Lateral mode engineering in diode lasers based on coupled ridges

A S Payusov1, A A Serin1, Yu M Shernyakov1, D A Rybalko1,2, M M Kulagina1, M V Maximov2, N Yu Gordeev1

1Ioffe Institute, 26 Polytechnicheskaya, St Petersburg 194021, Russia
2St. Petersburg Academic University, 8/3 Khlopina, St Petersburg 194021, Russia

Abstract. We present an experimental study on the edge-emitting lasers based on coupled ridges. The main idea of these structures is to ensure fundamental mode lasing in broadened multi-mode ridges by means of using a high-order mode filtering based on the resonant optical tunneling into a nearby passive stripe. For our experiments, we used a conventional InAs/InGaAs quantum dot (QD) laser wafer (λ~1.28μm) and placed a 3 μm passive dielectric-covered ridge at the distance of 4 μm from 10 μm main active ridge. The devices demonstrated stable far-field patterns with suppressed first-order mode lasing and without any deterioration of the main laser parameters. However, side lobes in the far-field patterns indicated second-order mode traces attributed to the current spread from the main stripe, which increase the effective stripe width. We assume that optimization of the laser wafer and etching technique may lead to a pure lateral single-mode lasing in the coupled ridge devices.

1. Introduction

Today spatial single-mode edge-emitting lasers with increased optical power are essential for various applications requiring high quality output beam. Often the maximal optical power is limited by the active region volume, which depends on the laser ridge width. Therefore, increasing optical power in conventional ridge-waveguide laser diodes requires the waveguide broadening in the lateral direction, which, in its turn, usually leads to multi-mode lasing and poor beam quality. A number of approaches have been developed to improve the beam quality of lasers with broadened ridge waveguides. Among them are tapered waveguides [1] and external cavities [2]. However, each approach has some drawbacks. For example, lateral far-fields of tapered lasers are quite unstable against current and temperature changes, external cavities are sensitive to adjustment and usually require additional optical components besides diffraction gratings. Hence, approaches allowing expanding ridge waveguide up to 10-20 μm ensuring fundamental mode lasing are still desired.

Recently a new approach of transverse mode engineering has been proposed. This approach utilizes coupled large optical cavity (CLOC) structures for effective suppression of high-order transverse...
modes in edge-emitting lasers with broadened waveguides [3]. The waveguide of the CLOC laser consists of a single-mode narrow passive waveguide optically coupled to a broadened active multi-mode waveguide. A high-order vertical mode of the broad active waveguide is suppressed due to the resonant tunneling into a coupled single mode passive waveguide. The idea can be modified for increasing the width of the lateral single-mode waveguide. However, practical implementation of the proposed design is not so trivial since the difference in the effective refractive index for the lateral modes is much smaller than for the vertical ones. In this paper, we present an experimental study on the edge-emitting lasers based on two laterally coupled ridges.

2. Experiment details and results

In order to determine optimal parameters for coupled ridge waveguide i.e. the distance between stripes and the etch depth, we carried on etch tests and numerical simulations with the FIMMWAVE mode solver. The aim of the etch tests was to find out the ridge sidewall profiles and their dependence on the ridge width. Then we allowed for the real ridge profiles in our simulations. Figure 1a shows the simulated intensity profile for the first-order mode of the broadened 10 μm laser stripe. When we put the single-mode ridge at a distance sufficient for optical coupling, the first-order mode of the broad ridge and the fundamental mode of the narrow ridge form two composite modes (figure 1b). One can see that the intensity redistributes between the two ridges. Thus, a 2D optical confinement factor for the high-order mode is reduced in favor to the fundamental mode of the broad ridge. Electrical isolation of the additional passive ridge introduces an extra optical loss to the high-order mode. As a result, the width of single-mode stripe could be increased approximately by a factor of two (e.g. from 4 μm to 10 μm as shown in fig. 1).

![Figure 1 Simulated intensity profiles for the first-order mode of the 10 μm single ridge (a) and the composite mode of the coupled ridges (b). Vertical and horizontal scales are different.](image)

The laser wafer under study was grown by molecular beam epitaxy. Ten layers of InAs quantum dots capped with InGaAs and separated by 35 nm GaAs were sandwiched between 1.5 μm Al_{0.35}Ga_{0.65}As claddings. The wafer was processed into shallow mesa ridge-waveguide lasers using standard photolithography. The stripes were formed with the reactive-ion etching through the p-contact and p-cladding layers. Two laser types were processed: reference 10 μm single-ridge samples and coupled-ridge lasers having the 10 μm active ridge and 3.5 μm passive ridge separated with a 4 μm-width trench (figure 2). Additional dielectric layer was deposited onto the passive ridge. All studied devices were mounted on copper heatsinks using indium solder in order to minimize overheating in continuous wave (cw) regime and improve current spread.

We have not found any significant differences in the basic parameters of both single-ridge and coupled-ridge devices. The 2 mm long lasers showed the threshold current density of 100 A/cm² and the lasing wavelength of 1.26 μm in cw regime, which corresponds to the lasing via the QD ground
state. Plotting reciprocal differential quantum efficiency versus cavity length yielded the internal quantum efficiency of 77% and the internal loss of 2.8 cm⁻¹.

![SEM image of the facet of the double ridge waveguide](image)

Figure 2. SEM image of the facet of the double ridge waveguide

In order to confirm the elimination of the first-order mode lasing in the coupled-ridge devices we studied far-field patterns of both reference and coupled-ridge devices. The results are shown in figure 3. Single 10 μm-width stripes demonstrate pronounced lateral multimode lasing (figure 3a) while the similar stripes possessing adjoined passive waveguide show one dominant lobe in the lateral far-field patterns (figure 3b). Its divergence of 4.5 deg. FWHM corresponds well to the simulated value for fundamental mode of the 10 μm-width waveguide. However, side lobes in the far-field pattern of the coupled-ridge device indicate traces of second-order mode lasing. We explain this effect by the current spreading from the main stripe into the additional stripe through the unetched highly doped p-cladding between the ridges. This current spreading increases effective stripe width and provides conditions for the second-order mode lasing. We assume that optimization of the laser heterostructure and the etching technique may lead to a pure lateral single-mode lasing in the coupled-ridge devices. In fact, two passive stripes can be located side by side with the active stripe, so further increasing of the laser stripe is feasible.

![Far-field patterns of the single ridge (a) and coupled-ridge (b) lasers measured in pulsed regime. The length of the devices were 2 and 2.2 mm respectively](image)

Figure 3. Far-field patterns of the single ridge (a) and coupled-ridge (b) lasers measured in pulsed regime. The length of the devices were 2 and 2.2 mm respectively
3. Conclusion
In conclusion, using a novel approach for lateral mode engineering we were able to modify far-field patterns of the conventional InAs/InGaAs QD lasers with coupled ridges without noticeable deterioration of the device performance. We assume that optimization of the laser heterostructure and etching technique may lead to a pure lateral single-mode lasing in the coupled ridge devices having higher optical power.

Acknowledgments
This work was supported by the Russian Science Foundation (project No 17-72-10060).

References
[1] Sumpf B et al 2008 Proc. SPIE 68760M
[2] Glebov L 2017 Proc. SPIE 1012319
[3] Gordeev N Yu et al 2015 Opt. Lett. 40 2150