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A Novel Intracavity Lens Design for Compact and High Efficiency Tapered Laser Diode

F. K. Lau, C. W. Tee, R. V. Penty, *Member, IEEE*, I. H. White, *Fellow, IEEE*, N. Michel, and M. Krakowski

***Abstract*—An integrated parabolic lens capable of introducing a diverging effect to the optical mode propagating within the cavity of a tapered laser is proposed and demonstrated. This idea allows broader high-power beams to be generated by shorter cavities. Diverging lenses with etch depths of 0.13 and 0.27 μm are implemented, with 12 (9.5%) and 16.8 μm (13.3%) overall broadening of the near-fields widths measured at $1/e^2$ intensity. The peak output power as well as the threshold current is found to increase following the lens etching process, confirming the beneficial broadening effect introduced by the diverging lens.**

***Index Terms*—Beam quality, catastrophic optical mirror damage (COMD), diverging lens, Gaussian beam, high-brightness lasers, high-power lasers, integrated lens, M^2 factor, mode expansion, tapered lasers.**

I. Introduction

HIGH-EFFICIENCY high-power laser diodes with a Gaussian beam output profile and having a long lifetime are always in great demand for a range of applications [1]. In order to ensure fundamental lateral mode operation, narrow laser waveguides of a few microns width are commonly used. However, the high optical intensity resulting from such a small output aperture readily leads to catastrophic optical mirror damage (COMD) [2], which results in degradation or device failure.

Several approaches for increasing the COMD threshold in narrow ridge waveguide laser diodes have been reported, with the majority concentrating on reducing the absorption coefficient of the facet regions by increasing their bandgap energy relative to the active section. This can be achieved by forming transparent windows near both facets using impurity induced layer disordering [3] and fabricating nonabsorbing mirrors by quantum well intermixing [4]. However, the necessity to engineer the bandgap of the cladding layers forces one to give up the freedom to separately optimize the vertical waveguide structure for a desired transverse field profile.

Alternatively, it is also feasible to approach this technological obstacle by using different waveguide structures. For example, tapered waveguide lasers [5] have received great attention due to their ease of implementation and compatibility with existing fabrication processes. This design has enabled the optical mode to diverge without compromising the properties of the vertical waveguide structure and the laser beam quality, leading to a reduced risk of COMD. However, the taper angle and the cavity length cannot be selected arbitrarily, since the tapered waveguide structure implicitly determines the divergence of the optical mode. In this letter, a novel cavity concept based on Fresnel lens optics theory [6] aimed at further expanding the lateral fundamental mode without compromising the laser beam quality is proposed and demonstrated. Modelling results show that the design allows a significantly more compact and efficient laser than one without. Section II describes the design methodology, and Section III presents an experimental demonstration of the implemented device. Finally, conclusions are drawn in Section IV.

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II. Simulation and Design

We propose the integration of a diverging parabolic lens capable of engineering the phase of the optical mode into the laser cavity, thereby amplifying the magnitude of modal diffraction as the mode propagates along the waveguide. When the lasing mode leaves the index-guided ridge section and enters the gain-guided tapered section, it can be viewed as a Gaussian beam propagating with a curved wavefront, whereby the magnitude of diffraction is directly related to the wavefront's radius of curvature. By enhancing the curvature of this wavefront, one can effectively increase the diffraction of the mode, and hence its eventual size at the laser's front facet. A desired beam shape at the emitting facet can therefore be obtained without modifying the laser geometry, resulting in a cavity design that can be easily interfaced with current fabrication process flow.

To verify that this design enhances the state-of-the-art technology, a time dynamic model is used to simulate the performances of six different devices, where all of them possess the same taper angle, but a different taper length (see Fig. 1). Lenses with etch depths of 1.3 and 2.7 μm are integrated into both long and short taper devices. The model is derived from the three-dimensional Helmholtz equation taking a phenomenological approach, whereby counterpropagating fields and their interaction with electron–hole pairs can be described by a set of coupled nonlinear partial differential equation, which can be numerically integrated in the time-domain using a Hopscotch finite difference method [7].

