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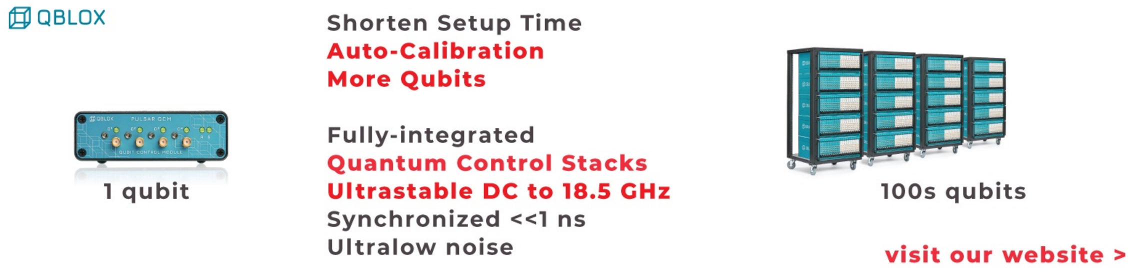

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Ultrahigh-brightness 850 nm GaAs/AlGaAs photonic crystal laser diodes

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One-dimensional photonic crystal lasers emitting in the 850 nm range show high internal quantum efficiencies of 93% and very narrow vertical beam divergence of 7.1° (full width at half maximum). 50 μm broad area lasers with unpassivated facets exhibit a high total output power of nearly 20 W in pulsed mode with a divergence of $9.5° \times 11.3°$ leading to a record brightness of 3×10^8 W cm^{-2} sr^{-1}, being presently the best value ever reported for a single broad area laser diode. 100 μm broad devices with unpassivated facets show continuous wave operation with an output power of 1.9 W. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3040322]

Energy efficient high power near-infrared laser diodes are indispensable as pump sources for solid state lasers, erbium-doped fiber amplifiers, and promising for welding, cutting, and drilling.[1–4] For any of these applications beam brightness is at least as important as output power. Direct application of high power laser diodes in welding, cutting, and drilling may become only possible when ultrahigh brightness is realized. Pulsed operation is advantageous for those applications where maximum peak power is decisive, such as upconversion. Design concepts presently used for the majority of semiconductor lasers found in consumer, data and telecommunication systems are not well suited for high brightness/power devices. Thus a lot of effort is presently put into development of laser concepts. Several approaches such as aluminum free laser structures, lasers with tapered gain sections, and broad waveguide structures are being followed.[5–8]

One important focus lies on expanding the vertical waveguide. This leads to an increase in the maximum single mode output power as well as to a reduction in the vertical far field and therefore results in higher brightness in single mode operation. In addition, low-cost optics can be used yielding high coupling efficiency. Previously, such attempts[9,10] based on the above concepts[5–8] resulted in a reduced vertical beam divergence down to 15°. A completely other type of waveguide structure for decreasing the vertical far field divergence was proposed recently by some of us.[11] Here an ultrabroad waveguide with layers having a periodically alternating refractive index is used to expand the optical mode spot size. The layers form a longitudinal photonic band crystal (PBC) with a deviation from the periodicity acting as an optical defect. The waveguide is designed in such a way that only the fundamental optical mode is localized at the defect and decays away from it, while all higher order modes expand over the entire waveguide and leak to or are absorbed by the substrate. Typically, the active gain region is positioned at the center of the optical defect, where the fundamental mode exhibits the optimum optical confinement while the high-order modes are more strongly damped. Experimental realizations of PBC-lasers showed already remarkable performance for single mode devices.[12–14]

In this letter we report on record breaking results of 840–850 nm range GaAs/AlGaAs multimode diode lasers based on a PBC waveguide, particularly suitable for high power applications. The layer structure was calculated using one-dimensional modeling. In addition to the fundamental mode, we calculated more than 20 higher-order modes and used the obtained losses and relative Γ-factors as mode-termination criteria. For the fundamental mode a confinement factor of 2% and leakage losses of 0.088 cm^{-1} were calculated. Each higher order mode has either severe leakage/absorption losses (up to 1100 cm^{-1}) or an extremely poor Γ-factor (as low as 0.0037%). We proved the robustness of the layout against uncertainties of the refractive indices, thickness tolerance, and alloy composition deviations. A deviation of 10% from the optimum parameters will not affect significantly the device performance. The laser structure was grown by metal-organic vapor phase epitaxy on 3 in. (001) GaAs substrates. It contains 4 GaAs quantum wells acting as the active region and 16 periods of $Al_{0.20}Ga_{0.80}As$/$Al_{0.35}Ga_{0.65}As$ layers representing the PBC used for filtering of higher order modes. The total thickness of the epitaxial structure is about 15 μm. X ray, photo- and electroluminescence, capacitance-voltage profiling, and optical and scanning electron microscopy were used to determine the quality of the grown structures in terms of composition, doping, thickness accuracy, and surface morphology.

