

Article

A 1064 nm Deep-Etched Wide-Ridge Waveguide Slab-Coupled Photonic Crystal Semiconductor Laser

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Abstract

Semiconductor lasers are key devices in optical communication, optical storage and other fields. Achieving single-mode, high-power and high-beam-quality output is an important research goal in laser technology. Conventional slab-coupled optical waveguide lasers can effectively suppress higher-order modes, but suffer from a low optical confinement factor and limited ridge width. This paper proposes a 1064 nm deep-etched wide-ridge waveguide slab-coupled photonic crystal semiconductor laser. A photonic crystal structure is introduced into the conventional slab-coupled optical waveguide. The optical field and mode characteristics are analyzed by numerical simulation, verifying the feasibility of the structure in improving the optical confinement factor and realizing single-mode operation with a deep-etched wide-ridge waveguide. Different from traditional photonic crystal lasers, this design provides a new route for high-performance photonic crystal semiconductor laser design.

Keywords: 1064 nm; photonic crystal laser; wide-ridge waveguide; slab-coupled

1. Introduction

Semiconductor lasers feature compact size, high electro-optical conversion efficiency and excellent controllability, making them indispensable light sources in optical communication, optical storage and other applications [1]. Simultaneously achieving single-mode operation, high output power and high-beam-quality remains a challenging objective in photonics and laser physics [2]. To overcome this bottleneck, researchers have proposed novel structures including asymmetric super large optical cavity [3], slab-coupled optical waveguide laser [4], longitudinal photonic crystal [5,6], high-brightness broad-area edge-emitting structure [7,8], quasi-PT-symmetric laser [9], supersymmetric laser [10–12], tapered semiconductor laser with an integrated multimode interference coupler [13] and so on.

Among them, the slab-coupled optical waveguide laser utilizes the slab-coupling effect to filter out higher-order modes, providing a larger mode field area and lower propagation loss for the fundamental mode [14]. A typical feature of such devices is the deep-etched ridge waveguide, whose etching depth usually penetrates the active region, enabling strong lateral confinement of photons, carriers and injection current, and supporting waveguide



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bends with smaller radii [15]. Theoretically, slab-coupled optical waveguides can achieve large-size low-loss single-mode operation. However, an overlarge slab waveguide thickness drastically reduces the optical confinement factor in the active region, making it difficult to meet the lasing threshold. In addition, to maintain a single lateral mode, the ridge width of deep-etched waveguides is usually much narrower than that of shallow-etched ones, increasing coupling difficulty and thermal resistance [16].

To address these issues, this paper introduces a photonic crystal structure into the slab region of a conventional slab-coupled optical waveguide to construct a deep-etched slab-coupled photonic crystal semiconductor laser. The optical field regulation and mode characteristics are systematically studied to verify the feasibility of improving the optical confinement factor and realizing single-mode lasing with a deep-etched wide-ridge waveguide. Different from conventional photonic crystal lasers—which are mostly based on high-confinement asymmetric or symmetric waveguides with photonic crystals introduced on one or both sides of the N-type or P-type waveguide layers—the proposed design starts from a low-confinement slab-coupled optical waveguide. The photonic crystal reduces the effective refractive index of the waveguide while preserving the mode-filtering capability of the slab-coupled structure, offering a new paradigm for photonic crystal semiconductor laser design.