Fig. 2 shows the simulated widths of the resulting near-fields for the six devices at different injection currents and the light–current (L–I) characteristics. The long tapered device has a tapered section of sufficient length for the mode to expand and spread widely on the output facet and the mode is further expanded with the integration of lenses. In contrast, the beam of the short taper device is concentrated on only a small fraction of the facet, owning to the short propagation distance inside the

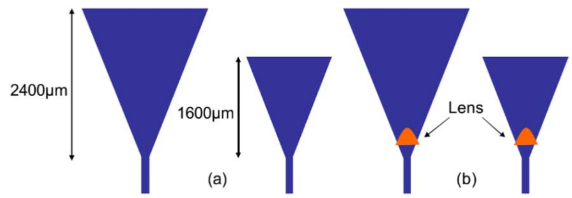

Fig. 1. Schematics of lasers (a) without lens, and (b) with lens etched to depth of either 1.3 or 2.7 μm.

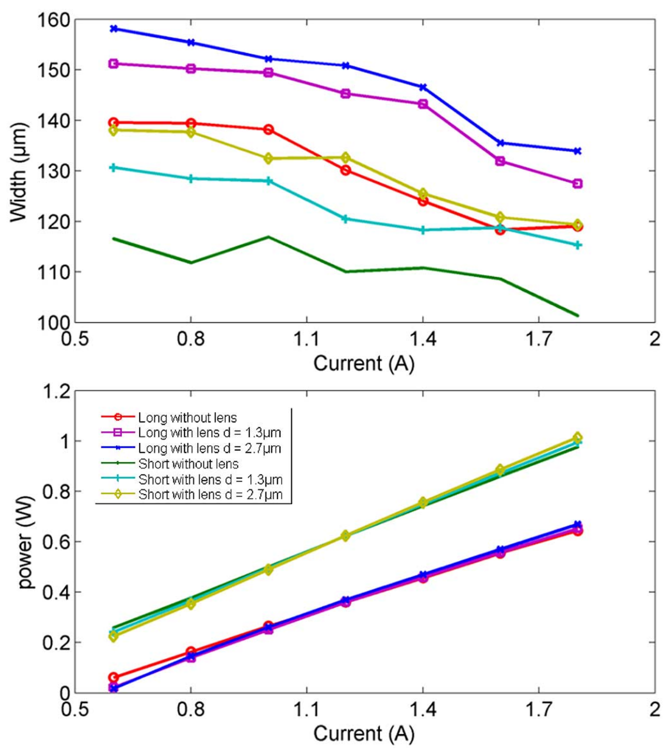

Fig. 2. (a) Evolution of near-field widths at $1/e^2$ intensity (top) and (b) L–I characteristics (bottom).

