Measurements of Cavity-Length-Dependent Internal Differential Quantum Efficiency and Internal Optical Loss in Laser Diodes

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We measured the cavity-length-dependence of the internal differential quantum efficiency $\eta_{\rm int}$ and the internal optical loss $\alpha_{\rm int}$ in 1500-nm-wavelength laser diodes (LDs). By evaluating $\alpha_{\rm int}$ directly from gain/absorption spectra for various injection current densities and measuring external differential quantum efficiency $\eta_{\rm ext}$, we obtained $\eta_{\rm int}$ and $\alpha_{\rm int}$ of each LD with different cavity length. The obtained $\eta_{\rm int}$ and $\alpha_{\rm int}$ respectively showed strong and slight cavity-length-dependence, and were both very different from those derived via the widely used method of plotting $\eta_{\rm ext}^{-1}$ against the cavity length.

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The internal differential quantum efficiency $\eta_{\rm int}$ and the internal optical loss $\alpha_{\rm int}$ are fundamental quantities representing losses of carriers and photons in a semiconductor laser diode (LD) respectively, and are used to model key device performances such as the threshold current density $J_{\rm th}$ and the external differential quantum efficiency $\eta_{\rm ext}$.[1] The external differential quantum efficiency $\eta_{\rm ext}$ is defined as the ratio of the increase of emitted photons to the increase of injected carriers, and is obtained from the slope of the light output power plotted as a function of injection current, or the L-I curve. For a laser with the cavity length L and the mirror reflectivity R for both facets (mirror loss $\alpha_{\rm m} = \ln(1/R)/L$), $\eta_{\rm int}$ and $\alpha_{\rm int}$ are related to $\eta_{\rm ext}$ by

$$\frac{1}{\eta_{\rm ext}} = \frac{\alpha_{\rm int}}{\ln(1/R)\cdot\eta_{\rm int}}\cdot L + \frac{1}{\eta_{\rm int}}. \qquad (1)$$

The widely used method to evaluate $\eta_{\rm int}$ and $\alpha_{\rm int}$ is to analyze L-dependence of $\eta_{\rm ext}$, where one measures $\eta_{\rm ext}$ for various LDs made of the same wafer but with different cavity lengths L, plots $\eta_{\rm ext}^{-1}$ against L, makes a straight-line fitting, reads a y-intercept and a slope of the line, and compares them with this equation.

This conventional method based on L-dependence of $\eta_{\rm ext}^{-1}$ relies on the assumption that $\eta_{\rm int}$ and $\alpha_{\rm int}$ are constant, or independent of L. This assumption is, however, not necessarily valid.[2–5] In LDs with shorter cavity length, increased $\alpha_{\rm m}$ causes higher $J_{\rm th}$, which may induce the decrease of $\eta_{\rm int}$ and increase of $\alpha_{\rm int}$. Piprek *et al.*[2] simulated L-dependence of $\eta_{\rm int}$ and $\alpha_{\rm int}$ due to the increased current

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density, and showed that the conventional method leads to significant errors in evaluation of them theoretically. Therefore, other methods are necessary to evaluate $\eta_{\rm int}$ and $\alpha_{\rm int}$ precisely.

Recently, we developed a measurement system to obtain gain/absorption spectra over wide ranges of injection currents and of wavelength covering far below the band gap energy,[6] and became able to measure $\alpha_{\rm int}$ for various injection current densities in a single LD device.[7]

In this report, we present experimental method to evaluate $\eta_{\rm int}$ and $\alpha_{\rm int}$, respectively. For LDs with various cavity lengths, we measured L-I curves and derived $\eta_{\rm ext}$ and $J_{\rm th}$. By measuring gain/absorption spectra over wide ranges of wavelength and injection current density in a LD with the shortest cavity length, we obtained current-density dependence of $\alpha_{\rm int}$ and evaluated $\alpha_{\rm int}$ at the threshold current densities of all the LDs. Using the evaluated $\alpha_{\rm int}$ and $\eta_{\rm ext}$, we calculated $\eta_{\rm int}$ of each LD with different cavity lengths. The obtained $\eta_{\rm int}$ and $\alpha_{\rm int}$ respectively showed strong and slight L-dependence, and were both very different from those obtained via the conventional method. The L-dependence of $\eta_{\rm int}$ and $\alpha_{\rm int}$ are ascribed to the L-dependence of $J_{\rm th}$, which reflects $\alpha_{\rm m}$ inversely proportional to L, as was suggested previously on the basis of numerical simulations.[2]

