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Integrated 10th Order Fresnel Lens Design for Beam Quality Enhancement in Tapered Laser Diode

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Abstract: An integrated 10th order Fresnel lens capable of improving the laser beam quality is reported. The far-field divergence is narrowed by an average of 1.9° (29%) and an overall M²-factor improvement of 15% is recorded.

OCIS codes: (140.3300) Laser beam shaping; (220.3620) Lens design; (140.5960) Semiconductor lasers

1. Introduction

High power laser diodes having small beam divergence and high beam quality are essential for a range of optical pumping applications [1]. Several approaches towards achieving high brightness high power lasers have been proposed [2]. Tapered waveguide lasers [3] have received great attention owing to their ease of implementation and compatibility with existing fabrication processes. However, due to its tapered waveguide structure, the laser exhibits a quadratic phase curvature which leads to a wide far-field divergence angle thus degrade the laser beam quality.

In this paper, a novel intra-cavity lens design based on high order Fresnel lens optics theory is proposed and demonstrated. The design is aimed to correct the inherent problem of tapered laser diode by flattening the curved wavefront of the beam at the laser facet, through phase modulation inside the laser cavity.

2. Laser and Lens Structure

3mm long 980nm high power tapered lasers [4], each consisting of an index-guided ridge section and a gain-guided tapered section with full angle of 4° are used as the prototype devices for the proposed design. The lasers have an MOCVD grown Al-free active region containing two GaInAs quantum wells, a large optical cavity and AlGaAs cladding layers. A pair of beam spoilers is etched at the taper and ridge boundary. The front and back facet are coated with anti-reflection and high-reflection coating, respectively. The laser chip is mounted p-side up to facilitate focused-ion beam etching (FIBE) process for design prototyping.

The profile of the lens is designed using the high order Fresnel lens optics theory. A 10th order lens with a focal length of 800μm was designed having considered the trade-off between the number of lens order and the fabrication tolerance. It is 150μm wide and 97μm long and is etched 40μm away from the front facet. The effective index of the lens area is reduced through material removal by FIBE. The schematic of the intra-cavity design is shown in Figure 1.

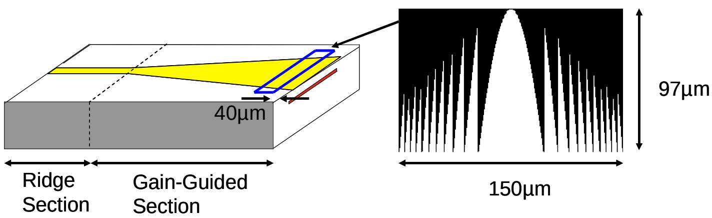
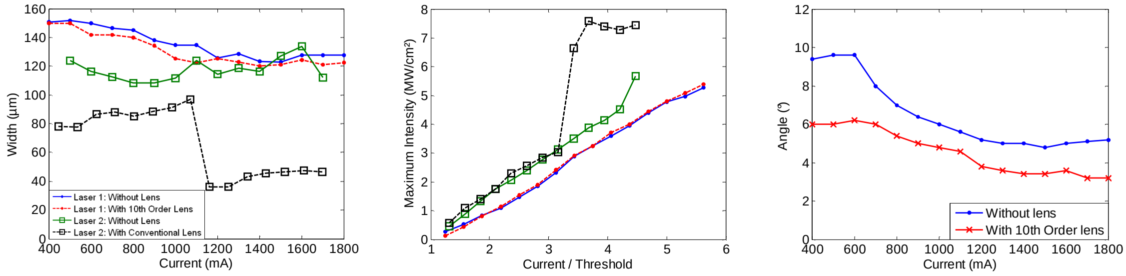


Fig. 1. Schematic of the tapered laser incorporating the intra-cavity 10th order Fresnel lens design

3. Device Characterisations

Before and after the inclusion of the 10th order Fresnel lens, the laser diode exhibits an identical power performance, having a threshold current of 0.32A and 0.88W output power at a bias of 1.84A in each case. The experimental data of the near-field widths at the facet at a $1/e^2$ intensity is shown in Figure 2a, showing an average reduction of 5μm (3.5%). This effect is negligible and does not result in increased catastrophic optical mirror damage (COMD). In order to show the step advance in the technology of the high order Fresnel lens design, a 40μm wide and 300μm long conventional lens (i.e. 0th order lens) is etched into a tapered laser. Due to the geometric limitation of the conventional lens, it must be etched at the back of the tapered section, which is 600μm away from the taper/ridge junction. The near-field widths at the facet at the $1/e^2$ intensity is also shown in Figure 2a, showing a significant average reduction of 49μm (40%). A substantial reduction in slope efficiency is observed and is attributed to the premature restriction of the beam diffraction, in which the utilisation of available gain within the laser cavity is reduced. Figure 2b shows the laser maximum output intensity as a function of the normalised injection current. Because the reduction of the beam size at the facet of laser diode having the 10th order lens is so small, the increase in the maximum output intensity at different injection current is completely negligible. In contrast, although the power output of laser diode with the integrated 0th order lens drops notably, an enormous increase in its maximum output intensity is still observed due to the significant reduction in its beam size at the facet. COMD is observed at high biased current.



(a) (b) (c)

Fig. 2. Evolution of (a) the near-field width of laser diode with the integrated 10th order lens and the conventional lens integrated laser at 1/e² intensity versus the injection current, (b) maximum output intensity versus the normalised injection current and (c) the far-field angle of laser diode with the integrated 10th order lens at 1/e² intensity versus the injection current

To verify the influence of the 10th order lens on the laser beam quality, the far-fields are measured (see Figure 2c). After lens etching, the average divergence angle at 1/e² intensity is narrowed by 1.9° (29%). Finally, the M²-factors at different currents are obtained. An average improvement of 0.4 (15%) is recorded. At 1.8A, the near-field width waist at 1/e² intensity is increased from 44μm to 54μm, the far-field divergence at 1/e² intensity is decreased from 5.2° to 3.2° and the M²-factor improved from 3.2 to 2.4.

4. Conclusions

In summary, an integrated 10th order Fresnel lens capable of improving the laser beam quality is successfully demonstrated. Overall far-field divergence reduction of 1.9° (29%) and M²-factor improvement of 0.4 (15%) are recorded. A negligible average reduction of 5μm (3.5%) in near-field width at 1/e² intensity is also record.

The output power does not change as a result of the etch and so the effect of the absorption of the unpumped lens area is negligible. Furthermore, it is also noted that there is no compromise in the slope efficiency for implementing the 10th order Fresnel lens, whereas a reduction in slope efficiency is observed for the case of conventional (0th order) lens. This effect can be attributed to the premature compensation of the curved wavefront for the case of the 0th order lens. In which the utilisation of available gain within the laser cavity is reduced, thereby reducing the output power. Since the 0th order lens needed to be etched close to the taper/ridge interface, a step reduction in the near-field width at the facet is manifest. This is once again due to the premature equalisation of the curved wavefront, causing the reduction in the diffraction of lightwave that is supposed to take place within the tapered laser cavity. On the other hand, no significant effect is observed for the 10th order Fresnel lens etched close to the front facet of the laser, which is highly desirable. This shows that there is no compromise between equalizing the curved wavefront close to the output facet and the risk of catastrophic optical mirror damage.

5. Acknowledgment

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