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Ridge-Type Semiconductor Lasers with Antiguiding Cladding Layers for Horizontal Transverse Modes

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1. Introduction

High power 980-nm semiconductor lasers are used as pumping sources of erbium-doped optical fiber amplifiers and contribute to wavelength division multiplexing optical fiber communication systems [1]. To reduce the number of pumping sources and to improve performance of optical fiber communication systems, higher light-output power is desired for 980-nm semiconductor lasers. Generally, 980-nm semiconductor lasers have ridge structures to prevent exposure of the active regions to air during fabrication. With an increase in injected current, kinks appear in current versus light-output (*I-L*) curves [2]. These kinks are associated with lasing in higher-order transverse modes, which is attributed to changes in local gain profile and refractive index due to spatial hole burning, free carrier plasma effect, and heating. Slope efficiency and fiber coupling efficiency above kink levels are lower than those below kink levels. Therefore, higher kink levels are needed to achieve lasing in the fundamental transverse mode with high light-output power maintaining high slope efficiency and high fiber coupling efficiency. To date, to increase kink levels, coupling of the optical field to the lossy metal layers outside the ridge [3], introduction of highly resistive regions at both sides of a ridge stripe [4], and incorporation of a graded V-shape layer [5] have been proposed. It was shown that kink levels were improved with an increase in cladding layer thickness at both sides of a mesa [5]. However, thick cladding layer at both sides of the mesa necessarily leads to an increase in threshold current due to lateral expansion of injected current. To overcome this problem, a novel ridge structure with antiguiding layers has been recently proposed [6], but it is considered that the fabricating process is relatively complicated.

In this paper, a novel ridge structure with antiguiding cladding layers for horizontal transverse modes is proposed, and lasing characteristics are theoretically analyzed. In the proposed ridge structure, kink levels are improved by suppressing spatial hole burning and lowering optical gains for higher-order transverse modes, with an increase in the step *d* of the antiguiding cladding layers, which are located at both sides of a mesa. For 100 nm ≤ *d* ≤ 230 nm, kink-free laser operation is obtained up to the injected current of 2 A.

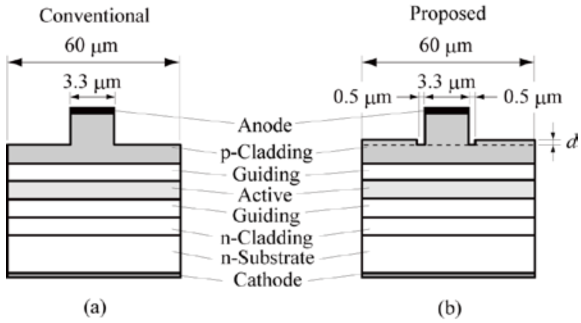

Fig.1 Schematic cross-sectional views of (a) a conventional ridge structure and (b) a proposed ridge structure with antiguiding cladding layers for horizontal transverse modes.

2. Laser Structures and Simulations

Figure 1 illustrates schematic cross-sectional views of (a) a conventional ridge structure and (b) a proposed ridge structure with antiguiding cladding layers for horizontal transverse modes. In Fig.1, *d* is a step in the cladding layer, which leads to antiguiding effect. Rectangular mesa is 1.55 μm high and 3.3 μm wide. The relatively wide mesa is selected in order to obtain high light-output power. The space between the edges of the mesa and the step is 0.5 μm. The base is 60 μm wide, and the cavity is 1200 μm long. 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 mass, and doping concentration are the same as those described in Ref. 6. Lasing characteristics are analyzed without including any thermal effects by solving Poisson's equations and Helmholtz equation with a finite element method. Physical parameters and their numerical values, which are used in the simulation, are the same as those described in Ref. 6.

