Horizontal Transverse Modes in Ridge-Type Laser Diodes with Transversal Diffraction Gratings

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***Abstract*—This paper reports on horizontal transverse modes in a ridge-type laser diodes with transversal diffraction gratings. It is found that the narrow spacing among the wave numbers defined by the optical cavity with the gratings leads to single horizontal transverse mode operation.**

Keywords—laser diode, ridge, grating, transverse

I. Introduction

Because of high excitation efficiency and low noise figure for erbium doped optical fiber amplifiers (EDFAs) in long-haul optical fiber communication systems, high power 980-nm laser diodes (LDs) have been adopted as pumping sources [1]. In the 980-nm LDs, AlGaAs layers are used as cladding layers and guiding layers. To avoid oxidization of AlGaAs layers during etching process for the 980-nm LDs, ridge structures have been utilized to confine horizontal transverse modes. To achieve high light output with low optical power density at facets of the LDs, the mesa width should be larger than 2 μm, causing that not only the fundamental horizontal transverse mode but also higher-order horizontal transverse modes oscillate. If a higher-order horizontal transverse mode oscillates, a kink appears in a light-output versus current (*L-I*) curve [2]. Once the kink appears in *L-I* curve, light coupling efficiency between 980-nm LDs and erbium doped optical fibers (EDFs) decreases.

To maintain high light coupling efficiency between 980-nm LDs and EDFs, high kink level or kink-free operation is required for 980-nm LDs. To satisfy this requirement in 980-nm ridge-type LDs, lossy metal layers [3], highly resistive regions in both sides of ridge stripe [4], incorporation of a graded V-shape layer [5], optical antiguiding layers [6], [7], separate confinement of carriers and horizontal transverse mode [8], horizontal coupling of horizontal trans-verse modes by a groove in the mesa [9], and transversal diffraction gratings [10]-[13] have been reported.

In this paper, ridge-type LDs with transversal diffraction gratings are studied, and it is found that the narrow spacing among the wave numbers defined by the optical cavity with the gratings leads to single horizontal transverse mode operation.

II. Theory

Figure 1 shows a conventional ridge structure; the upper figure shows a top view and the lower one a cross-sectional view. From left to right, there are Region I $(x \leq -W)$, Region II $(-W \leq x \leq 0)$, and Region III $(0 \leq x)$. Effective refractive index of Regions I and III is N_{B}; effective refractive index of Region I is N_{T}.

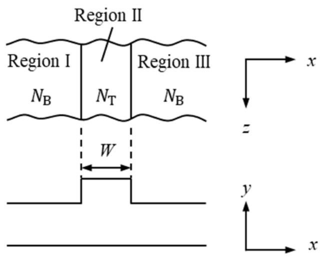

Fig. 1 Conventional ridge waveguide.

The electric field of a laser beam which propagates the optical waveguide $E(x)$ is given by [14]

$$E(x) = \begin{cases} E_{\mathrm{I}} \exp[\gamma(x+W)] & (x \leq -W), \\ E_{\mathrm{II}} \cos(k_x x + \phi) & (-W \leq x \leq 0), \\ E_{\mathrm{III}} \exp(-\gamma x) & (0 \leq x). \end{cases} \quad (1)$$

Here E_{I}, E_{II}, and E_{III} are field amplitudes in Region I, II, and III, respectively; ϕ is a phase shift at the boundary of Regions II and III; W is mesa width; $N, \gamma, and\ k_x$ are defined as follows:

$$N = N_{\mathrm{T}} \sin\theta, \gamma = k_n\sqrt{N^2 - N_{\mathrm{B}}{}^2}, k_x = k_n\sqrt{N_{\mathrm{T}}{}^2 - N^2}, \quad (2)$$

where $k_n = 2\pi/\lambda_n$ is a wave number in vacuum and λ_n is a wavelength of a laser light in vacuum.

A near field pattern (NFP) is obtained by

$$|E(x)|^2 = |E(k_n, m, x)|^2$$

which is indicated by the wave number in vacuum k_n and the mode number m $(m = 0, 1, 2, \cdots)$. In the convention ridge structure, the NFPs for the higher order transverse modes are

$$|E(k_0, 1, x)|^2, |E(k_0, 2, x)|^2, |E(k_0, 3, x)|^2, \cdots,$$

where k_0 is wave number in vacuum. In the ridge structure with the transversal diffraction gratings, the NFPs for the higher order transverse modes are

$$|E(k_0, 1, x)|^2, |E(k_0, 2, x)|^2, |E(k_0, 3, x)|^2, \cdots,$$
$$|E(k_1, 0, x)|^2, |E(k_1, 1, x)|^2, |E(k_1, 2, x)|^2, \cdots,$$
$$|E(k_2, 0, x)|^2, |E(k_2, 1, x)|^2, |E(k_2, 2, x)|^2, \cdots.$$

because several wave numbers k_0, k_1, k_2 $\cdots$ are generated by the transversal diffraction gratings. As shown in Figure 2, an optical confinement factor for the horizontal transverse mode decreases with an increase in the mode number m. Therefore, the oscillation thresholds for $|E(k_1, 0, x)|^2$ and $|E(k_2, 0, x)|^2$ with single peaks may become lower than those for $|E(k_0, 1, x)|^2$ with double peaks and $|E(k_0, 2, x)|^2$ with triple peaks. As a result, when the transversal diffraction gratings work properly, the first and second order modes become $|E(k_1, 0, x)|^2$ and $|E(k_2, 0, x)|^2$ rather than $|E(k_0, 1, x)|^2$ and $|E(k_0, 2, x)|^2$.

