Lateral mode behaviour in diode lasers based on coupled ridges

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Abstract. We present a study of diode lasers with two identical optically coupled ridges. Two coupled ridges were made gradually divergent to a distance of 50 μm which allowed creating three electrically isolated sections within a single laser. We carried out numerical simulations of the electromagnetic modes in the coupled ridge waveguide and calculated far-field patterns for each mode. The results are in good agreement with the experimental data. We have found that current spreading provided unwanted optical gain in the active region in between ridges and dramatically changed the structure of the lasing modes. The obtained numerical and experimental results can be used to design twin-ridge diode lasers able to operate in mode-locking regimes.

1. Introduction

Coupled-ridge semiconductor lasers offer many interesting effects for studying such as optical bistability, chaotic mode behavior [1], mode selectivity [2] and the modulation rates higher than relaxation oscillation frequency [3,4]. Some of these effects have been successfully utilized to improve device characteristics. For example, phase-locked arrays of the optically coupled ridges allow increasing output optical power in a spatially single-mode regime due to the broadened lateral waveguide [5]. In twin-ridge lasers, each ridge is designed as a single-mode one. Single-mode lasers having two electrically isolated sections (gain section and absorber) and operating in a mode-locking regime are used to produce trains of short light pulses [6]. The pulse parameters (repetition frequency, duration) are defined by the laser cavity. In the case of two laterally coupled mode-locked lasers, chaotic mode hopping can be expected without external modulation, in contrast with twin-ridge lasers [1] However, the absorber sections should be placed at a distance larger than 15 μm [1] to provide their independent biasing and to suppress their coupling. This can be achieved with fabricating gradually diverging ridges. Our work was aimed to fabricate and characterize a prototype of twin-ridge diode lasers able to operate in mode-locking regimes.
2. Experiment details

The laser heterostructure was grown on a GaAs (100) substrate misoriented on 6° toward (111) using a metal-organic vapor phase epitaxy (MOVPE). The active region contains 4 layers of quantum well dots (QWDs) each of those was formed by the deposition of 8 monolayers (ML) of In$_{0.4}$Ga$_{0.6}$As [7]. The QWD layers were separated with 40 nm thick GaAs layers and placed in the center of the 400 nm thick GaAs waveguide. The waveguide was sandwiched between 1 μm and 1.4 μm Al$_{0.25}$Ga$_{0.75}$As p- and n-claddings respectively.

Twin-ridge waveguides (each 5.6 μm wide) were formed by plasma etching. The distance between the ridges was 4 μm (fig. 1b). The residual p-cladding thickness outside the ridges was 200 nm and 400 nm in between. This difference occurred due to the lower etching rate between the ridges, which commonly occurs during the plasma etching process. In order to enable the lasers to operate in mode-locking regimes the ridges were made gradually divergent to a distance of 50 μm (fig 1a, c) and these parts of the ridges were made electrically isolated from each other (see labels on fig 1c). The cavity length of all investigated lasers was about 2 mm and the length of the section where two ridges are more than 4 μm from each other was 200-300 μm depending on the sample. No facet coatings were used.

Laser diodes were mounted p-side up onto the copper heat-sinks using indium solder. Several gold wires were bonded to lasers to provide electrical contact. All measurements were carried out in a pulsed regime (duration of 300 ns, rate of 7 kHz).

Figure 1. SEM images of the rear (a) and the front (b) facets of the laser, (c) is a top view of the laser diode. 1, 2 and 3 indicate areas electrically isolated from each other, but in our experiments, all these were pumped all together.

To identify the optical modes, on which the coupled ridge waveguides operate, TE mode electrical fields were simulated. 2D numerical simulation was carried out with MIT Photonic Bands (MPB) software package. It computes the eigenstates of Maxwell's equations in dielectric structures using block-iterative frequency-domain methods [8]. To simplify the numerical simulations, we considered the infinitely long structure with parallel ridges. Current and temperature-induced changes in dielectric function were omitted.

Far-field patterns have been calculated for each optical mode and then were compared with our experimental results. Far-fields were measured using a standard setup consisted of two rotation stages and a photodiode placed at 50 cm from the pivot point. “Zero” angle corresponds to the position where the normal of the laser facet is pointed at the photodiode.
3. Results and discussion

Our twin-ridge lasers demonstrated higher threshold current densities than broad-area lasers processed from the same wafer (fig. 2) mainly due to two reasons. First, the contribution of current spreading in shallow-mesa narrow-ridge lasers is stronger compared to broad area devices [9]. Second, some additional optical loss is introduced at the ridge curves.

Light-current characteristics of all tested devices have kink in the current range of 0.2-0.4 A (fig. 2). Spectral measurements revealed that lasing wavelength non-monotonously shifts within the same current range (inset in fig. 2) indicating the multi-mode lasing. Far-field measurements confirmed that devices operate in a multi-mode regime at all pump currents (fig. 3).

![Figure 2](image1.png)  ![Figure 3](image2.png)

Figure 2. Light-current characteristic of the twin-ridge laser. The inset shows lasing spectra and arrows indicating the pump current for each spectrum.

Figure 3. Lateral far-fields of the twin-ridge laser measured at different currents.

The numerical simulation shows that the difference in the etching depth affects the composite modes of the coupled ridges (fig. 4). Along with the modes formed from the eigenmodes of each ridge such as TE\(_{00}\) and TE\(_{01}\), several modes that have significant field intensity in between ridges occur, namely TE\(_{02}\) and TE\(_{04}\).

One can see that calculated far-fields are in good agreement with the experimental data (fig. 5). From the comparison shown in figure 5, we can conclude that at low pump currents the laser operates on at three modes TE\(_{00}\), TE\(_{02}\) and TE\(_{04}\). This is an unexpected result since TE\(_{02}\) and TE\(_{04}\) modes have higher optical loss resulting from the significant intensity in the unpumped region. As the current increases, the in-phase mode TE\(_{00}\) vanishes and out-of-phase mode TE\(_{01}\) emerges. Then the laser steadily operates on TE\(_{01}\), TE\(_{02}\) and TE\(_{04}\) modes. This mode hopping causes the kink in the light-current characteristic. We believe that the current spreading provided unwanted optical gain in the active region in between ridges and dramatically changed the composition of the lasing modes.

In conclusion, we have fabricated and studied both numerically and experimentally diode lasers with two optically coupled ridges. Two coupled ridges were made gradually divergent to a distance of 50 \(\mu\)m to make the devices suitable for mode-locking operation. The obtained numerical results are in good agreement with the experimental data and have shown that the curved ridges have little effect on the mode structure. In contrast, the current spreading has a dramatic effect on the mode structure of the coupled ridge lasers. This fact need to be taken into account while designing coupled ridge waveguides.
Figure 4. The 2D pattern of the electric field amplitude for the first six TE modes existing in the coupled waveguide. Red and blue colours denote positive and negative signs respectively.

Figure 5. Simulated (bottom six) and measured (top three) far-field profiles of the twin-ridge lasers.

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