The samples used in the experiments were 1500-nm-wavelength GaInAsP-InP multiple-quantum-well (MQW) LDs with a buried hetero-structure using Fe-doped semi-insulating InP (i-InP). Fabry-Pérot cavities with several different cavity length L of 300, 420, 660 and 1270 μm were formed by cleavage from a single wafer. The as-cleaved facets on both sides of waveguides were used as cavity mirrors. Measurements of L-I curves were performed at room temperature (RT) under CW operation for all the LDs. For a LD with the shortest cavity length of 300 μm, the amplified spontaneous emission (ASE) and transmittance spectra were measured at RT under CW operation. Gain/absorption spectra were derived by analyzing the obtained ASE and transmittance spectra using Hakki-Paoli-Cassidy technique.[8] Details on fabrication of the samples and measurements of gain/absorption spectra are described in a separate paper.[6]

Figure 1(a) plots L-I curves for all the LDs. The slope and the x-intercept of the linear region above the threshold in each L-I curve show the values of $\eta_{\rm ext}$ and $J_{\rm th}$, respectively. Figure 1(b) shows plots of $\eta_{\rm ext}^{-1}$ (filled dots, left vertical axis) and $J_{\rm th}$ (crosses, right vertical axis) against L. The solid straight line represents the fitted line for the best-measured data of $\eta_{\rm ext}^{-1}$. With the value of R=0.3, we obtained $\eta_{\rm int}^{\rm c}$ = 40% and $\alpha_{\rm int}^{\rm c}$ = 20 cm^{-1} via the conventional method. It is obvious, however, in Fig. 1(b), that $J_{\rm th}$ rises for shorter cavity length, indicating that the carrier densities in the active region were different when we measured $\eta_{\rm ext}$ in LDs with different cavity lengths.

Figure 2(a) shows the spectra of modal gain/absorption $\Gamma \cdot g - \alpha_{\rm int}$ derived from the ASE and transmittance spectra of the LD with the shortest cavity length of 300 μm and the best $\eta_{\rm ext}$, which is 27%, among all the devices we measured.[6] Here, Γ is the optical confinement factor of the active layer, and g is the material gain. The dotted horizontal line represents the calculated $\alpha_{\rm m}$= 40.1cm^{-1} for R = 0.3 and L = 300 μm. Note that the peak of gain/absorption spectrum at the threshold current ($I_{\rm th}$ = 38 mA) touches this dotted line, which is consistent with the gain threshold condition $\Gamma \cdot g - \alpha_{\rm int} = \alpha_{\rm m}$

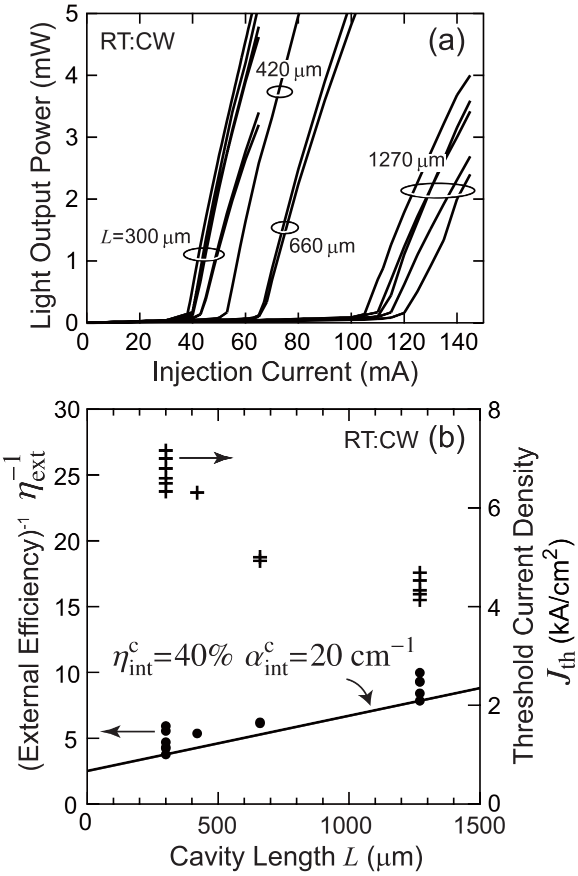

Fig. 1. (a) Total light output power emitted from both facets versus injection current of InGaAsP-InP MQW LDs with different cavity lengths L=300, 420, 660, 1270 μm at RT under CW operation. (b) Reciprocal external differential quantum efficiency η_{ext}^{-1} (•) and threshold current density J_{th} (+) derived from each L-I curve against L. Solid straight line represents the fitted line for the best-measured data of η_{ext}^{-1}.

