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Communication

Coupling Performance Enhancement of GaSb-Based Single-Transverse-Mode Lasers with Reduced Beam Divergence Obtained via near Field Modulation

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Abstract: Symmetric narrow waveguide structure has been developed and fabricated to achieve low beam divergence and improved coupling performance of the 1.95 μm GaSb-based single-transverse-mode diode lasers. The near-field expansion effect of the narrowed 150 nm vertical waveguide design leads to a reduced fast-axis beam divergence of 44.2° full width at half maximum (FWHM) as well as 62% single-mode fiber (SMF) coupling efficiency, which has 55% relative promotion compared to the 40% efficiency of the conventional 270 nm waveguide design with 60.4° FWHM. The highest SMF coupling power of 113 mW was obtained by the 210 nm narrow waveguide lasers with lower internal optical loss at a 55% coupling efficiency, which performed balanced optimal performance with a narrowed divergence of 53.4° and a relatively high optical power of 206 mW. The high coupling efficiency and power will provide more promising prospects for the GaSb-based single-transverse-mode lasers in the widespread fiber-based and external-cavity applications.

Keywords: GaSb-based diode lasers; single-transverse-mode; vertical beam divergence; fiber coupling

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1. Introduction

Mid-infrared (mid-IR) 2–4 μm GaSb-based single-transverse-mode diode lasers with high power and simultaneously good beam quality have been ideal light sources for various scientific and commercial applications [1], such as pumping Tm-doped or Ho-doped fiber amplifiers [2], seeding external-cavity and hybrid photonics integration applications [3,4], gas spectroscopy [5], medical diagnostics and therapy [6], materials welding and processing, and nonlinear frequency conversion [7]. However, the widely adopted broadened waveguide-structure design of GaSb-based diode lasers characterized by wide waveguide layers of 300–400 nm thickness resulting in a large vertical beam divergence of 63°–67° full width at half maximum (FWHM) [8,9] are barriers for coupling with conventional fibers and optical systems for the mid-IR wavelength region [10,11]. The large beam divergence is especially detrimental for the single-transverse-mode diode lasers while considering the rigid coupling condition with the mid-IR region single-mode fiber (SMF) or polarization-maintaining fiber (PMF), which possesses a finite numerical aperture (NA) of 0.2 and a small core diameter of 7 μm. The consequent low-coupling efficiency will lead to insufficient exploitability of the limited single-transverse-mode optical power as well as heavy reliance on expensive and complicated collection optics.

In order to increase the extractable power, effective approaches such as super-large optical cavity (SLOC) and photonic band crystal (PBC) have been proposed for the vertical divergence reduction relying on the concept of vertical field extension in previous research on GaAs material systems [12–14]. For GaSb-based diode lasers, the thick optical-mode expansion layers will bring more severe penalties of high thermal and series resistance. Consequently, the narrow waveguide scheme has been demonstrated to be a perspective alternative scheme for expanding the model field and narrowing the divergence profile without causing extra epitaxial-growth complexity [1,15]. The following studies mainly focused on compensating for the increased free carrier absorption originating from the overlap of the expanded optical mode with the heavily doped p-cladding by introducing an asymmetric waveguide structure to selectively spread the optical mode into n-cladding [2,16–18]. However, the asymmetric expanded near-field distribution is unsuitable for the single-transverse-mode lasers while coupling with the SMF of symmetric fundamental guided mode, since the mode mismatch may inversely reduce the coupling efficiency. Previous research mainly focused on beam profile compression and output power preservation for broad-area lasers and rarely paid attention to the fiber coupling of narrow-ridge single-transverse-mode lasers, which are playing a considerable critical role in current practical applications.

