Simulation of a Ridge-Type Semiconductor Laser with Selectively Proton-Implanted Cladding Layers

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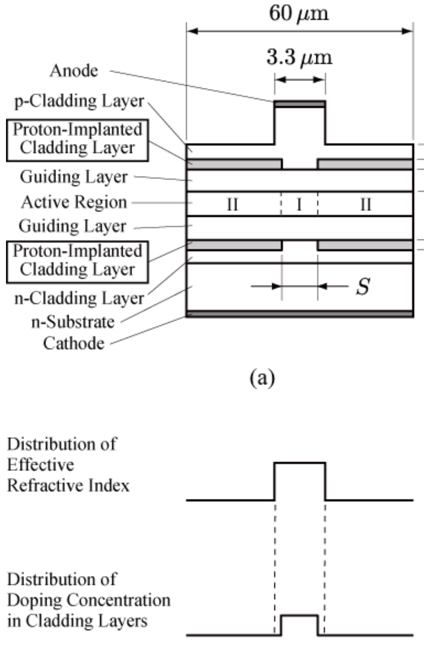
1. Introduction

High power 980-nm semiconductor lasers are indispensable for pumping sources of erbium doped optical fiber amplifiers [1]. Generally, 980-nm semiconductor lasers have ridge structures so as not to expose their active regions to air during their fabrication, because the active regions are easily oxidized and degraded in air. In the ridge structures, higher-order transverse modes as well as the fundamental transverse mode are confined. As a result, with an increase in injected current, higher-order transverse modes lase; kinks appear in their current versus light-output (*I-L*) curves [2]. These kinks are attributed to changes in the local gain profile and refractive index owing to spatial hole burning, the free-carrier plasma effect, and heating. To obtain high fiber-coupled optical power, semiconductor lasers with high kink levels operating in the fundamental transverse mode are required. To date, to increase kink levels, coupling of the optical field to the lossy metal layers outside the ridge [3], highly resistive regions in both sides of ridge stripe [4], and incorporation of a graded V-shape layer [5] have been demonstrated. To increase kink level and decrease the threshold current further, a ridge structure with optical antiguiding layers have been proposed [6], [7], but the fabrication process is fairly complicated.

In this paper, a ridge-type semiconductor laser with selectively proton-implanted cladding layers is proposed to make the fabrication process more simple, increase kink level, and decrease threshold current. In this semiconductor laser, horizontal transverse modes are confined by the ridge structure; carrier distributions are controlled by selectively proton-implanted cladding layers. From simulations of lasing characteristics, it is found that the kink level is higher and the threshold current is lower than those of the ridge-type semiconductor lasers with optical antiguiding layers for horizontal transverse modes [6], [7]. In addition, it is revealed that they are optimal when the space between the proton-implanted regions *S* is 1.98 μm.

2. Laser Structure and Device Simulation

Fig. 1 (a) shows a schematic cross-sectional view of a proposed ridge structure with proton-implanted cladding layers; Fig. 1(b) shows distributions of the effective refractive index of the semiconductor laser and doping concentration of the cladding layers. The light is confined by the distribution of the effective refractive index of the semiconductor laser; the carriers are confined by the distribution of the doping concentration of the cladding layers, because the flow path of the injected current is restricted to the doped region in the cladding layers.



(a)

(b)

Fig. 1 (a) Schematic cross-sectional view of a proposed ridge structure with proton-implanted cladding layers and (b) distributions of the effective refractive index of the semiconductor laser and doping concentration of the cladding layers. Here, Δt is the thickness of the proton-implanted regions, *S* is the space between the proton-implanted regions, and *d* is the distance from the bottom of the mesa to the bottom of the upper guiding layer.

In Fig.1 (a), the shaded areas are the proton-implanted regions, Δt is the thickness of the proton-implanted regions, *S* is the space between the proton-implanted regions, and *d* is the distance from the bottom of the mesa to the bottom of the upper guiding layer. The rectangular mesa is 1.55 μm high and 3.3 μm wide. Active region I has a width of *S*; active region II is located beside active region I. The mesa width of 3.3 μm is relatively large to obtain a high light output power. The base is 60 μm wide, and the cavity is 1200 μm long. When *S* is fixed to 3.3 μm, d = 250 nm has resulted in the lowest threshold current. As a result, d = 250 nm is used in this paper. The thickness of the proton-implanted regions Δt is 50 nm. Reflectivities of the front and rear facets are 2 and 90%, respectively.

Layer parameters such as band gap energy, refractive index, thickness, electron effective mass, hole effective

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mass, and doping concentration are the same as those described in ref. 6. The dependences of kink level, threshold current, and wall-plug efficiency on the space *S* between the proton-implanted regions are examined by using a device simulation software, ATLAS (Silvaco).