and confirms the accuracy of our gain/absorption measurements.

In the long-wavelength region far below the band-gap energy, material gain g should be negligibly small and the obtained modal gain directly gives α_{int},[7] which are plotted in Fig. 2(b) against the injection current density J. Note that the plots explicitly show the injection-current-density (J) dependence of α_{int}, which increases gradually with J from 40 cm^{-1} (J=0 kA/cm^2) to 54 cm^{-1} (J=7.2 kA/cm^2).

The arrows at the bottom of Fig. 2(b) indicate the threshold current densities J_{th} of all the LDs measured in Fig. 1(b). Assuming that α_{int} as a function of injection current density J and mirror reflectivity R are the same for all the LDs, we can evaluate α_{int} of LDs with various cavity lengths at their lasing thresholds from Fig. 2(b). For LDs with longer cavity length, the Hakki-Paoli-Cassidy technique analyzing Fabry-Pérot modulation in ASE and transmittance spectra requires a higher wavelength resolution of the measurement system.[8] Thus, we made gain/absorption measurements only for a LD with the shortest cavity length.

The filled circles in Fig. 3(a) show the obtained α_{int} as a function of L. Though the obtained α_{int}

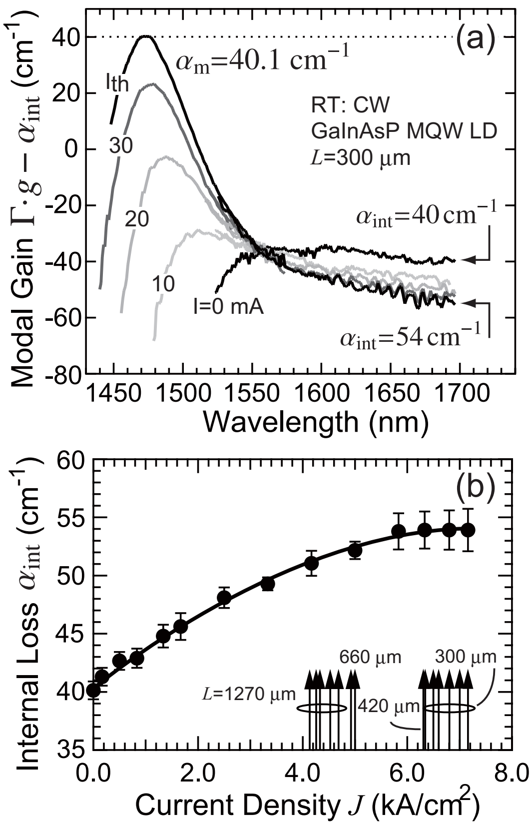

Fig. 2. (a) Spectra of modal gain $\Gamma \cdot g - \alpha_{int}$ obtained from the ASE and transmittance spectra of a LD with the shortest cavity length of 300 μm for various injection current from 0 mA to the threshold current I_{th} = 38 mA at RT under CW operation. (b) Internal optical loss α_{int} against the injection current denisity J for L=300 μm evaluated from the gain/absorption spectra shown in (a).

changed only slightly with L from 54 cm^{-1} (L=300 μm) to about 50 cm^{-1} (L=1270 μm), the values were very different from α_{int}^{c} = 20 cm^{-1} derived via the conventional method.

Since η_{ext} and α_{int} were obtained as shown in Fig. 1(b) and in Fig. 3(a), the values of η_{int} are evaluated via Eq. (1), and are plotted as a function of L in Fig. 3(b). The obtained η_{int} showed serious deviation from η_{int}^{c} = 40% derived via the conventional method. Moreover, they changed significantly with L from 40-60% (L=300 μm) to 60-80% (L=1270 μm).

