x)\) and \(K(y)\) are obtained by 2-D waveguide analysis using the weighted-index method (WIM). Since \(g\) in the active layer is almost constant along the \(y\) axis, only the lateral and longitudinal distribution of \(g(x, z)\) are considered. The optical field and carrier density are obtained by using the following rate equation:

\[
\frac{J(x, z)}{q_d} = -D\frac{\partial^2 N(x, z)}{\partial x^2} + \frac{N(x, z)}{\tau_{nr}} + BN^2(x, z) + v_g g_N|F(x)|^2
\]

(3)

where the parameters \(D\), \(d\), \(\tau_{nr}\), and \(B\) denote the diffusion coefficient, active layer thickness, nonradiative carrier lifetime, and effective recombination rate, respectively. The term on the left-hand side of (3) represents the injected carrier density distribution. The terms on the right-hand side represent carrier diffusion in the lateral direction, carrier recombination of the nonradiative process, spontaneous emission, and stimulated emission, respectively. The group velocity is represented by \(v_g\). The dependence of the optical gain on the carrier density is represented by \(g_N(N, x)\), which is expressed in (7).

The laser cavity is divided into 50 segments. The threshold condition of the SSC-LD is evaluated by the following

\[
\sqrt{R_{\text{act}}R_{\text{ssc}}C_{\text{eff}}} \prod_{i=1}^{2m} e^{(\gamma_i - \tau_i)\Delta z_i/2} = 1
\]

(4)

where \(R_{\text{act}}\) and \(R_{\text{ssc}}\) are the reflectivity at the facets of the active and SSC regions, respectively. The average coupling coefficient at the interface of the active and SSC regions is denoted by \(C_{\text{eff}}\). \(\Delta z_i\) is the length of the segment. The mean optical gain and optical loss at the \(i\)th-segment are denoted by \(g_i\) and \(\alpha_i\), and are expressed as follows:

\[
\bar{g}_i = \int \frac{E_i g_N E_i^* dx dy}{\int E_i E_i^* dx dy}
\]

(5)

\[
\bar{\alpha}_i = \gamma_0 C_{\text{act}} + (1 - \gamma_0)C_{\text{ll}} + \int \frac{F_i N_i F_i^* dx}{F_i F_i^* dx}
\]

(6)

where \(\kappa\) denotes the loss coefficient of the free carrier absorption. The value of \(g_N\) is obtained by

\[
g_N = \frac{\alpha(N - \alpha_0)}{1 + \varepsilon F_0 F_i^*}
\]

(7)

where \(\alpha\) and \(\varepsilon\) denote the linear gain and gain saturation coefficients, respectively.

The optical output of the guide mode from both facets can be obtained by solving (5)–(7). The effects of the radiation mode on the output power of the SSC facet are analyzed by using the following boundary conditions:

\[
P_{\text{out},\text{mod}|z=0_+} = C_{\text{out}} P_{\text{out},\text{mod}|z=0_+}
\]

(8)

\[
P_{\text{out},\text{mod}|z=L_{\text{ssc}}-} = (1 - R_{\text{ssc}}) P_{\text{out},\text{mod}|z=L_{\text{ssc}}-}
\]

(9)

\[
P_{\text{out},\text{mod}|z=0} = (1 - C_{\text{out}}) P_{\text{out},\text{mod}|z=0} + (1 - C_{\text{out}}) P_{\text{out},\text{mod}|z=0_+}
\]

(10)

\[
P_{\text{out},\text{mod}|z=L_{\text{ssc}}-} = T_{\text{eff}} P_{\text{out},\text{mod}|z=0}
\]

(11)

\[
P_{\text{out},\text{mod}|z=L_{\text{ssc}}-} = P_{\text{out},\text{mod}|z=L_{\text{ssc}}-}
\]

(12)

\[
P_{\text{out},\text{mod}|z=0_+} = P_{\text{out},\text{mod}|z=0_+}
\]