The structure was processed into 100 μm wide broad area lasers for the analysis of general device characteristics. The deposited p-metallization was subsequently used as etching mask for the following wet etching. Only the highly doped upper layers were removed. Devices were cleaved into bars after substrate thinning and n-metallization. Neither facet protection nor soldering was used for the present measurements. Laser diodes with different cavity lengths were tested in pulsed mode using 800 ns pulses at 1 kHz repetition rate in order to determine maximum peak power. Another set of devices was processed being suitable for p-side down mounting. Here dry etching was utilized. Facet coatings with 99% high reflection (HR) at the rear facet and 5% antireflection (AR) coatings were deposited and devices were

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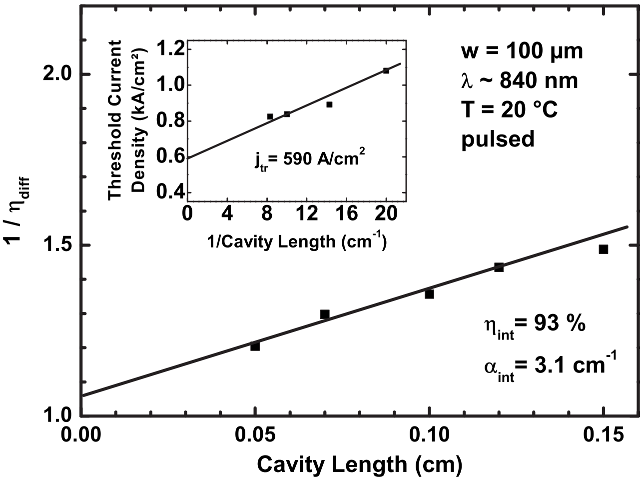

FIG. 1. Reciprocal differential efficiency against cavity length for 100 μm wide PBC lasers measured in pulsed mode at a heat sink temperature of 20 °C. The inset shows the corresponding threshold current density against inverse cavity length.

mounted on standard copper mounts. Those devices were tested under cw operation, although the mounting technique was not yet optimized.

The cavity length dependence of the measured reciprocal differential efficiency is presented in Fig. 1. From a linear extrapolation to zero length, a high internal differential efficiency η_{int} of 93% and low internal loss α_{int} of 3.1 cm^{-1} are determined. The corresponding linear fit of the threshold current versus the inverse cavity length is shown in the inset of Fig. 1. The deduced transparency current density j_{tr} is 590 A/cm^2.

The temperature dependence of the threshold current density for a 100 μm wide and 0.5 mm long device is shown in Fig. 2. A high characteristic temperature T_0 of 215 K was found within the temperature range of 0–25 °C. This value decreases to a still high value of 120 K within the temperature range of 25–80 °C. The emission spectrum at an injection current level of $I=3.5I_{\text{th}}$ is shown in the inset of Fig. 2. For all applied currents the emission wavelength is between 840 and 850 nm (not shown here).

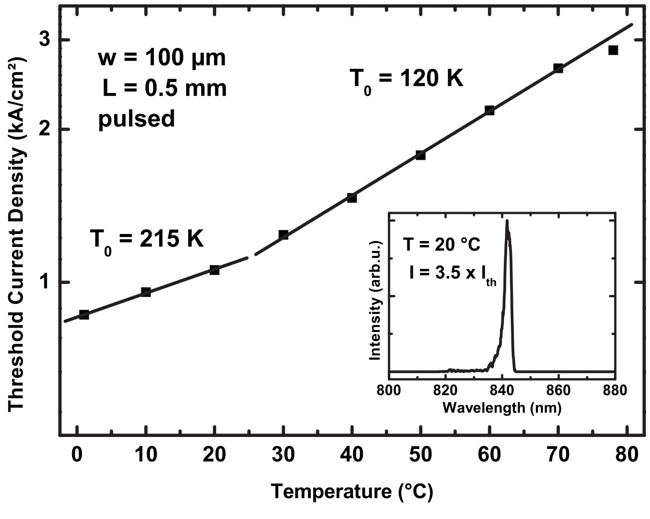

FIG. 2. Threshold current density for a 100 μm wide and 0.5 mm long stripe PBC laser measured in pulsed mode at different heat sink temperatures. The inset shows the electroluminescence spectrum at the drive current $I=3.5I_{\text{th}}$ for the corresponding laser measured at 20 °C in pulsed mode.