2. Design and Simulation

For comparison, this paper first investigates the 1064 nm-band slab-coupled optical waveguide laser shown in Figure 1a, because 1064 nm-band semiconductor lasers are widely used in fiber laser seed sources, sensing, frequency conversion and other important applications [11]. We set the ridge width $w_g = 6 \mu\text{m}$, the distance from the active region to the N-type cladding $h = 6.835 \mu\text{m}$, and the slab thickness $t = 6.45 \mu\text{m}$. The selection of these parameters is based on Marcatili's theory [15], which states that for lossless passive ridge waveguides, the number of supported modes depends on the geometry configuration rather than the absolute dimensions. The effective waveguide dimensions can be defined as: $W = w_g(1 + c_{wg})$, $H = h(1 + c_h)$, $T = t(1 + c_t)$, where the effective dimensions are approximated by the actual physical dimensions plus the field decay lengths in the adjacent regions. Theoretically, the number of guided modes is determined only by the ratios T/H and T/W . Single-mode operation can be achieved when T/H and T/W are close to unity. Therefore, in conventional slab-coupled optical waveguide lasers, a large ridge width w_g requires a large effective slab thickness T , which inevitably leads to a low optical confinement factor for the fundamental mode. To highlight this issue, the values of w_g , h , and t used in this work are deliberately set much larger than those reported in previous studies [17]. Figure 1b shows the refractive index profile along the epitaxial (vertical) direction of the laser structure. The device is grown on an N-doped GaAs substrate. The N-type cladding is graded from $\text{Al}_{0.6}\text{GaAs}$ to $\text{Al}_{0.4}\text{GaAs}$, and the N-type waveguide layer is $\text{Al}_{0.18}\text{GaAs}$. The active region consists of GaPAs and GaAs barrier layers as well as a GaInAs single quantum well (QW), with thicknesses of 10 nm, 10 nm, and 9 nm, respectively. The P-type waveguide layer is $\text{Al}_{0.18}\text{GaAs}$, and the P-type cladding is graded from $\text{Al}_{0.4}\text{GaAs}$ to $\text{Al}_{0.6}\text{GaAs}$. Since no low-refractive-index layers are inserted in the N-type waveguide layer, it is labeled as zero, indicating zero inserted low-index layers. Figure 1b also marks the deep etching positions on both sides of the ridge waveguide. Based on the structure shown in Figure 1a and the material distribution in Figure 1b, a two-dimensional simulation model was established using COMSOL Multiphysics 6.3. Simulation results show that the laser operates in a single mode. From the fundamental-mode electric field output in the computational domain, it can be observed that the fundamental-mode field distribution is mainly concentrated in the N-type waveguide layer and is significantly expanded in

the lateral direction, as shown in Figure 1c. Figure 1d illustrates the fundamental-mode field distribution captured at the center of the broad-ridge waveguide along the vertical direction, which shows that the mode field is largely displaced away from the active region. The optical confinement factor of the fundamental mode is only 9.9088×10^{-5} , making it difficult for the laser to achieve lasing.

To address the issue that conventional slab-coupled optical waveguide lasers cannot lase due to an excessively low optical confinement factor, this paper inserts a photonic crystal structure into the slab waveguide of a conventional slab-coupled optical waveguide laser to regulate the optical field distribution in the slab waveguide. The peak optical field intensity is shifted toward the active region, thereby increasing the optical confinement factor of the laser and satisfying the lasing condition. The structure is shown in Figure 2a. Based on the structure depicted in Figure 2a, a two-dimensional simulation model was constructed in COMSOL, with the design objectives of achieving a high optical confinement factor and a well-extended mode field distribution. The N-type waveguide layer is $\text{Al}_{0.18}\text{GaAs}$, and the adjacent N-type cladding is $\text{Al}_{0.4}\text{GaAs}$. When inserting low-refractive-index layers into the N-type waveguide layer of the slab-coupled optical waveguide laser, an excessively high Al composition hinders the expansion of the optical mode field, whereas an excessively low Al composition limits the optical confinement factor. After a comprehensive trade-off and with reference to [11], $\text{Al}_{0.3}\text{GaAs}$ was selected as the material for the low-refractive-index layers. An insufficient number of low-refractive-index layers cannot exert the photonic crystal modulation effect on the optical field, while an excessive number would introduce difficulties in both numerical simulation and practical epitaxial growth. Therefore, the number of low-refractive-index layers was set to 10. These layers are labeled sequentially from the substrate toward the active region, consistent with the order of layer insertion and the total count of inserted layers, as illustrated in Figure 2b. It can also be observed that the deep-etched regions on both sides of the ridge waveguide extend to the position of the tenth low-refractive-index layer. With the material and number of low-refractive-index layers determined, parametric simulations were carried out with respect to the layer thickness. It was found that when the low-refractive-index layers are $0.15\text{ }\mu\text{m}$ thick, each with $0.05\text{ }\mu\text{m}$ buffer layers on both sides for composition grading between $\text{Al}_{0.18}\text{GaAs}$ and $\text{Al}_{0.3}\text{GaAs}$, the spacing between adjacent low-refractive-index layers is $0.5\text{ }\mu\text{m}$, and the period of the photonic crystal structure h_1 is $0.65\text{ }\mu\text{m}$, the fundamental-mode field of the laser shifts significantly toward the active layer. Meanwhile, under periodic modulation, the mode field is expanded within the N-type waveguide layer and decays upon reaching the N-type cladding, as clearly shown in Figure 2c. This behavior is also verified by the vertical cross-sectional fundamental-mode field profile in Figure 2d. At this point, the parameters of the photonic crystal structure inserted in the N-type waveguide layer of the slab-coupled optical waveguide laser were finalized, and the overall laser structure and design parameters are summarized in Figure 2b. As can be seen from the above discussion, the selection of the material and number of low-refractive-index layers relies to some extent on empirical considerations. We believe that a fully coupled parametric sweep over the material composition, number, and thickness of the low-refractive-index layers could further optimize the device toward the design goals of high optical confinement factor and favorable mode field distribution.

