Novel concepts for designing semiconductor lasers

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Abstract. We review novel concepts and demonstrate recent experimental data for edge-emitting semiconductor lasers with broad vertical waveguide. The ultimate case for waveguide extension in the vertical direction can be implemented by using the Tilted Wave Laser (TWL) approach. A TWL is composed of a thin active waveguide (typically 0.3-2 µm) optically coupled to a thick passive waveguide (10-150 µm). A TWL with a 26 µm-thick passive waveguide demonstrated low internal loss of 1.4 cm⁻¹, maximum pulsed power 18 W and maximum CW power 4.7 W. Vertical far field of the TWL consists of two tilted narrow lobs of 2 degrees full width at half maximum each.

1. Introduction

Development of single mode edge-emitting lasers with ultra thick and ultra broad waveguide is very important to achieve higher powers from one chip before reaching catastrophic optical mirror damage (COMD) level, reduce thermal effects and optical nonlinearities, facilitate coupling into optical fibers and simplify designs of various external-cavity systems [1, 2]. A number of different approaches for waveguide engineering have been proposed to extend the lasing mode and reduce beam divergence in edge emitting lasers [3-8]. Figure 1 represents schematically the main concepts of the laser diodes with ultra-thick vertical waveguides.

Large optical cavity laser in the frame of conventional approach is shown in Fig. 1(a). Small refractive index step between the cavity and cladding layers allows selection of the fundamental vertical optical mode. A moderately asymmetric positioning of the active region off-center in the cavity may improve the vertical mode discrimination by suppressing lasing of the high order optical modes with n=3, 5,…. Optical losses less than 0.4 cm⁻¹ were reported for thick undoped waveguide laser diodes with vertical beam divergence 30° FWHM [3]. Once significantly lower beam divergence is targeted (8° FWHM was achieved in the off–centre gain approach [5]), a large part of the optical cavity above the active region must be p–doped. Then a significant part of the optical wave is located in the p–doped region which implies higher modal losses due to free carrier absorption.

An alternative concept [5, 6] employs lasers based on vertical photonic band crystals – a periodic sequence of high and low refraction index layers (Fig. 1(b)). The active region is placed asymmetrically, and only a small part of the waveguiding structure is p–doped. All vertical optical modes have different profiles in the vertical direction and the n–doped photonic band crystal provides the selection of these modes. The proper configuring of the photonic band crystal (PBC) gives...
Figure 1. Schematic view of edge-emitting diode lasers with thick vertical waveguides and corresponding far field patterns: (a) large optical cavity laser, (b) laser based on a vertical photonic band crystal, (c) tilted wave laser.

preference for the fundamental vertical optical mode and discriminates high-order vertical optical modes by decreasing their optical confinement factor and/or increasing the leakage losses to the substrate. The narrow vertical beam of 5° FWHM was reached in this approach [6] while the field intensity was by far concentrated in the n-doped all-epitaxial PBC waveguide.

The ultimate case for waveguide extension in the vertical direction can be implemented by using the Tilted Wave Laser (TWL) approach [7] exploited in the present work. TWLs are based on a thin active waveguide containing quantum wells or quantum dots and an optically coupled thick passive waveguide. The lasing optical modes in the coupled waveguides are formed due to the leakage of a part of light from the active waveguide, its propagation through the thick passive waveguide in a form of a tilted wave, its return back to the active waveguide, and interference with the light amplified in the active medium. If a transparent substrate is employed as a passive waveguide, its thickness may be as high as 130 µm. The 130 µm–thick substrate–based TWLs [8] demonstrated diffraction limited
vertical lobes as narrow as 0.65 degree full width at half maximum (FWHM). The disadvantage of this approach, however, is the need to use wafer backside polishing in combination with two-sided processing to fabricate low loss dielectric mirrors on the substrate side. In this paper we present recent results on high power TWL laser with 26 µm-thick epitaxial waveguide.

2. Experiment
The laser epi-structure was grown by MOCVD on GaAs substrate at low pressure by using the laboratory installation with horizontal reactor. The active region contained four compressively strained InGaAs QWs with the photoluminescence maximum at room temperature around 1040 nm. No strain compensation layers were used. Separation between neighbouring QWs was 70 nm to prevent defect formation. The thickness of the GaAs active waveguide was 700 nm. The thickness of the passive waveguide was 26 µm and its doping level was 1·10^17 cm^-3. The thickness of the intermediate cladding layer between the thin active and the thick passive waveguides was chosen as 110 nm.

The grown wafer was processed into 50 µm-wide broad area lasers, cleaved to bars, and then separated to single chips. The chips were mounted p-side down on copper heat-sinks using indium solder. The devices were characterized in pulsed (300 ns, 1 kHz) and continuous-wave (CW) modes.

3. Results
Figure 2a shows the dependence of threshold current density and lasing wavelength on the cavity length. For a 2 mm long cavity, the threshold current density is about 500 A/cm^2 (125 A/cm^2 per one QW layer). The lasing wavelength is 1039 nm. For the shortest cavity studied (400 µm), the threshold current density is 1300 A/cm^2 and the lasing wavelength is 1030 nm.

Fig. 2b shows the dependence of the reciprocal differential quantum efficiency (1/\( \eta_{\text{Diff}} \)) on the cavity length. Using the well-known equation \( \eta_{\text{Diff}} = \eta_i \alpha_m / (\alpha_m + \alpha_i) \) we derived the internal differential quantum efficiency \( \eta_i \) and internal loss \( \alpha_i \) which are equal to 97% and 1.4 cm^-1, respectively. Taking into account the large thickness of the doped passive waveguide the internal loss is sufficiently small. As a result, the differential efficiency for a 1.5 mm long device is as high as 81%.
The light-current characteristics were studied in pulsed and CW modes at room temperature. For 1.5 mm long and 50 µm–wide broad area devices, the maximum pulsed power is about 18 W limited by available current source. CW power exceeds 4.7 W without noticeable thermal roll-over (Fig. 3). This value is likely limited by our laboratory technology of laser mounting on heat sinks. The lasing wavelength is about 1035 nm.

The vertical far field pattern of TWLs consists of two tilted narrow beams and angularly broad emission between them (Fig. 4), which originates from a fraction of the light confined in the narrow waveguide. The FWHM of the lobes is 2°, which corresponds very well to the results of our simulations. No shift and broadening of the vertical lobes were observed up to the high injection current densities. The double–lobed emission pattern may be advantageous for certain applications. For example, one lobe can be used for wavelength stabilization or tuning, whereas the other one for light outcoupling. Such external cavity design will reduce parasitic interference effects characteristic to single-lobe based external resonators. In another approach, the tilted beams may be used for the vertical coupling of different laser bars into a coherent laser stack.
4. Conclusions
Novel device designs to achieve high performance lasing applying ultra-thick waveguides are described. The thickest vertical waveguides (up to 130 \( \mu \)) can be implemented by using Tilted Wave Laser concept. Broad-area Tilted Wave Lasers with very thick waveguide (26 \( \mu \)) show low internal loss of 1.4 cm\(^{-1}\) and high differential efficiency of 81% for a 1.5 mm long cavity with as-cleaved facets. The maximum pulsed power is about 18 W and maximal CW power exceeds 4.7 W. The lasers operate on a high-order single vertical mode and most of the output power is concentrated in two narrow vertical beams, each 2\(^\circ\) FWHM in a good agreement with the theory. One of the lobes can be used for wavelength stabilization/tuning or for coherent coupling of individual devices into arrays. A very large spot size and single vertical mode operation makes TWLs particular promising candidate for applications in external cavity systems.

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