3. Simulated Results and Discussions

Fig. 2 shows simulated *I-L* curves. The parameter is the space *S* between the proton-implanted regions. The dotted, broken, solid, dash-dotted, and dash-double-dotted lines represent S = 0.66, 1.32, 1.98, 2.64, and 3.30 μm, respectively. At kink levels, the first-order transverse mode started to oscillate and the second-order or higher-order transverse modes did not oscillate.

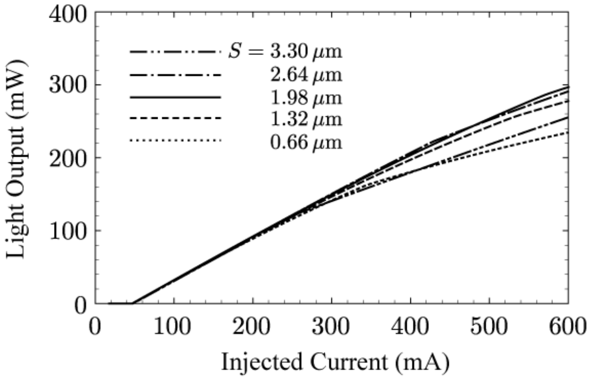

Fig.2 *I-L* curves for the proposed ridge structure. The parameter is the space *S* between the proton-implanted regions. The dotted, broken, solid, dash-dotted, and dash-double-dotted lines represent S = 0.66, 1.32, 1.98, 2.64, and 3.30 μm, respectively.

Fig. 3 shows kink level as a function of the space *S* between the proton-implanted regions. With a decrease in *S*, the kink level increases and then decreases. The kink level has a maximum value at S = 1.98 μm, and the kink level at S = 1.98 μm is 2.54 times as large as that at S = 3.3 μm; 1.58 times as large as the highest value for the ridge structure with optical antiguiding layers [7].

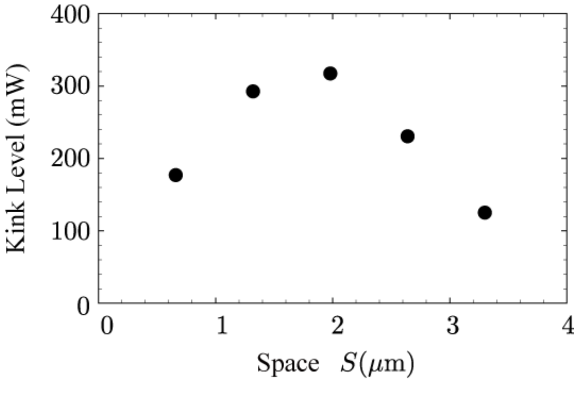

Fig. 3 Kink level as a function of the space *S* between the proton-implanted regions.

Fig. 4 shows the threshold current for the fundamental transverse mode I_{th0} as a function of the space *S* between the proton-implanted regions. The threshold current I_{th0} decreases and then increases with a decrease in *S*, which reflects overlapping of the electron distribution below the threshold current and the horizontal NFP for the fundamental mode. The lowest threshold current I_{th0} = 46.8 mA at S = 1.98 μm is 0.975 times as large as the largest value of 48.0 mA at S = 3.3 μm; 0.95 times as large as the lowest value of 49.1 mA for the ridge structure with optical antiguiding layers [7].

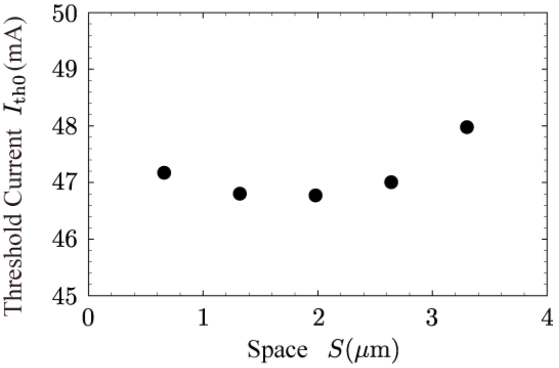

Fig.4 Threshold current for the fundamental transverse mode as a function of the space *S* between the proton-implanted regions.

4. Conclusions

A ridge-type semiconductor laser with selectively proton-implanted cladding layers was proposed and simulated. Here, horizontal transverse modes were confined by the ridge structure; carrier distributions were controlled by proton-implanted regions. Compared with the results of the ridge structure with optical antiguiding layers, the kink level was 1.58 times as large as the previous highest value; the threshold current for the fundamental transverse mode was 0.95 times as large as the previous lowest value.

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