Radiative characteristics of semiconductor injection lasers based on narrow asymmetric waveguides

S D Chervinskii\textsuperscript{1,4}, B S Ryvkin\textsuperscript{2}, Yu M Shernyakov\textsuperscript{2,3}, A S Payusov\textsuperscript{2,3}, N Yu Gordeev\textsuperscript{2,3}

\textsuperscript{1} St.Petersburg State Polytechnical University, Polytekhnicheskaya 29, 195251, St.Petersburg, Russia
\textsuperscript{2} Ioffe Physical-Technical Institute, Polytekhnicheskaya 26, 194021, St.Petersburg, Russia
\textsuperscript{3} St.Petersburg Academic University - Nanotechnology Research and Education Centre, Khlopina 8/3, 194021, St. Petersburg, Russia

E-mail: semen.chervinsky@gmail.com

Abstract. Quantum well InGaAs/GaAs lasers based on narrow asymmetric waveguide were created and investigated in pulse and CW modes. Broad-area 50\textmu m stripe lasers showed internal quantum efficiency as high as 95\%, threshold current density as low as 160 A/cm\textsuperscript{2}. Wall-plug efficiency in CW mode reached the value of 75\%. The obtained parameters make the concept of narrow asymmetric waveguide promising for high-power laser diodes.

1. Introduction
High-power semiconductor lasers are widely used for pumping active medium, in material processing, in medical, and in a number of other applications. Combination of high optical power and good laser beam quality is essential for all these applications. In the recent years the most used concept for obtaining high optical power was one based on broadened waveguides [1-3]. However, at very high injection current densities these lasers faced significant limitations due to carrier accumulation in the waveguide layer. Recently E. Avrutin and B. Ryvkin proposed new laser waveguide design to overcome these limitations [4]. For these lasers based on narrow asymmetric waveguide (NAW) it was analytically shown that they can have smaller free-carrier absorption losses at very high injection current densities with no degradation of other main parameters [5].

Key feature of the lasers based on narrow asymmetric waveguide design is remarkably different refractive indices of \textit{p}- and \textit{n}-claddings. Thus, only fundamental mode exists in the waveguide, asymmetry of the waveguide caused asymmetric field penetration in \textit{p}- and \textit{n}-claddings (figure 1). Whereas free-carrier absorption coefficient in \textit{p}-cladding sufficiently exceeds that one in \textit{n}-cladding, the value of internal losses consequently decreased. Carrier accumulation in the NAW and corresponding optical losses are small. Moreover, noticeable field penetration in \textit{n}-cladding results in a spot size comparable to those of broadened waveguides [6].
2. Laser diode design

Laser waveguide profile and simulated optical mode intensity profile are shown in figure 1. The laser wafers were grown by metal-organic chemical vapour deposition (MOCVD). Asymmetric waveguide is formed by 5.0 μm-thick Al$_{0.1}$Ga$_{0.9}$As $n$-cladding (graded doping 0.2-2×10$^{18}$cm$^{-3}$) and 1.0 μm-thick Al$_{0.6}$Ga$_{0.4}$As p-cladding (graded doping 0.5-2×10$^{18}$cm$^{-3}$) with 0.5 μm-thick GaAs in between. Active region contains one 90 Å-thick InGaAs quantum well (emitting wavelength 1060nm). The laser wafer was processed into lasers with 50 μm stripe width and cavity length of 0.5-2mm. No facet coatings were used. The laser samples were mounted $p$-side down on cooper heatsinks using indium solder.

3. Laser diode characteristics

The laser samples were measured both in pulsed and CW modes at 25°C. The lasers showed threshold current density as low as 160 A/cm$^2$. The lasing wavelength at room temperature varies in the range of 1050-1070 nm depending on the cavity length and the pump current. Resistivity of lasers based on narrow asymmetric waveguide was equal to 4.6-6.0×10$^{-5}$Ω·cm$^2$. Differential quantum efficiency reached the value of 92%. Internal losses and internal quantum efficiency were calculated in a common way from a set of light-current curves measured for lasers with different cavity lengths. The lasers showed internal quantum efficiency as high as 95% and intrinsic losses as low as 2.5 cm$^{-1}$.

Laser beam divergence in vertical direction was as large as 35-40 deg. FWHM, which corresponds to the value obtained in the waveguide numerical simulation. The concept of narrow asymmetric waveguide is very promising for decreasing the beam divergence as it allows designing the optical mode profile. Our calculations shows that with 0.4 μm-thick GaAs waveguide layer laser beam divergence in vertical direction will be only ~25 deg. FWHM. Large internal quantum efficiency allowed obtaining very high values of CW wall-plug efficiency which is defined as the optical power out relative to the electrical power in. The last one is the product of the drive current and the total voltage across the laser terminals. Wall-plug efficiency for the best laser sample was as large as 75 % (figure 2) at the pumping current of 1.3 A (corresponding output optical power ~ 1.2W).

Figure 1. Refractive index and transverse optical mode profile for lasers based on narrow asymmetric waveguide.
Figure 2. Optical power, voltage, and wall-plug efficiency vs. drive current for the laser based on narrow asymmetric waveguide with the cavity length of 1.4 mm.

4. Conclusion
Lasers based on narrow asymmetric waveguide were experimentally tested and showed good radiative characteristics corresponding with analytically predicted ones. The concept can be very effective to reduce the vertical beam divergence.

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