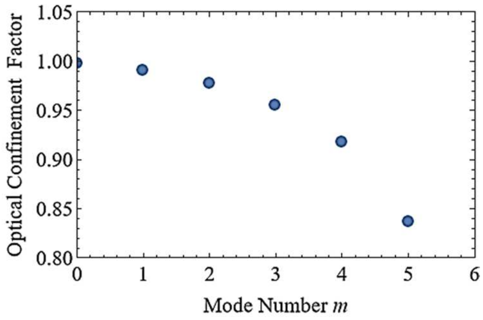

Fig. 2 Optical confinement factor for a horizontal transverse mode.

III. STRUCTURE

Figure 3 shows a schematic cross-sectional view of the facet of the 980-nm ridge-type LD with transversal diffraction gratings. The mesa width W is 10 μm, the grating pitch Λ is 428.7 nm, the grating depth d is 250 nm (the coupling constant κ of 69.8 cm-1), and the number of periods in one side of the mesa N is 20. There are flat regions between the mesa and the diffraction gratings and the length of flat region in one side of the mesa is expressed as by $N_{\mathrm{flat}}\Lambda$. Both the flat regions and the diffraction gratings are formed symmetrically with respect to the central axis of the mesa. The device width is 120 μm, the height of the mesa is 1.55 μm, and the cavity length is 1200 μm. Power reflectivity of the front facet and that of the rear facet are 2 and 90%, respectively. Layer parameters are the same as those reported in Refs. 6-13.

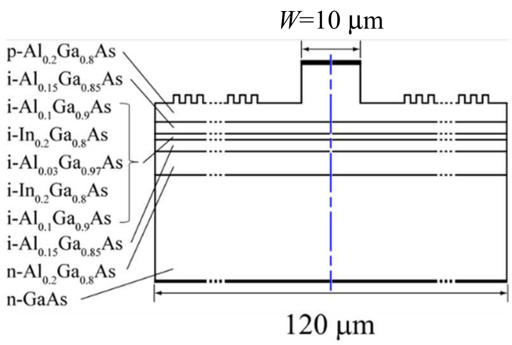

Fig. 3 Schematic cross-sectional view of the facet of the 980-nm ridge-type diode laser with transversal diffraction gratings.

IV. SIMULATED RESULTS AND DISCUSSIONS

Figure 4 shows the number of oscillating modes as a function of N_{flat}. With an increase in N_{flat}, the number of oscillating modes decreases abruptly; when $N_{\mathrm{flat}} \geq 80$ single transverse mode operation with kink-free is obtained.

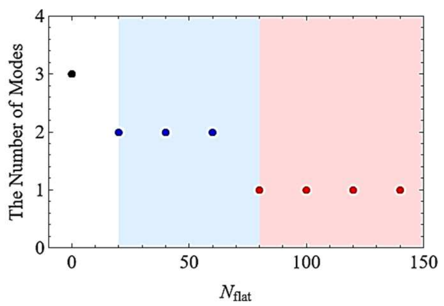

Fig.4 The number of oscillating modes as a function of the number of periods of the removed gratings N_{flat}.

Figure 5 shows peak positions of first/second-order modes along the horizontal line in Fig. 3. The shaded area shows optical gain region just below the mesa. Both the first-order modes and the second-order modes have single peaks indicated by $\left|E\left(k_{1},0,x\right)\right|^2$ and $\left|E\left(k_{2},0,x\right)\right|^2$.

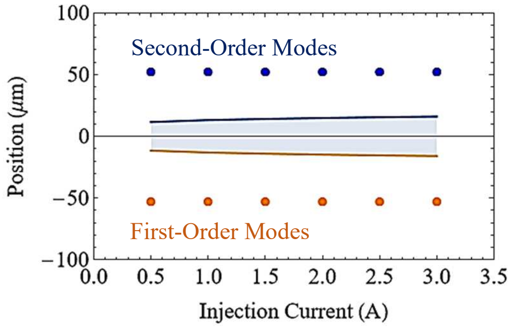

Fig.5 Peak positions of the horizontal modes.

The optical cavity for the transverse mode is regarded as Fabry-Perot cavity with reflectors whose reflectance is highly dependent on light wavelength. With an increase in N_{flat}, the length of the Fabry-Perot cavity increases, which leads to narrow spacing of wave numbers for resonance modes. Since NFPs are Fourier transforms of resonant spectra, narrow spacing of wave numbers results in wide spacing between the fundamental transverse mode and the higher-order transverse modes. When the spacing between the fundamental transverse mode and the higher-order transverse modes is large enough so that only the fundamental mode exists in the optical gain region and the higher-order transverse modes place in optical loss region, single transverse mode operation with the fundamental mode is obtained.

V. CONCLUSIONS

It is found that the narrow spacing among the wave numbers defined by the optical cavity with the gratings leads to increase in the spacing between the fundamental transverse mode, which results in single horizontal transverse mode operation.

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