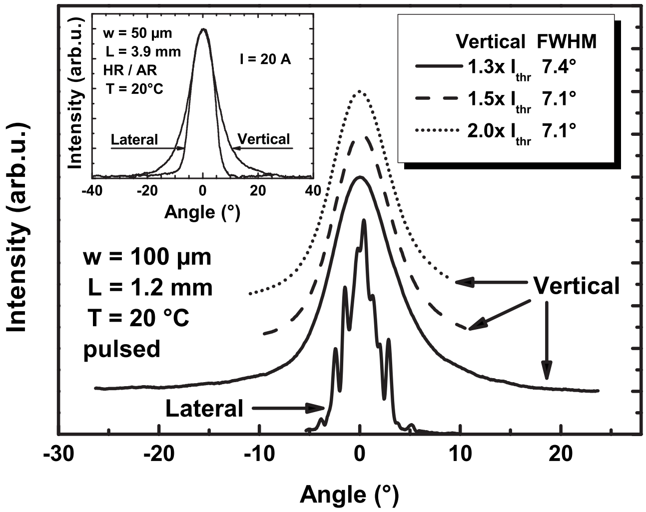

FIG. 3. Lateral and vertical far field patterns of a 100 μm wide and 1.2 mm long stripe laser under different pump currents. The inset shows the normalized lateral and vertical far field patterns at a drive current $I=20$ A for a 50 μm wide and 3.9 mm long stripe laser at 20 °C with HR/AR coatings.

Measurements of the vertical far fields of 100 μm broad area devices at various currents are presented in Fig. 3. The values vary between only 7.1° and 7.4° full width at half maximum (FWHM). We observed a single mode vertical far field with a clear Gaussian shape for all applied currents. In the lateral direction, we found a multimodal far field with a FWHM of 3.3°, as expected for such lasers. The width of separate modes was as narrow as 0.8° (FWHM), in agreement with the diffraction limit for a 100 μm wide aperture and indicating that no significant beam filamentation takes place. The inset in Fig. 3 shows the far field at a high output power for a 50 μm wide and 3.9 mm long device at 20 °C and a drive current of 20 A. The FWHM in the vertical and parallel directions to the *p*-*n* junction are 11.3° and 9.5°, respectively. The aspect ratio is 1:1.2. The intensity distribution in the vertical direction is still clear single mode Gaussian, whereas in the lateral direction the field distribution is multimodal without any beam filaments.

For measurements of the output power in pulsed mode, we used the *p*-side down mounted devices. The measured light current curve for a 50 μm wide and 1.3 mm long device at 20 °C is presented in Fig. 4. High differential efficiency of 71% and a maximum output power of about 20 W are achieved. The maximum output power is limited by catastrophic optical mirror damage (COMD), confirmed by scanning electron microscopy. We estimated the maximum power density at the front facet before COMD to be 13 MW/cm^2, which is in good agreement with earlier reports.[15] It is important to re-emphasize that yet no facet passivation was applied. The inset in Fig. 4 shows the measured light current curve from the front facet of a 100 μm wide and 4 mm long device under cw conditions at 20 °C. Here maximum cw power of 1.9 W is achieved. Higher output power is clearly limited by thermal effects since no optimization in mounting was done.

From these results we calculated a brightness of 3×10^8 W cm^{-2} sr^{-1}, being one of the highest value ever reported for single broad area semiconductor laser diodes.

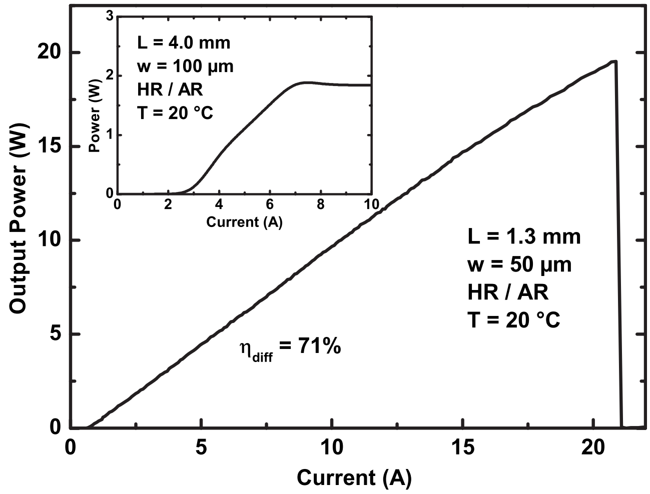

FIG. 4. Pulsed light-current curve for a 50 µm wide and 1.3 mm long stripe PBC laser at 20 °C with HR/AR coatings. The inset shows light-current dependence of a 100 µm wide and 4.0 mm long laser under cw operation.

Presently higher values can only be achieved by beam combining techniques.[16]

In summary, we have investigated 840–850 nm range PBC laser diodes with very narrow vertical beam emission ranging from 7.1° to 11.3°. The vertical far field pattern kept a clear Gaussian shape across the whole investigated current range. The structure showed high internal quantum efficiencies of 93% and low losses of 3.1 cm^{-1}. The highest pulsed optical output power of nearly 20 W was achieved with a 50 µm stripe, limited by COMD. A record brightness of $3\times10^{8}\ \mathrm{W\ cm}^{-2}\ \mathrm{sr}^{-1}$ is determined here. The highest obtained cw power was 1.9 W, limited by thermal effects. Our results lead us to conclude that 850 nm range laser diodes based on one-dimensional PBC structures are very promising for low cost high power and high brightness applications. We believe that facet-passivated devices and optimized mounting may deliver ultimate power in the pulsed mode and also substantial power in the cw regime.

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