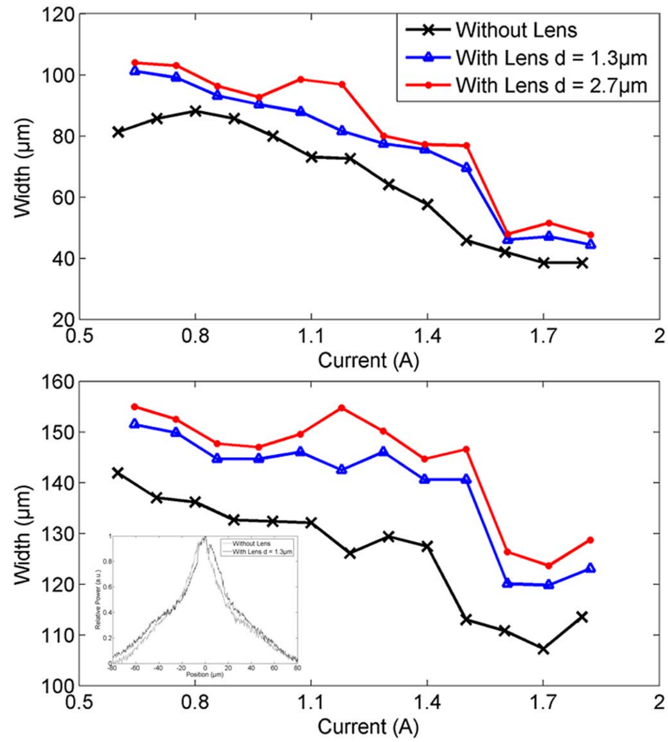

Fig. 3. Evolution of near-field widths at (a) $1/2$ intensity (top) and (b) $1/e^2$ intensity (bottom).

cavity. However, the short taper device with the integrated lens has a beam size at the facet which is comparable to that of the long taper laser. As for output power, the long taper laser is the worst. This is attributed to its large pumping area. The shorter device benefits from a lower threshold current and a higher slope efficiency.

Modelling results show that the lens allows the design of a compact and high efficiency tapered laser diode. The modelling also shows that the lens has an extremely high fabrication tolerance, where the variation of the output power and the near-field width at $1/e^2$ intensity is only ∼30 mW and ∼4 μm for a mask misalignment of ±4 μm laterally or ±30 μm longitudinally.

A high-power tapered laser [8] with an output wavelength of 980 nm is used as the prototype device for the proposed design. The laser has a metal–organic chemical vapor deposition grown Al-free active region containing two GaInAs quantum wells, a large optical cavity, and AlGaAs cladding layers. The 3-mm-long laser consists of a 600-μm-long index-guided ridge section and a gain-guided tapered section with full angle of 6°. A pair of beam spoilers is etched at the taper and ridge boundary. The front facet and back facets are coated with an antireflection and a high-reflection coating, respectively. The device is mounted p-side up to facilitate focused-ion-beam etching processes for design prototyping.

The profile of the lens can be designed using Fresnel lens optics theory, where a different etch-depth results in a different degree of modulation to the effective index of the optical mode. The diverging Fresnel lens has a 40-μm width and a length of 300 μm. In contrast to conventional lenses where the lens area is at a higher refractive index to the surrounding area, in this work, the effective index of the lenses area is reduced by removing the material. Thus, a convex lens provides a diverging effect. The curvature profile is suitable for wavefront engineering and lies within the fabrication tolerance of the focused ion beam etching process. The lens is placed within the taper, 600 μm away from the taper/ridge interface. This allows the optical mode to expand to a ∼20-μm width before reaching the lens.

Devices with two different etch depths have been implemented to provide a consistent framework for prototype comparison in order to isolate and quantify the effect of wavefront engineering. The two etch depths are calculated to be 0.13 and 0.27 μm, measured from the top of the large optical cavity of the laser.

III. Device Characterization

Before etching of the lens, the laser diode exhibited a threshold current of 550 mA. After the inclusion of the lenses, the threshold increases to 590 mA. This is because the curvature of the wavefront of the optical mode is enhanced by the diverging effect of the lenses, thereby reducing the reflected power from the front facet since back coupling of reflected power decreases with increasing glancing angle of the incident ray. However, the output power for the etch depth of 0.13 μm remains identical at 625 mW at 3 I/Ith, while the 0.27-μm etch