In this paper, we focused on promoting the fiber coupling efficiency and extractable coupling power of the GaSb-based single-transverse-mode diode lasers via further investigation and development of the symmetric narrow-waveguides scheme. Five designed structures labeled as WG1–WG5 with a gradient reduction of waveguide layers' thickness from 270 to 150 nm at a 30 nm step have been proposed and grown by molecular beam epitaxy (MBE) based on our previous work on 2 µm high-power GaSb-based diode lasers [11,19]. The optical field expansion effect of the narrowing waveguide scheme has been verified with the near-field distribution simulation of the designed structures. The five epi-wafers have been simultaneously fabricated into prototype GaSb-based narrow ridge waveguide diode lasers with a 6.5 µm ridge width and a 1 mm cavity length, resulting in single-transverse-mode operation with a uniform lateral far-field beam divergence of 10° and a center emission wavelength of 1950 nm. The measured vertical beam divergence of WG1–WG5 realized prominent gradual reductions from 60.4° to 44.2° at the expense of reduced output power from 246 mW to 142 mW, originating from the gradually released optical confinement of the narrowed waveguide cores from 586 to 346 nm. Commercial SM1950 fibers with tapered ends have been used for direct coupling to characterize the impact of the narrow beam divergence profile on fiber coupling efficiency and coupling power. A prominent 22% enhancement of the coupling efficiency has been realized by the 150 nm waveguides (WG5) of 62% efficiency compared with the conventional 270 nm waveguides (WG1) of 40% efficiency. Moreover, the highest coupling power of 113 mW has been realized by the 210 nm waveguides (WG3) with a 53.4° vertical beam divergence device and 206 mW optical output power, which performed a better balance between the beam divergence suppression and internal loss restrain.

2. Materials and Methods

Separate confinement laser structures were grown by solid-state MBE on n-doped (100)-oriented GaSb substrates. The active region contained two 13 nm $In_{0.18}GaSb$ quantum wells (QWs) spaced apart by a 20 nm $Al_{0.25}GaAs_{0.02}Sb$ barrier, embedding between two symmetric lattice-matched $Al_{0.25}GaAs_{0.02}Sb$ waveguide layers. The 1.5 µm n-doped (1.08×10^{17} cm^{-3}) and p-doped (1.4×10^{18} cm^{-3}) $Al_{0.5}GaAs_{0.04}Sb$ cladding layers were grown adjacent to the two sides of the waveguide core. A 250 nm highly p-doped (5×10^{18} cm^{-3}) GaSb contact layer was grown on top of the p-cladding layer.

Five laser structures labeled as WG1–WG5 with gradually reduced symmetric waveguide thicknesses from 270 to 150 nm with a 30 nm step were designed based on our previous work on high-output power GaSb-based laser devices, which adopted 270 nm waveguide layers [11,19]. The refractive index profiles together with the simulated near-field fundamental mode intensity distributions of the five samples are depicted in Figure 1a. The gradual reduction in waveguide layer thickness as well as the relatively small refractive index step of approximately 0.15 between the waveguide and cladding layer resulted in the gradually released optical-confinement effect of the waveguide core. Figure 1b shows the corresponding near-field expansion effect of WG1–WG5 characterized by the 15% increment of the $1/e^2$ spot sizes. Furthermore, the mode expansion effect was found to be more prominent with narrower waveguides lower than 200 nm.