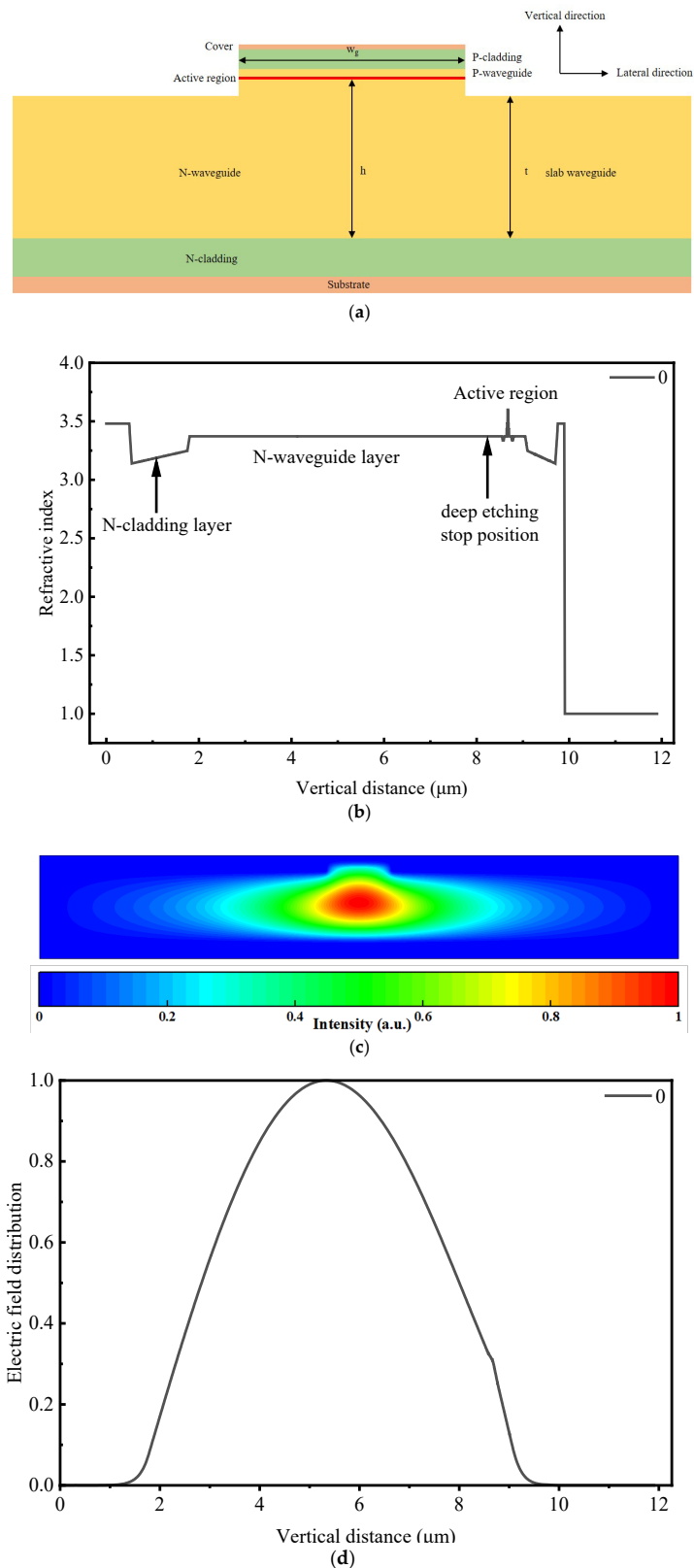


Figure 1. The conventional slab-coupled optical waveguide laser: (a) schematic diagram, (b) refractive index profile in the vertical direction, (c) fundamental-mode electric field distribution (Colors represent the magnitude of the electric field ($\text{norm}E$); darker red corresponds to a larger $\text{norm}E$ value), and (d) fundamental-mode profile captured at the center of the broad-ridge waveguide along the vertical direction.