(13)

\[
P_{\text{out},\text{mod}|z=L_{\text{ssc}}-} = P_{\text{out},\text{mod}|z=L_{\text{ssc}}-}
\]

(14)
Eq. (8) and (9) suggest that the optical couplings of the guide mode propagating to different directions are the same at the interface, which is expressed by the average coupling coefficient $C_{\text{out}}$. Equations (10) describes the optical output power components in relation to the guide mode at the SSC facet. The first and second terms in (11) represent the radiation mode components propagating in the $+z$ and $-z$ directions, respectively. There may exist some optical loss in the radiation modes at the substrate or cap layer before arriving at the facet, and each radiation mode may experience a different transmittance at the SSC’s facet. We simplified these by using the effective transmittance $T_{\text{eff}}$ of the radiation modes in (12). Equations (13) and (14) represent the total optical output powers at the active and SSC facets. Both guide mode and radiation mode coexist at the SSC region, but only the guide mode exists at the active region. The second term of (14) explains the asymmetry of the optical output powers.

IV. RESULTS AND DISCUSSIONS

The structural and material parameters used in the analysis are summarized in Table I. The lasing mode intensity profiles along the cavity are shown in Fig. 6 as a function of the average coupling coefficient ($C_{\text{out}}$). The intensity of the lasing mode at two facets is almost the same regardless of the values of $C_{\text{out}}$. The decrease of intensity in the longitudinal direction in the SSC region is caused by the optical propagation loss which is assumed to be 12 cm$^{-1}$ in the calculation. As the value of $C_{\text{out}}$ decreases, the lasing mode intensity increases at the interface (at $z = 0$) and SHB occurs greatly in the active region.

SHB needs to be treated in detail in order to exactly evaluate the lasing performance since the optical gain and loss profiles to the cavity direction greatly influence the optical output. Furthermore, the FFP of the output beam can become abnormal. In fabricated devices, FFPs from the active region facet were very similar to those observed in gain-guide lasers. This indicates that strong SHB can occur in the fabricated SSC-LD, which results from small values of $C_{\text{out}}$. On the contrary, the FFP from the facet of SSC side is narrow and circular, which implies that much of the optical beam is converted into the guide mode of the SSC region.

The values of $C_{\text{out}}$ in the fabricated devices were estimated by the slope efficiency $\eta_{\text{slope}}$ from the facet of the active region. In our model, the optical output power $P_\gamma$ is determined only by $C_{\text{out}}$. Fig. 7 shows $\eta_{\text{slope}}$ as a function of the average coupling coefficient $C_{\text{out}}$. The values of $C_{\text{out}}$ are estimated as 25%–30% by $\eta_{\text{slope}}$ which was measured to be 0.09 mW/mA–0.1 mW/mA. Fig. 8 shows the dependency of the optical output power ratio ($P_{\text{out},\gamma}/P_{\text{out},\lambda}$) on both $C_{\text{out}}$ and $T_{\text{eff}}$. The experimental value of $P_{\text{out},\gamma}/P_{\text{out},\lambda}$ is about 3–4, as shown in Fig. 2. The effective transmittance coefficient $T_{\text{eff}}$ of the radiation modes can be estimated to be as large as 50%–60% for $C_{\text{out}}$ of 25%–30%. It can be inferred that a smaller $T_{\text{eff}}$ value of radiation modes compared to that of the guide mode ($\sim$70%) results from the differences of reflectivity and optical loss among the radiation modes.
Fig. 9. Dependencies of the calculated slope efficiency on the average coupling coefficient ($C_{\text{eff}}$) and the effective transmittance ($T_{\text{eff}}$).

Fig. 10. Dependency of the calculated threshold current on the average coupling coefficient ($C_{\text{eff}}$).