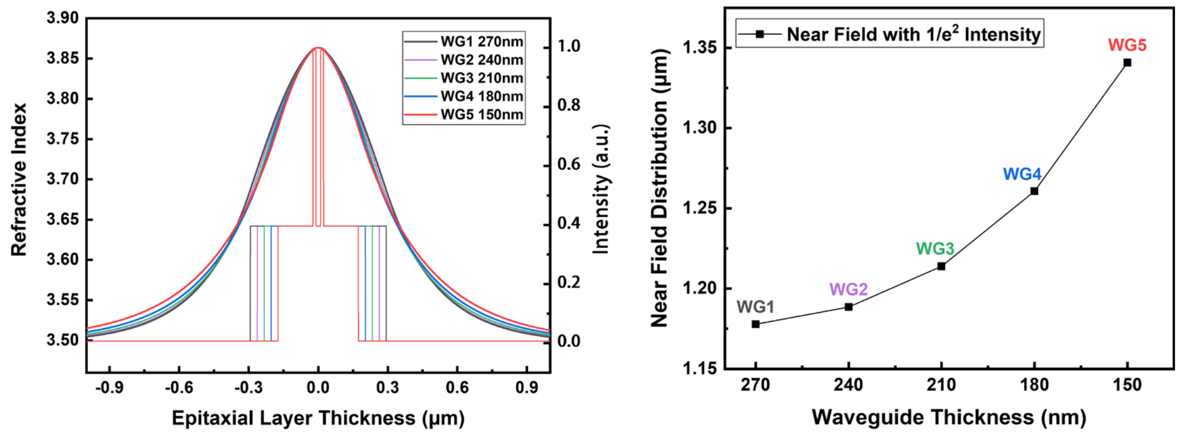

Figure 1. (**a**) Refractive index profile with simulated near-field optical mode intensity of WG1–WG5 with different waveguide-layer thicknesses; (**b**) Near-field $1/e^2$ spot size expansion of WG1–WG5 with narrowing waveguide-layer thicknesses.

The five epitaxial samples were then simultaneously fabricated into narrow ridge waveguide laser diodes with a 6.5 μm ridge width to guarantee single-transverse mode operation while providing high optical power output. The ridge waveguide was defined by contact lithography and formed by inductively coupled plasma (ICP) dry etching with an etched depth of 1.55 μm. A 250 nm SiO_2 dielectric layer was then deposited by plasma-enhanced chemical vapor deposition as insulation. A current injection window with a width of 3 μm was opened at the center of the ridge through negative photoresist lithography and ICP etching. Electrode layers composed of Ti/Pt/Au and AuGe/Ni/Au were sputtered and annealed on the p-type and n-type sides of the wafer after the substrate thinning process. For subsequent continuous-wave (CW) characterization, the devices were cleaved into 1 mm cavity length and coated with 2%/95% AR/HR films. The single emitters were finally mounted epi-side down onto the Cu heat sinks.

3. Results

Figure 2 demonstrates the measured vertical far-field characteristics of the WG1–WG5 by a rotating photoelectric detector at an injection current of 800 mA and 20 °C room temperature. The corresponding FWHM divergence angles are indicated in the legend. Effective beam divergence reduction from 60.4° to 44.2° has been realized and attributed to the gradual near-field expansion, with WG1–WG5 of the waveguide core narrowing from 586 to 346 nm. The inset presents the typical slow-axis far-field beam intensity distribution with a divergence angle of 9.9° FWHM, regardless of the different vertical waveguide structures. The single-lobe bell-shaped far-field distributions in the lateral and vertical directions verify the high stability and purity of the fundamental-mode emissions of the diode lasers.

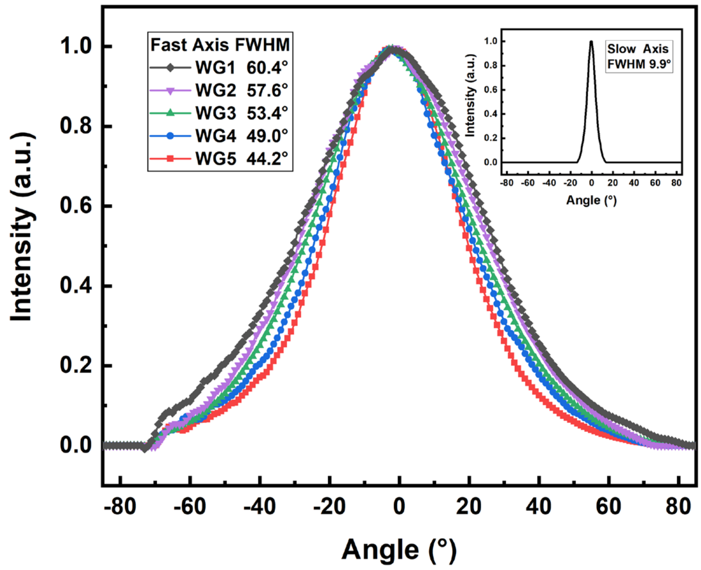

Figure 2. Measured fast-axis far-field distributions and corresponding full width at half maximum (FWHM) divergence of GaSb-based single-transverse-mode diode lasers WG1–WG5 with different waveguide thicknesses. The inset presents the typical slow-axis far-field distributions of the lasers.