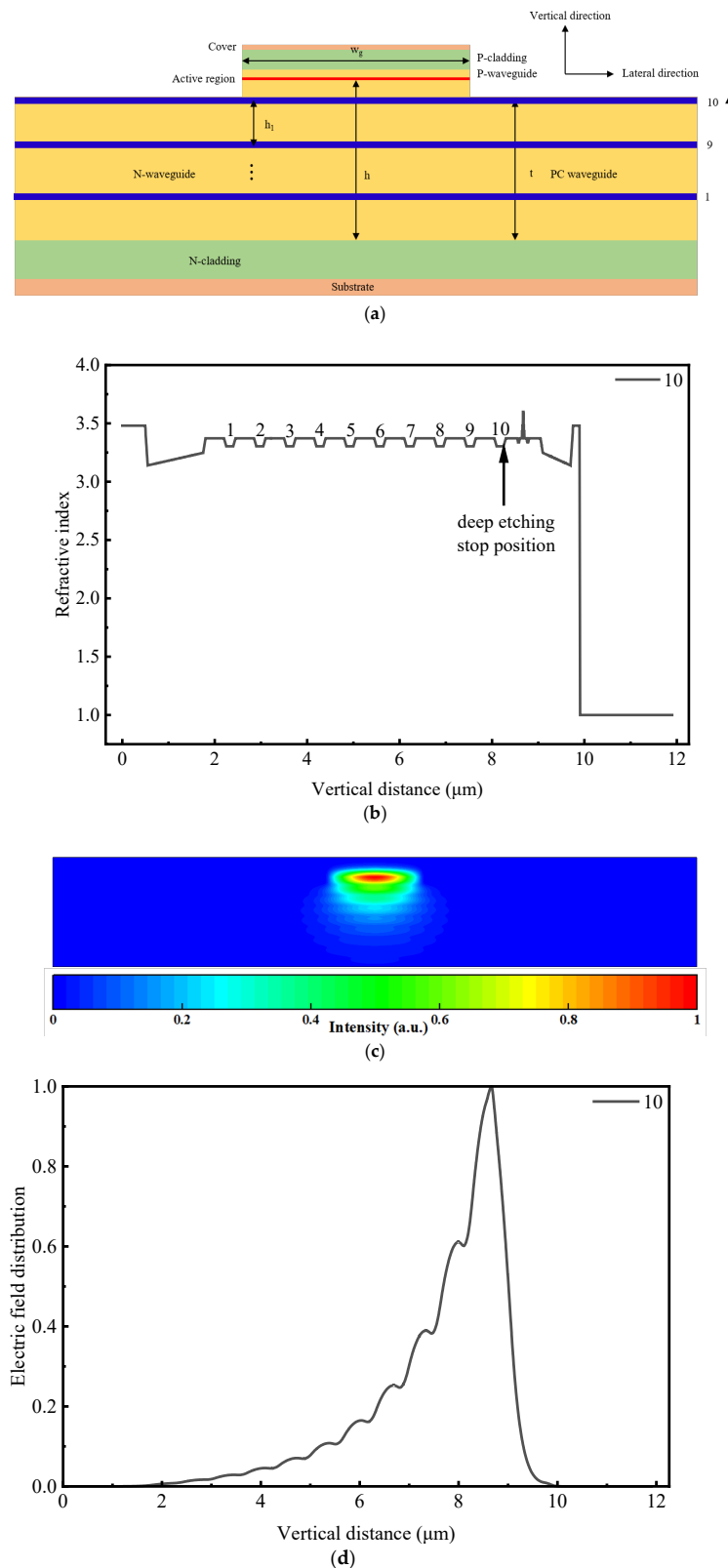


Figure 2. The slab-coupled photonic crystal semiconductor laser: (a) schematic diagram, (b) refractive index profile in the vertical direction, (c) fundamental-mode electric field distribution (Colors represent the magnitude of the electric field (normE); darker red corresponds to a larger normE value), and (d) fundamental-mode profile captured at the center of the broad-ridge waveguide along the vertical direction.

To investigate the modulation mechanism of the introduced photonic crystal structure on the slab waveguide modes, nine intermediate simulation models were constructed in this work by gradually inserting low-refractive-index layers one by one according to the sequence labeled in Figure 2b. The number of inserted low-refractive-index layers corresponds to the model order. For instance, the first model contains one