Investigation of lasers based on coupled waveguides by near-field scanning optical microscopy

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Abstract. We have investigated near field intensity distributions of InGaAs/GaAs/AlGaAs lasers possessing broadened waveguides based on coupled large optical cavity structures (CLOC) by scanning near-field optical microscopy (SNOM). The concept allows effective suppressing of the transverse high-order mode lasing. The obtained results can be considered to be the direct proof of pure transverse single-mode emission of the CLOC lasers.

1. Introduction

Many important applications of power semiconductor lasers, such as spectroscopy, frequency converting, surgery, optical pumping sources for solid state lasers or for fiber lasers, require the high optical emission power and the high beam quality[1]-[4]. One of the essential problems limiting the maximum output power of semiconductor lasers is the catastrophic optical mirror damage (COMD). An effective method of reducing the optical power density is an expansion of the efficient mode size in the transverse and lateral directions. It can be reached by simple increasing of the corresponding geometric waveguide size. However, this expansion induces spatial multimode lasing spoiling the far-field patterns and beam quality. Thus a waveguide should be designed in such a way that its thickness does not exceed the boundary condition for high order modes or high order modes are suppressed by gain or loss engineering. The increase of the losses for high order modes is reached by the increase of their overlap with absorbing laser structure layers. The gain selectivity means the adjustment of the active region position so that only the fundamental mode has the high optical confinement factor.

There are many methods of the mode size expansion in the transverse direction. Among them are broadening vertical waveguides based on the photonic crystal [6], super large cavity designs [7], and tapered ridge waveguides [8, 9]. A simple and efficient method of the high order mode suppression was proposed in our recent work [10]. The idea of this approach utilizes resonance coupling in two parallel waveguides with a small distance between them. The waveguides of such lasers are complex and consist of a narrow passive waveguide and broadened waveguide with an active region inside. The effective refractive indices of the eigenmodes of each waveguide have close or equal values to satisfy the phase-matching condition. So the high order mode of the broadened waveguide and the mode of the narrow waveguide are converted into two composite modes (Figure 1) due to the resonance coupling, whereas the fundamental mode of active waveguide does not tunnel into the narrow waveguide. The initial mode intensity is redistributed between the two waveguides and the fundamental mode remains the only lasing mode, thus, the composite modes do not take part in the lasing due to the reduced optical confinement factor (OCF) and increased optical losses resulted from the free-carrier adsorption in the highly doped layers.
Figure 1. Refractive index profile and simulated intensity distributions of the fundamental (red line), second-order (blue line) and one composite (magenta line) modes for the reference (a) and CLOC (b) lasers.

Accurate and unambiguous information on the laser optical modes can be extracted from the near-field radiation distributions measured directly on the surface of the emitting facet of lasers [12,13] by near-field scanning optical microscopy (SNOM). In this paper, we report on the study of the spatial emission properties of the CLOC and reference lasers investigated by SNOM with the resolution of 100 nm.

2. Experiment and discussion
Both the reference and CLOC laser wafers emitting at the wavelength $\lambda \approx 1.04 \, \mu m$ were grown by metal-organic chemical vapor deposition (MOCVD) on n-GaAs (100) substrates. The laser structures are much the same as ones investigated earlier [10]. The active GaAs waveguides of the both structures have the thickness of 2.5 $\mu m$, just below the cut-off of the fourth-order transverse mode. The CLOC laser structure has an extra 625-nm-thick n-GaAs passive waveguide separated from the active waveguide with 250-nm-thick n-Al$_{0.15}$Ga$_{0.85}$As optical barrier. Both wafers were processed into 50-$\mu m$ stripe lasers. The samples were mounted p-side down on copper heatsinks. Both the CLOC and reference lasers showed the parameters very close to the reported earlier [10].

The near-field intensity distributions at the emitting facet formed after cleaving of the laser wafers, were measured with sub-wavelength spatial resolution using an optical spectrometer (spectral resolution 0.46 nm) integrated with SNOM with an aperture cantilever. In the SNOM regime, we used cantilevers with metal coated pyramidal SiO$_2$ probes. The aperture of 100 nm was created on the probe ends with the focused ion beam process. Such cantilevers can also be used simultaneously for surface topography imaging with standard atomic force microscopy (AFM) techniques. The radiation penetrating through the nanoperture was collected with a lens with $NA = 0.5$.

Near-field distribution maps were measured at different currents. At all the excitation levels, the CLOC lasers showed stable single-mode emission. Intensity distributions of the near field patterns of the reference and CLOC lasers measured in pulsed mode at the drive current of 1A are presented in Figure 2. Figures 2a and 2b demonstrate intensity distributions for the reference and CLOC lasers, respectively, in the whole spectrum. The intensity distribution map of the reference laser has a complex pattern manifesting high order mode lasing both in the vertical and lateral directions.
The intensity distribution map for the CLOC laser has pure transverse single-mode pattern but multi-mode pattern in the lateral direction. The vertical profiles of the intensity distributions are shown in Figure 3. Red lines show simulated intensity distributions of the second-order and fundamental modes for the reference and CLOC lasers, respectively. The measured profiles of the CLOC and reference laser modes are very close to the simulated ones. This fact indicates that the experiment and calculation are in good agreement.

**Figure 2.** Near-field intensity distribution maps of the reference and CLOC lasers at the current of 1A. White dashed line shows waveguide edges.

**Figure 3.** Vertical intensity distribution profiles for the reference and CLOC lasers at the current of 1A. Blue dashed line shows waveguide edges.
3. Conclusions
To conclude, for the first time we have investigated near field intensity distributions of InGaAs/GaAs/AlGaAs lasers based on coupled large optical cavity structures by scanning near-field optical microscopy. We have directly proved pure transverse single-mode lasing having compared the CLOC and reference lasers. The obtained results confirm that the lasers based on Coupled Large Optical Cavities can be the promising for many applications due to their simple design and good beam quality.

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