3. Simulation Results and Discussions

Figure 2 shows a kink level as a function of the step in the antiguiding cladding layers *d*. For *d* < 100 nm, the kink level increases with an increase in

d. For 100 nm ≤ d ≤ 230 nm, it should be noted that the kink does not appear when the injected current I is less than 2 A. For 230 nm < d, the fundamental transverse mode does not oscillate at all and the second-order mode oscillates. For the transverse modes to exist, the wave-numbers for the transverse modes satisfy the transverse resonance condition. For d ≤ 230 nm, the real-valued wave-number, which only contains the real part, for the fundamental transverse mode exists. For 230 nm < d, the real-valued wave-number for the fundamental transverse mode does not exist, and the wave-number for the fundamental transverse mode becomes complex-valued, which means that the wave-number contains the imaginary part. This imaginary part represents the optical gain, which is required for the fundamental transverse mode to exist. For 230 nm < d, the optical gains, which are required for the higher-order transverse modes to exist, are lower than that for the fundamental transverse mode, and the optical gain for the second-order transverse mode is lower than those for the first-order and fundamental transverse modes. Therefore, only the second-order transverse mode oscillates, and the first-order and fundamental transverse modes do not oscillate for 230 nm < d. From Fig.2, it can be said that the step d contributes to antiguiding of horizontal transverse modes.

Figure 3 shows threshold current for the fundamental transverse mode I_{th} as a function of the step in the antiguiding cladding layers d. The threshold current I_{th} monotonically increases with an increase in d, because injected carriers are spread to the side regions of the mesa. The threshold current I_{th} = 60.9 mA at d = 230 nm is 1.14 times as large as I_{th} = 53.5 mA at d = 0 nm.

Figure 4 shows horizontal far field patterns (FFPs) for the injected current I = 200 mA as a function of the radiation angle θ with d as a parameter. The broken and solid lines correspond to d = 0 and 230 nm, respectively. As shown in Fig.4, FFPs are not highly degraded by the step. Half widths at half maximum of horizontal FFP for d = 0 nm and that for 230 nm are 16.4 and 9.8 deg, respectively.

4. Conclusions

To improve kink levels in ridge-type semiconductor lasers, a novel ridge structure with antiguiding cladding layers for horizontal transverse modes was proposed and simulated. It is found that kink-free laser operation is obtained up to the injected current of 2 A.

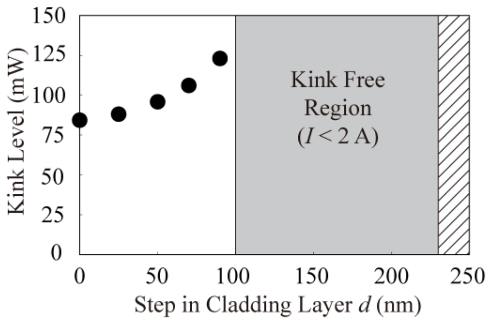

Fig.2 Kink level as a function of the step in the antiguiding cladding layers d.

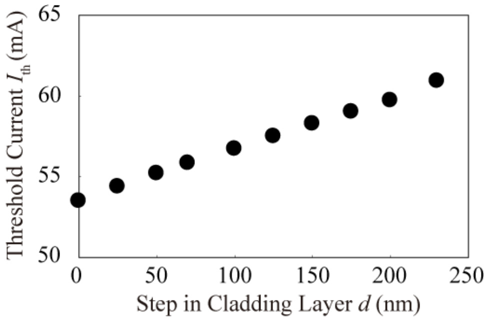

Fig.3 Threshold current for the fundamental transverse mode I_{th} as a function of the step in the antiguiding cladding layers d.

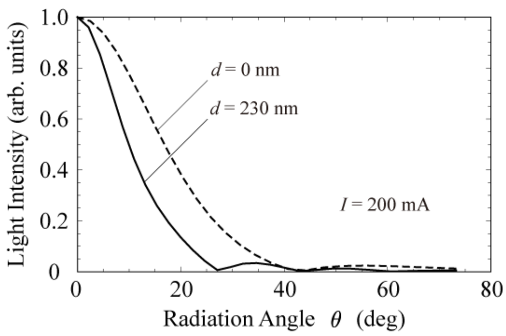

Fig.4 Horizontal far field patterns.

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