low-refractive-index layer inserted in the N-type waveguide layer from the substrate toward the active region, while the ninth model contains nine such layers. Accordingly, Figure 1a represents the zeroth model, and Figure 2a represents the tenth model. Figure 3 plots the effective refractive index and optical confinement factor of different modes versus the number of low-refractive-index layers. The fundamental-mode effective refractive index decreases from 3.3714 to 3.3541, and the optical confinement factor increases from 9.9088×10^{-5} to 0.009468. The second-order mode appears at the 5th layer and the third-order mode at the 8th layer; both vanish after the 10th layer.

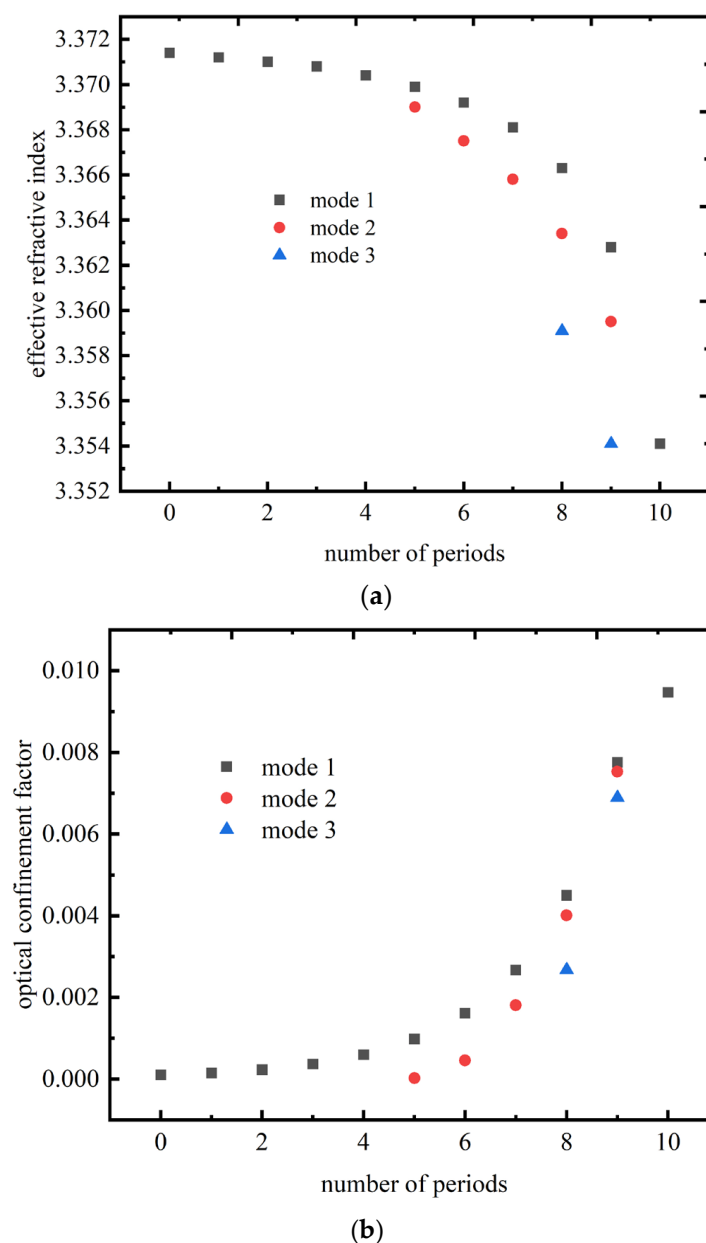


Figure 3. Variations in effective refractive index (a) and optical confinement factor (b) of different modes with increasing number of low-refractive-index layers.