The power–current–voltage (P-I-V) characteristics of WG1–WG5 under CW operation are presented in Figure 3. The single-transverse-mode output power of WG1 with 270 nm waveguides was 246 mW at a driving current of 800 mA, while WG3 with 210 nm waveguides was 206 mW, and WG5 with 150 nm was 142 mW, limited by thermal saturation. Moreover, the threshold current slightly grew from 28 mA of WG1 to 59 mA of WG5 with the narrowed waveguides. Gradual reduction in the optical power and efficiency as well as the increased threshold current of the narrowing waveguide core results from the penalty associated with the optical mode leakage into the cladding layers that induces the internal optical loss, especially for the p-cladding with higher free carrier absorption [17].

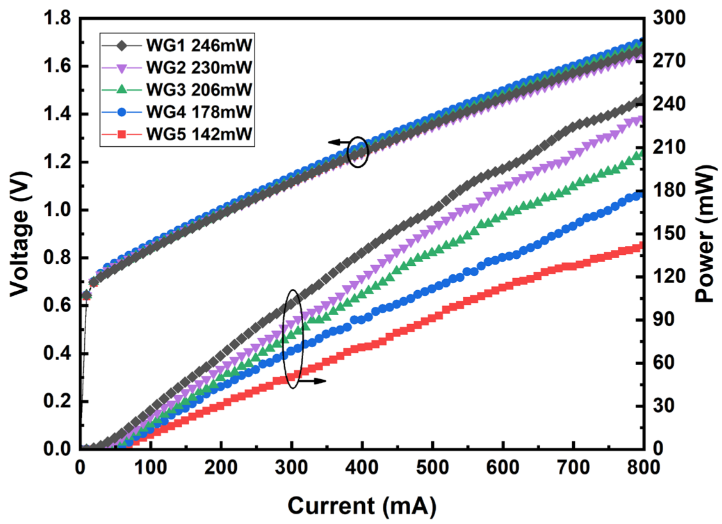

Figure 3. Power–current–voltage characteristics of the GaSb-based single-transverse-mode diode lasers WG1–WG5 with different waveguide thicknesses.

The reduction in waveguide core thickness brings a favorable reduction in the beam divergence but unfavorable degradation of the optical power. Therefore, the actual effectiveness of the narrow waveguide scheme in promoting fiber power-coupling efficiency requires further verification. We employed the commercial single-mode fiber SM1950 and measured the fiber pigtail output power for coupling efficiency calculation, which possesses a core diameter of 7 μm and an NA of 0.2. The coupling facet of the fiber is fabricated into a wedge structure with a tapered angle in the vertical direction to maximize the emitted light collection, while the lateral direction is direct coupling since the slow-axis beam divergence of 9.9° is narrower than the acceptance angle of the SM1950. The tapered angle is determined by the 95% power divergence angle of WG1–WG5 while considering the total internally reflected acceptance-limitation of the fiber.

As demonstrated in Figure 4, WG1 with conventional 270 nm thick waveguides exhibited a 40% power-coupling efficiency, while WG5 realized a 22% efficiency promotion to 62%. The reduced vertical beam divergence of 44° FWHM of WG1 can be efficiently collected using the tapered fiber or standard lens. The residual coupling efficiency loss can be explained by the mode-mismatch of the high-ellipticity diode lasers emitted mode with the SMF Gaussian-guided mode. However, the WG5 fiber pigtail output power of 88 mW is lower than the 98 mW of the WG1 because of the increased internal optical loss of the narrow waveguide scheme. The highest coupling output power of 113 mW was achieved by WG3 with 210 nm waveguides at a 55% coupling efficiency, which exhibited narrowed vertical-beam divergence of 53° FWHM and a relatively high optical power of 206 mW, leading to a better balance in the trade-off between high coupling efficiency and low optical power loss.