Fig. 9 shows the calculated slope efficiency $\eta_{\text{ld}}$ from the SSC facet, correlated to $C_{\text{eff}}$ and $T_{\text{eff}}$. The values of $\eta_{\text{ld}}$ are expected to be 0.3 mW/mA–0.35 mW/mA for $C_{\text{eff}}$ of 25%–35% and $T_{\text{eff}}$ of 50%–60%. The calculated $\eta_{\text{ld}}$s show excellent agreement with the experiments, which in turn implies that values for $C_{\text{eff}}$ of 25%–35% and for $T_{\text{eff}}$ of 50%–60% are reasonable. From this analysis, it is known that 10%–20% of the beams scattered at the butt–joint interface, as well as at the nonuniform SSC region are lost without contributing to the optical output power. In the case of $T_{\text{eff}} > 0.5$, the larger optical output power from the SSC facet is expected for $C_{\text{eff}} < 1.0$ instead of $C_{\text{eff}} = 1.0$, which is the ideal coupling case between active and SSC regions. The output beam consists of the guided mode and radiation modes for $C_{\text{eff}} < 1.0$. The radiation modes increase the values of FWHM in the FFP and threshold current. This results in the degradation of temperature characteristics of the SSC-LD and coupling loss between the SSC-LD to a single-mode fiber.

Fig. 10 shows the calculated threshold current versus $C_{\text{eff}}$. Low threshold current is maintained for $C_{\text{eff}} > 0.7$. However, the current increases slightly with decreasing $C_{\text{eff}}$ and shows a rapid rise for $C_{\text{eff}} < 0.2$. Since $C_{\text{eff}}$ of the fabricated SSC-LDs is estimated to be approximately 0.3, it is known that the threshold current of a fabricated SSC-LD can increase by 30% compared to that for the device with a perfect coupling of $C_{\text{eff}} = 1.0$. In order to realize a low threshold current, high slope efficiency, and narrow beam pattern in SSC-LDs simultaneously, it is essential to suppress the radiation mode in the output beam. Figs. 7–9 may be useful in interpreting the coupling coefficient $C_{\text{eff}}$ at the butt–joint interface and determining the contribution of the radiation mode to the total output power.

**V. Conclusion**

As a promising light source in an access network, a 1.3-μm SSC-LD was fabricated and analyzed. The tapered SSC waveguide was grown by selective area growth and was butt-jointed by LP-MOVPE. The lengths of the active and SSC regions was 300 μm in length. The slope efficiency of 0.23 mW/mA–0.32 mW/mA, the FFP FWHM of 9.5°–12.3°, and a 1-dB alignment tolerance of ±2.5 μm in the parallel direction and ±2.3 μm in the vertical direction were obtained from the fabricated devices with as-cleaved facets. However, the increase of threshold current, asymmetry in the optical output power from both facets, and the limited FWHM values in the FFP were observed in the fabricated devices. We modeled the SSC-LD that includes the radiation modes in SSC region in order to clarify these particular properties of the SSC-LD. The properties were explained by the SHB effect in the active region and radiation modes originated from both the butt–joint interface and the nonuniform waveguide in the SSC region. The average coupling coefficient $C_{\text{eff}}$ for the guide mode between the active and SSC regions and the effective transmission coefficient $T_{\text{eff}}$ for the radiation modes at the SSC facet were estimated to be 25%–35% and 50%–60%, respectively. It was also clarified that the asymmetric output power was caused by the effect of a the different radiation mode on the output powers from both facets. The limited reduction of the FWHM in the FFP was also explained by the incorporation of the radiation mode in the output beam. As the average coupling coefficient $C_{\text{eff}}$ at the butt–joint interface decreased, the SHB in the active region and propagation loss in the SSC region increased. This increase became significant for $C_{\text{eff}} < 0.3$. The broad FFP from the active side facet and the poor thermal characteristics of the devices occurred when the value of $C_{\text{eff}}$ was small and the SHB in the active region was large. The ideal interface between the active and SSC regions, adiabatic mode conversion in the SSC region, and high-/low-reflection coating were important in order to realize low threshold current, high slope efficiency, and a narrow beam pattern in the SSC-LD. We believe that the analyzed results in this paper will be helpful in estimating the coupling coefficient at the butt–joint interface and the percentage of radiation modes that are incorporated into the total output power.

**REFERENCES**


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