To analyze the emergence and disappearance of high-order modes, the field distributions of the fundamental mode for 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 inserted low-refractive-index layers, as well as those of the second- and third-order modes for 9 inserted layers, are derived in this work and illustrated in Figure 4. Meanwhile, the field distribution of the fundamental mode along the epitaxial direction is also extracted and shown in Figure 5. For comparison, the fundamental-mode field distributions shown in Figures 1d and 2d are also included in the figure.

According to Figures 1c, 2c, 4 and 5, combined with Marcatili's theory, the mechanism can be explained as follows: inserting low-refractive-index layers into the slab-coupled waveguide effectively reduces the slab thickness t , shifting the fundamental-mode field toward the active layer and lowering the propagation constant $\sqrt{k^2 n^2 - (\frac{\pi}{t})^2}$ of the slab-guided modes below β_2 and β_3 of higher-order modes, leading to the appearance of higher-order modes at the 5th and 8th layers. When the 10th layer is inserted, the photonic crystal waveguide forms an integrated slab with a periodic refractive index distribution, restoring the effective slab thickness to the original value. Higher-order modes are thus effectively filtered out by the photonic crystal structure.

Benefiting from the modulation of the laser mode field by the photonic crystal, the slab-coupled photonic crystal semiconductor laser achieves far-field divergence angles of 12.9° in the lateral direction and 18.3° in the vertical direction at full width at half maximum (FWHM), with a nearly circular spatial mode profile as shown in Figure 6. Thus, butt coupling to a single-mode fiber with high coupling efficiency can be realized without additional lenses.

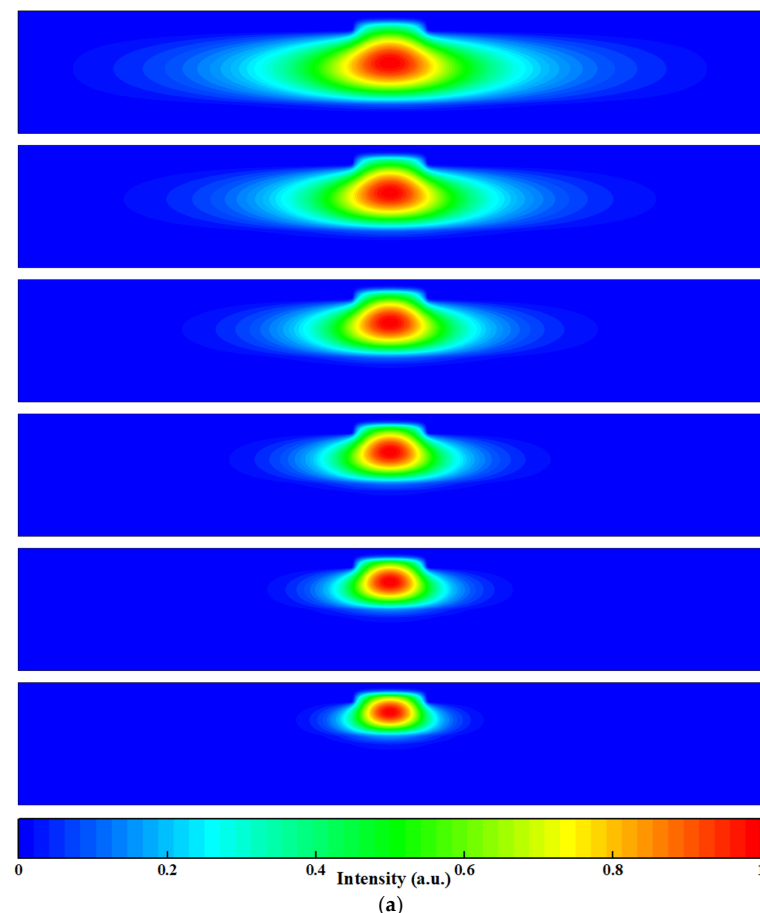


Figure 4. Cont.

