Novel Design for High-Power Single-Lateral-Mode Lasers

A. E. Huber, *Member, IEEE*, T. S. Yeoh, *Member, IEEE*, R. B. Swint, *Member, IEEE*, C. Y. Woo, K. E. Lee, S. D. Roh, J. J. Coleman, *Fellow, IEEE*, B. O. Faircloth, and M. S. Zediker

Abstract—A new laser design for single-mode high-power applications is reported. The waveguide is a laterally flaring and transversely tapering GaAs buried ridge fabricated by selective area epitaxy. Single-lateral-mode powers of 200 mW were achieved.

Index Terms—High power, single lateral mode.

I. INTRODUCTION

TODAY'S rising power requirements for semiconductor lasers has created much interest in the development of high-power single-lateral-mode lasers. This type of laser is being used in materials processing, medical treatment, and most commonly, as pumps for erbium-doped fiber amplifiers (EDFAs). In recent years, laser designs incorporating a large optical cavity (LOC), first proposed by [1] and successfully demonstrated by [2], have proven to be very effective for obtaining high-power operation in both broad area [3], [4] and narrow stripe [5] lasers. The LOC design sacrifices low threshold operation in order to attain higher slope efficiencies and higher catastrophic optical mirror damage (COMD) levels. The LOC design attains higher COMD levels because of the larger spot size at the facet, which decreases the optical power density. Higher slope efficiencies are attained in LOC designs because only a small fraction of the optical field overlaps the doped cladding layers, which have substantially higher optical loss.

Single-lateral-mode lasers are generally narrow in the lateral dimension in order to cutoff propagation of higher order lateral modes. Several problems arise from the narrow geometry such as reduced COMD levels, larger diffraction angles, and limited output power due to the small gain volume. Recently, flared waveguides have been studied as a means to increase both the gain volume and spot size on the output facet [6]. A problem with flaring the waveguide is that as the waveguide increases in width, it can support propagation of higher order modes.

To address this issue, we describe in this letter a flared and tapered buried ridge laser structure grown by selective area epitaxy (SAE). Using SAE the waveguide can be varied in two di-

Fig. 1. Schematic of laser structure before metals deposition. The upper cladding layers have been displaced to reveal the flared and tapered waveguide layer.

mensions, which allows the optical mode to be reshaped at the output facet and results in high single-lateral-mode powers.

II. DEVICE DESIGN AND FABRICATION

The flared and tapered laser structure we report here, is shown schematically in Fig. 1 (in the figure, the upper cladding layer has been displaced to show the flared and tapered waveguide layer). The lateral waveguide consists of a straight and narrow buried ridge, which flares exponentially as it approaches the output facet of the laser. As the ridge gets wider, the ridge also gets thinner in order to diminish support for propagation of higher order modes in the wider waveguide. The transverse waveguide design is a LOC structure. The thickness of the transverse waveguide was chosen to be less than the critical value ($1.2 \mu\text{m}$), at which the second-order transverse mode could be guided. Guidance of the first-order transverse mode does not pose a problem as the optical field has a null at the quantum well. The thickness of the waveguide was chosen to be nominally $1 \mu\text{m}$ thicker in the narrow section and thinner in the flared section. Since the thickness of the transverse waveguide changes along the length of the laser, it is not possible to center the quantum well in the waveguide for the whole length of the laser. In our implementation, we have chosen to center the quantum well when the waveguide is narrow (and thicker). Consequently, the wide end of the laser is asymmetric in the transverse dimension, with the quantum well closer to the p-cladding than the n-cladding.

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A. E. Huber, T. S. Yeoh, R. B. Swint, C. Y. Woo, K. E. Lee, S. D. Roh, and J. J. Coleman are with the Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801 USA.

B. O. Faircloth and M. S. Zediker are with Nuvonyx Inc., Bridgeton, MO 63044 USA.

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Fig. 2. Plot of the actual (solid line) and maximum allowable (dashed line) index step of the buried ridge index guide along length of the 1000- μm long laser.

A critical feature of this device structure is an engineered decrease in the thickness of a waveguide layer corresponding to the increase in the waveguide width and designed to more closely follow the fundamental lateral mode condition everywhere along the length. We utilize a SAE mask design to create the flared and tapered ridge. The flare is obtained by increasing the space between the dual oxide stripes. The taper is achieved by varying the width of the stripes in the dual stripe oxide pattern. The relative growth enhancement is affected by both the spacing between stripes and the width of the stripes. In order to account for these two effects, three-dimensional (3-D) modeling of the gas phase diffusion over the dual oxide pattern was employed to design a pattern that creates a softly tapering ridge [7].

