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 performance of 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 $100 \text{ nm} \leq d \leq 230 \text{ nm}$, kink-free laser operation is obtained up to the injected current of 2 A.

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.

![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.](https://example.com/fig1.jpg)

For $100 \text{ nm} \leq d \leq 230 \text{ nm}$, kink-free laser operation is obtained up to the injected current of 2 A.

3. Simulation Results and Discussions
Figure 2 shows a kink level as a function of the step $d$ of the antiguiding cladding layers $d$. For $d < 100 \text{ nm}$, the kink level increases with an increase in
For $100 \, \text{nm} \leq d \leq 230 \, \text{nm}$, it should be noted that the kink does not appear when the injected current $I$ is less than 2 A. For $230 \, \text{nm} < d$, 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 $d \leq 230 \, \text{nm}$, the real-valued wave-number, which only contains the real part, for the fundamental transverse mode exists. For $230 \, \text{nm} < d$, 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 $230 \, \text{nm} < d$, 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 $230 \, \text{nm} < d$. 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 $I_{th} = 60.9 \, \text{mA}$ at $d = 230 \, \text{nm}$ is 1.14 times as large as $I_{th} = 53.5 \, \text{mA}$ at $d = 0 \, \text{nm}$.

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

References