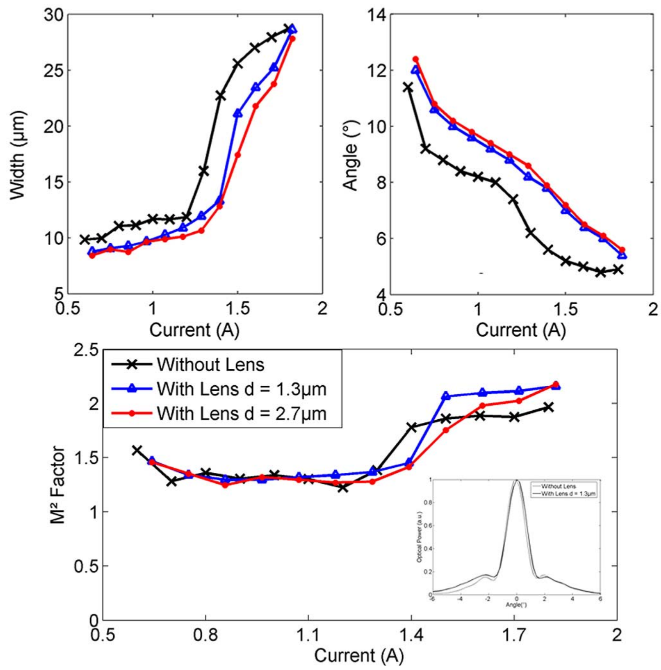

Fig. 4. Evolution of (a) widths of near-field at waist at $1/e^2$ intensity (top left), (b) divergence angles of far-field at $1/e^2$ intensity (top right), and (c) M^2 factor (bottom).

depth results in an increase to in output power of 635 mW. This observation matches with the modelling results and provides evidence that the density of the high carrier density wings known to accumulate on both sides of the tapered section due to spatial-hole-burning is reduced with the optical mode expanded laterally to fill up the tapered section. Beyond that, it also shows that the diverging effect can be amplified by increasing the etch depth of the lens.

The experimental data for the near-field is shown in Fig. 3, illustrating the trend of the diverging effects introduced by the lens with increasing etch depth. For the 0.13- and 0.27-μm etch depths, the average width of near-fields at full-width at half-maximum (FWHM) intensity are found to broaden by 8 (12.2%) and 12.9 μm (19.7%), respectively, and the average width at $1/e^2$ intensity increase by 12 (9.5%) and 16.8 μm (13.3%), respectively. At 3 I/Ith, the near-fields are increased from 107 to 123 μm and 130 μm.

To verify the influence of the lenses on the expanded mode shape, the waist beam distributions and far-fields are measured. The widths of near-field at the waist at $1/e^2$ intensity are narrowed by an average of 1.5 μm (8.8%) for the lens with an etch depth of 0.13 and 2.4 μm (14%) for the lens with an etch depth of 0.27 μm [see Fig. 4(a)]. The average divergence angle at $1/e^2$ intensity is increased by 1.1° (15.6%) and 1.3° (18.5%), respectively [see Fig. 4(b)].

Finally, the M^2 factor of the laser is calculated based on the emission wavelength, the divergence angle of the far-field at $1/e^2$ intensity, and width of the near-field at waist at $1/e^2$ intensity [8]. The pre-etch device has a mean M^2 value of 1.68, while the M^2 factors for lens with the etch depth of 0.13 and 0.27 μm are increased by an average of 0.09 and 0.03, which can be neglected when considering their corresponding impact on the laser beam quality. The worst M^2 factor among all three sets of data is 2.17, which is favorable as far as fiber coupling efficiency is concerned.

IV. Conclusion

Diverging Fresnel lenses with different etch depths are designed and demonstrated successfully. The Gaussian output profile is maintained throughout the current range tested. Experimental results show that in addition to enhancing the maximum output power, the parabolic diverging lenses with 0.13- and 0.27-μm etch depth broadened the near-fields at facet by 8 (12.2%) and 12.9 μm (19.7%) at FWHM and 12 (9.5%) and 16.8 μm (13.3%) at $1/e^2$ intensity, respectively. Meanwhile, the variations in M^2 factors are negligible in terms of its impact on the laser beam quality. A key result of this work is that the diverging effect on an optical mode is a thoroughly scalable effect that can be engineered by varying the etch depth of the integrated lens.

This opens up new prospect in device design, with the beam width along the lateral direction being a parameter that can be optimized in isolation. Therefore, a compact and high efficiency tapered laser can be realized.

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