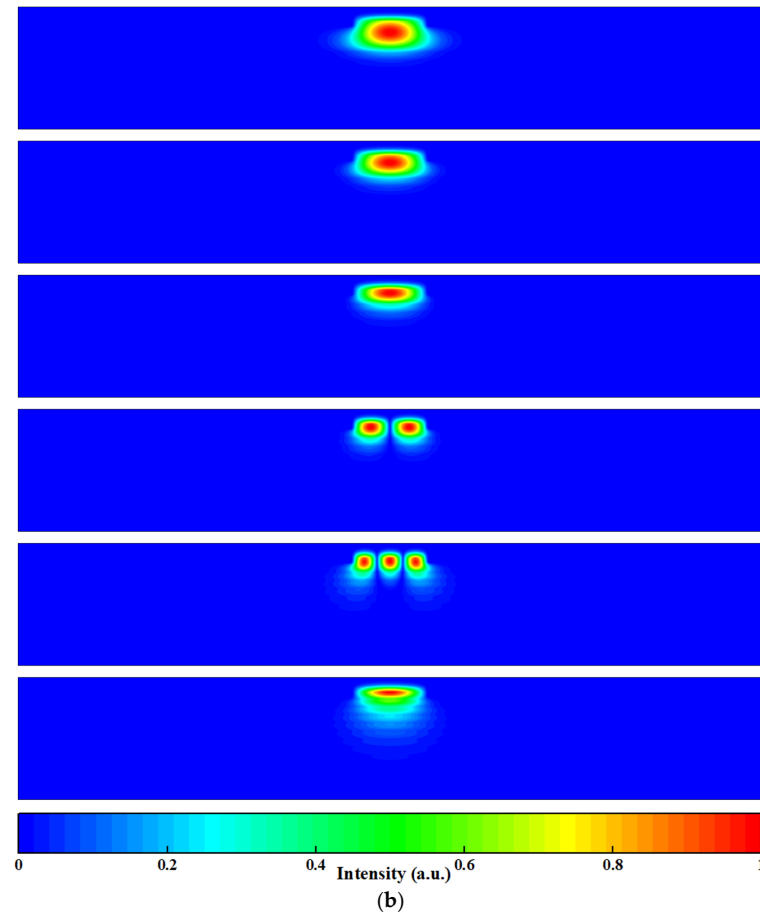


Figure 4. (a) The fundamental-mode field distributions for 1, 2, 3, 4, 5, and 6 inserted low-refractive-index layers, (b) the fundamental-mode field distributions for 7 and 8 inserted low-refractive-index layers, the fundamental, second-order, and third-order mode field distributions for 9 inserted low-refractive-index layers, and the fundamental mode for 10 inserted low-refractive-index layers. (Colors represent the magnitude of the electric field (normE); darker red corresponds to a larger normE value).