The waveguide has a 500- μm -long straight narrow section that is 2 μm wide. The flared section is also 500 μm long with a width that increases exponentially from 2 to 8 μm . The ridge thickness is designed to taper smoothly such that the ridge thickness at the wide end is approximately half that at the narrow end. The resulting index step, calculated for our actual devices by the effective index method [8], is shown in Fig. 2. The index step decreases as the waveguide gets wider. Also plotted in Fig. 2 is the maximum allowable index step that will still cutoff propagation of higher order modes, according to the effective index method. The cutoff level decreases as the waveguide increases in width. The reduction in index step also allows the mode to expand laterally, yielding a bigger spot size and smaller diffraction angle.

The lasers were grown using a three-step metal-organic chemical vapor deposition (MOCVD) process. The first growth included a 1.0- μm n-type $\text{Al}_{0.20}\text{Ga}_{0.80}\text{As}$ lower cladding, 0.5- μm GaAs lower barrier, 76- $\text{\AA}$ $\text{In}_{0.29}\text{Ga}_{0.71}\text{As}$ quantum well, and 0.3 μm of the GaAs upper barrier. The sample then had 600 $\text{\AA}$ of SiO_2 deposited by plasma enhanced chemical vapor deposition (PECVD). The SAE dual stripe pattern was etched into the oxide using standard contact lithography. The oxide-patterned sample was then returned to the reactor and a layer of GaAs was grown to create the flared and tapered ridge. The thickness of the ridge in the laser reported tapers from 170 nm in the narrow section to 95 nm in the wide section. The ridge was slightly thinner than the planned 200 nm, which would have centered the QW in the waveguide at

Fig. 3. Plot of power (solid line) and differential quantum efficiency (dashed line) versus current for flared tapered laser.

the narrow end of the laser. The oxide pattern was removed and then the 0.8- μm p-type $\text{Al}_{0.20}\text{Ga}_{0.80}\text{As}$ upper cladding layer and 0.1- μm GaAs p-cap were grown.

After the growths, the p-cap layer was etched to flare from 4 to 9 μm aligned over the flare of the buried ridge. Then 3000 $\text{\AA}$ of SiO_2 was deposited by PECVD. A contact window was opened in the SiO_2 that flared from 2 to 8 μm . Ti-Pt-Au contacts were then evaporated onto the p-side. The sample was thinned and Ge-Au-Ni-Au was evaporated and alloyed on the n-side. An evaporation of Ti-Pt-Au completed the n-side contacts. The processed lasers' facets were coated to yield reflectivities of 95% and 3% on the back and front facets, respectively.

III. EXPERIMENTAL RESULTS

The lasers were tested under pulsed conditions, with pulsewidths of 2 μs . The lasing wavelength was 1.03 μm . For uncoated lasers, the threshold current was 24 mA and peak differential quantum efficiency was 41%. The uncoated lasers show single-lateral-mode operation up to 60 mW. Coated lasers had threshold currents of 27 mA and peak differential quantum efficiencies of 72%. The light versus output power curve and differential quantum efficiency plots for a coated buried ridge flared laser are shown in Fig. 3. The coated lasers display single-lateral-mode operation up to 200 mW. Straight lasers of the same length also moved to multimode operation at similar levels. The lateral far-field pattern for the flared laser, shown in Fig. 4(a), has a full-width at half-maximum (FWHM) of 7° . The near-field pattern, measured using a microscope in conjunction with a charged coupled devices (CCD) camera, has a beam waist measured to be 4- μm -wide FWHM [see Fig. 4(b)]. No beam steering was observed. Measurement also showed the location of the beam waist, relative to the facet, to be stable with drive current. This indicates the laser is mainly index guided and has minimal astigmatism [8]–[10].

IV. DISCUSSION AND CONCLUSION

In this letter, a tapered flared buried ridge laser structure is introduced. The taper adds another degree of freedom when designing waveguides with no additional fabrication difficulty. By tailoring the SAE dual stripe oxide pattern, the waveguide can be varied in two dimensions. This allows the optical mode to be reshaped at the output facet resulting in high single-lateral-mode powers.

Fig. 4. (a) Far field intensity profile and (b) near-field intensity profile with increasing drive current.

The flared lasers reported here had single-lateral-mode output powers of at least 200 mW under pulsed conditions. Since lasers without the flare section broke into multimode operation at the same point, we can determine that the single-lateral-mode output power of the flared lasers was limited by the mode qualities of the narrow section of the flared laser. A thinner ridge with a smaller index step may afford higher single-lateral-mode output powers. Additionally, these

lasers suffered from high contact resistances due to insufficient doping in the p^+ -cap layer, which caused significant heating even under pulsed conditions. Higher single-lateral-mode output powers might be expected from devices that were heat sunk. Investigations are underway to determine if the single-lateral-mode output power can be increased with the indicated improvements.

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