In the conventional method, α_{int} and η_{int} were assumed to be constant against L. The obtained α_{int} in Fig. 3(a) showed only a small change with L, while the change of η_{int} with L in Fig. 3(b) was very large. Thus, the strong L-dependence of η_{int} is the most probable reason for the large errors in the derived η_{int}^{c} and α_{int}^{c} via the conventional method.

In Fig. 3(a), additionally plotted are the mirror loss α_m (=ln(1/R)/L, solid curve), the total loss $\alpha_m + \alpha_{int}$ (broken curve with open circles), and the threshold current density J_{th} (crosses, right vertical axis). Note that the plots of α_m + α_{int} and J_{th} show similar L-dependence. This is reasonable because the total loss $\alpha_m + \alpha_{int}$ is equal to the threshold gain $\Gamma \cdot g_{th}$ and determines J_{th}. Since the L-dependence

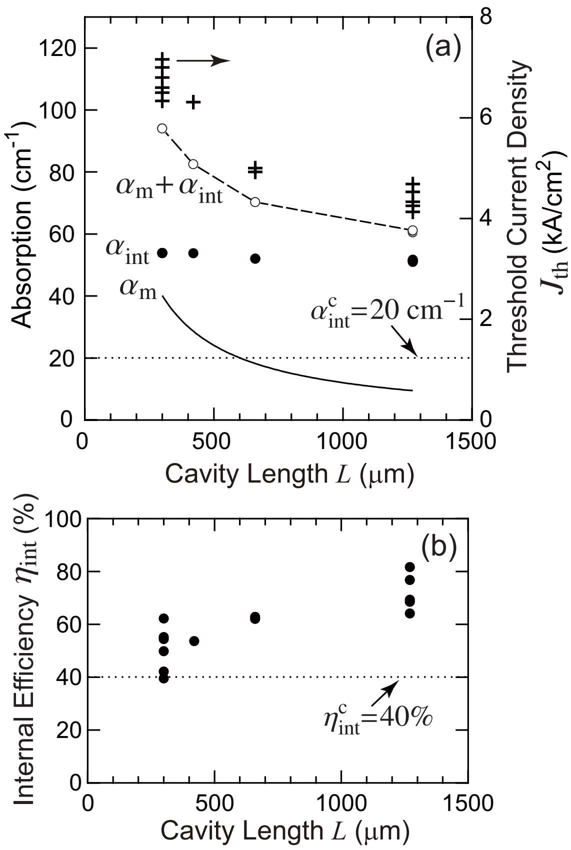

Fig. 3. (a) Internal optical loss α_{int} (•) evaluated from gain spectra, mirror loss α_m (solid curve), total loss $\alpha_{int} + \alpha_m$ (broken curve with ∘), and threshold current density J_{th} (+, right vertical axis) against the cavity length L. Dotted horizontal line represents the value of α^c_{int} derived via the conventional method. (b) Internal differential quantum efficiency η_{int} evaluated via Eq. (1) against the cavity length L. Dotted horizontal line represents the value of η^c_{int} derived via the conventional method.

of $\alpha_m + \alpha_{int}$ is dominated by that of α_m, so should be the L-dependence of J_{th}. In this way, the present results as a whole support the scenario addressed by Piprek.*et al.*[2]

Direct measurements of L-dependent or carrier-density-dependent η_{int} and α_{int} are important to microscopically investigate carrier loss and photon loss processes.[2–4,9,10] It should be commented that, in this work, we experimentally evaluated L-dependent η_{int} and α_{int} for each device by measuring gain/absorption spectra for various injection current densities, which could not be obtained via the conventional method assuming η_{int} and α_{int} to be independent of L.

In summary, we achieved an experimental method to evaluate L-dependent η_{int} and α_{int}. By evaluating α_{int} directly from gain/absorption spectra for various injection current densities and measuring η_{ext}, we obtained η_{int} and α_{int} of each LD with different cavity length. The obtained η_{int} and α_{int} respectively showed strong and slight L-dependence, and were both very different from those obtained via the conventional method. The L-dependence of J_{th} was similar to that of $\alpha_{int} + \alpha_m$ and we can consider that it caused the L-dependence of η_{int} and α_{int}. These results support the theoretical simulated result by Piprek *et al.*[2]

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