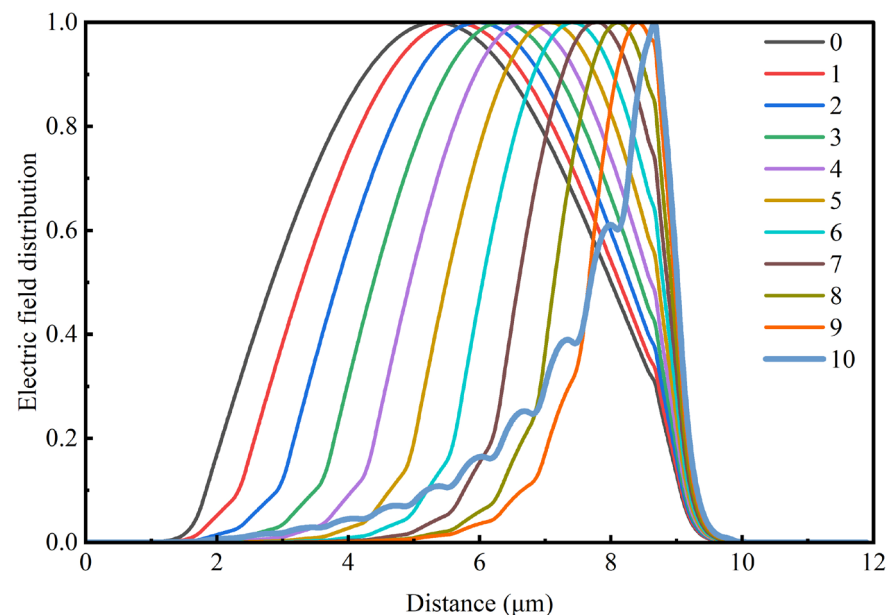


Figure 5. Fundamental-mode field distributions of the correspondingly numbered simulation models when 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 low-refractive-index layers are inserted along the vertical direction.

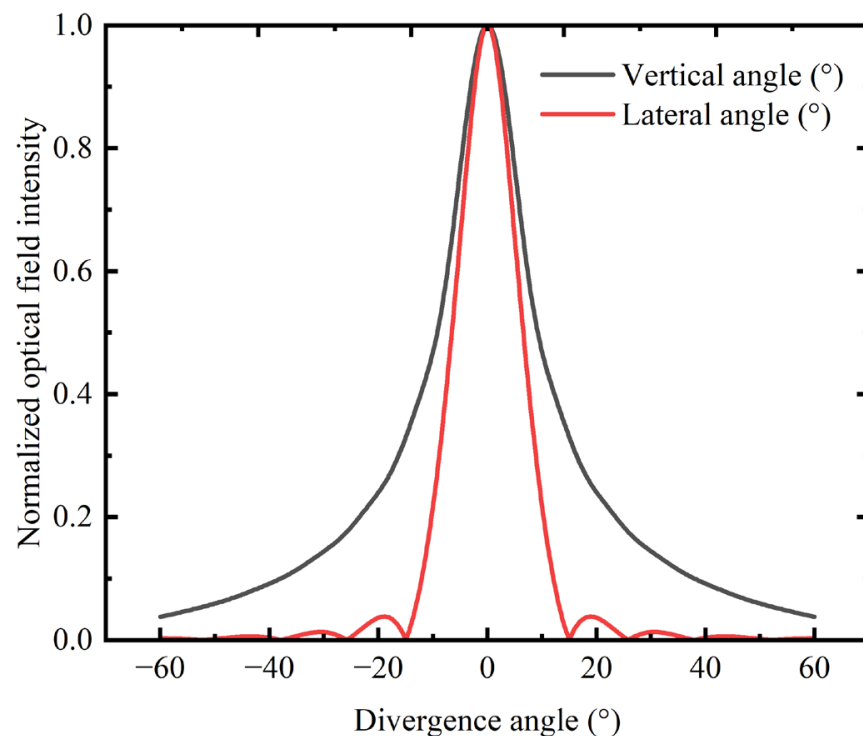


Figure 6. Divergence angles of the slab-coupled photonic crystal semiconductor laser in the vertical and horizontal directions.

3. Conclusions

This paper addresses the bottleneck of extremely low optical confinement factor and difficult lasing in wide-ridge slab-coupled optical waveguide lasers by introducing a photonic crystal structure into the slab waveguide, and systematically studies the optical field regulation of the novel device. Simulations demonstrate that layer-by-layer insertion of low-refractive-index layers precisely tailors the optical field, shifting it toward the active region and boosting the fundamental-mode optical confinement factor from 9.9088×10^{-5} to 0.009468. After inserting 10 low-refractive-index layers, higher-order modes are effectively suppressed, and the device achieves stable single-mode output. The horizontal and vertical divergence angles are 13.2° and 18.6° , respectively, with a nearly circular mode profile suitable for direct high-efficiency coupling to single-mode fibers. This work verifies the feasibility of photonic crystal structures in enhancing the optical confinement factor and realizing single-mode lasing in deep-etched wide-ridge waveguides, providing a new approach for designing high-beam-quality 1064 nm photonic crystal semiconductor lasers.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Author Xinmin Fan is employed by Shandong Leishuo Laser Technology Co., Ltd. The remaining authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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