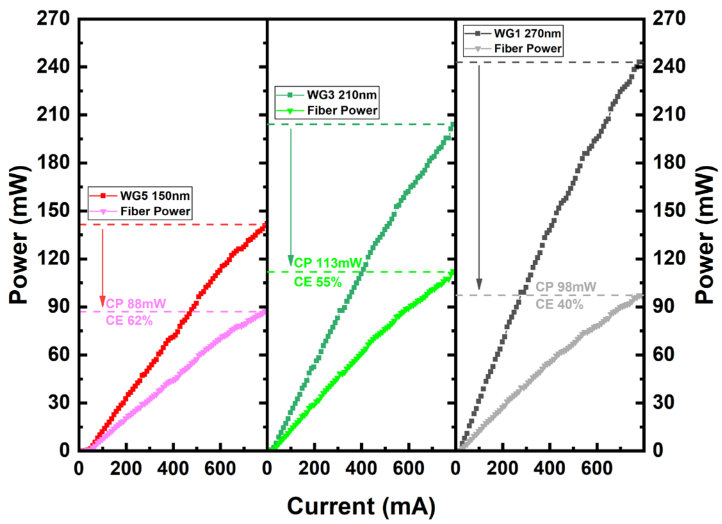

Figure 4. Single-mode fiber (SMF) pigtail output current–power characteristics of WG1, WG3, and WG5 with corresponding diode optical power, coupling efficiency (CE), and coupling power (CP).

4. Discussions

As the preceding sections presented, the symmetric narrow waveguide scheme effectively achieves vertical beam divergence reduction and coupling performance enhancement for the GaSb-based narrow RW lasers while maintaining preferable single-transverse-mode power characteristics. The 346 nm narrow waveguide core design yielded vertical beam divergence of 44.2° FWHM and a recorded high of 62% SMF coupling efficiency in the 2 μm wavelength region. The narrow beam profile below 45° FWHM can be efficiently collected by a commercial lens with a 0.7 numerical aperture. The high collection efficiency facilitates the strong coupling of external-cavity grating and hybrid integrated elements [4,11,20]. The 466 nm narrow waveguide core design provided an optimal equilibrium between low beam divergence and high optical power characteristics, resulting in improved SMF coupling efficiency of 55% and exceeding 100 mW SMF output power. The improved coupling power is especially favorable as the ideal candidate for direct or resonant pumping of the 2 μm fiber or solid-state laser hosts [2], which are currently seeded by light sources of 15–40 mW power level [21,22]. Moreover, the GaSb-based narrow waveguide scheme with optimized single-transverse-mode beam characteristics is also compatible with other laser devices that employ analogous epitaxial layers and waveguide structures, such as DFB, DBR, SOA, and SLD [23,24]. The optimized far-field beam profile and improved coupling performance enable the use of simple and low-cost standard optics for the collimation and focus of these devices while facilitating the promotion of extractable optical power for further utilization.

5. Conclusions

High-power 1.95 μm single-transverse-mode diode lasers with symmetric narrow waveguides of a series of thicknesses between 270 nm and 150 nm were designed, fabricated, and characterized. Vertical far-field beam divergence profile has been reduced from above 60° to 53.4° FWHM when the waveguide thickness narrowed from 270 to 210 nm. Corresponding coupling efficiency with SM1950 increases from 40% to 55%. The prototype diode lasers with 210 nm waveguide exhibited the highest extractable fiber pigtail output power of 113 mW at an injection current of 800 mA and 20 °C. Further narrowing of the waveguide thickness to 150 nm leading to further narrowed beam divergence of 44.2° FWHM and enhanced coupling efficiency to 62% would adversely increase internal optical loss and degrade the output power. The enhancements of the coupling efficiency and power with the narrow waveguide scheme provide promising prospects for GaSb-based single-transverse-mode diode lasers in pumping fiber amplifiers while opening up various external-cavity applications.

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