14.3 W quasicontinuous wave front-facet power from broad-waveguide Al-free 970 nm diode lasers

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(Received 27 May 1997; accepted for publication 24 June 1997)

Wide-stripe, 0.97 μm emitting Al-free InGaAs(P)/InGaP/GaAs broad-waveguide separate confinement heterostructure quantum-well lasers demonstrate a record value for quasicontinuous wave (QCW) output power: 14.3 W (100-μm-wide stripe, 100 μs-wide pulses); and reach catastrophic optical mirror damage (COMD) in QCW operation at an optical power density of 22.5 MW/cm^2; that is, 40% higher than COMD levels in cw operation. The devices have low internal losses ($\alpha_i = 1$ cm^{-1}) and high external differential quantum efficiency (86% for 2-mm-long lasers), and exhibit only 10–20 °C temperature rises in the active region at 10 W QCW power. We also show that long-cavity, large-contact-area devices exhibit relatively little spectral broadening with increased output power. © *1997 American Institute of Physics.* [S0003-6951(97)01235-7]

Broad-waveguide separate confinement heterostructure quantum-well (BW-SCH-QW) diode lasers have shown high cw powers from Al-free 0.97 μm emitting devices[1] as well as from 1.5 μm emitting devices.[2] Low internal losses and very high external differential quantum efficiencies in BW-type lasers enable the use of 2- to 4-mm-long cavity devices, that have recently allowed the achievement of record-high cw powers for these wavelengths.[3,4] The quasicontinuous wave (QCW) regime for diode laser operation is important for solid-state laser and fiber laser pumping, as well as for many medical applications, since higher peak output powers are available in the QCW regime than in the cw regime. In the QCW operation the current-pulse duration (τ) is longer than the diode's thermal time constant, which is about 1 μs, so that the laser reaches its steady-state temperature near the beginning of the pulse. Therefore, the QCW regime is useful to investigate the laser's high-power behavior, since very high peak output powers can be obtained and overheating of the mount and laser itself can be discriminated by varying the current-pulse duration.

Here we demonstrate the achievement of record QCW power for $\lambda = 0.97$-μm-wide stripe (100 μm$\times$2 mm) lasers, using the BW structure shown in Fig. 1. The QCW result (100-μs-wide pulses) is 14.3 W, which is 80% higher than the best previously published result[5] for 100 μm stripe devices. We also show that 200 μm$\times$4 mm stripe devices have significantly reduced spectral broadening with increased output power compared with devices of smaller stripe area (100 μm$\times$2 mm).

The InGaAs(P)/InGaP/GaAs laser structure was grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) in an Aixtron A-200 system on nominally exact-oriented (100) GaAs substrates.[1] The structure consists of a 1.2-μm-wide InGaAsP ($E_g = 1.6$ eV) waveguide region, $In_{0.51}Ga_{0.49}P$ cladding layers, and a p^+ carbon-doped GaAs cap layer for low contact resistance. The lasing wavelength at 15 °C was 0.97 μm. Similar structures, for short-cavity length (i.e., 0.5 mm), have demonstrated record-high cw wallplug efficiency (66%) values,[6] due to low internal loss and the intrinsically lower series resistance of Al-free devices compared with that of Al-containing devices.

Fabry–Perot lasers with 100 and 200 μm stripe contacts, W, were fabricated by techniques described elsewhere.[1,3] Lasers with high-reflectivity (HR-95%) and anti-reflective coatings (AR=3%), having cavity lengths, L, of 2 or 4 mm, were mounted p side down onto copper submounts measuring $2\times11\times3$ mm^3. The submounts were bolted to water-cooled copper blocks. A large-area thermopile detector and/or integrating sphere with small-area thermopile detector were used to measure the shape of the light pulse. The examination of the lateral near- and far-field distributions did not reveal any considerable change throughout the entire range of driving current. The modulation of the near field was less than 10% at currents exceeding twice the threshold current. The full width at half maximum (FWHM) of the

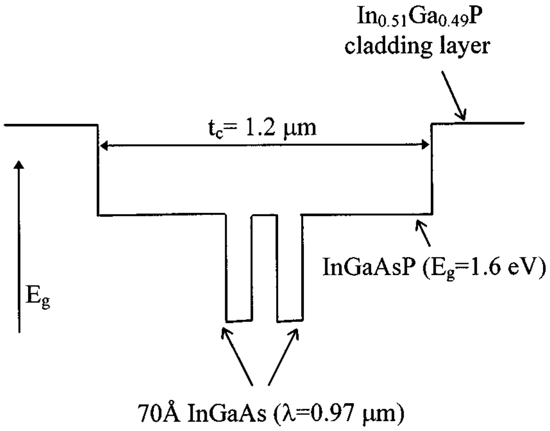

FIG. 1. Schematic diagram of double-quantum well Al-free laser structure with broad waveguide design.

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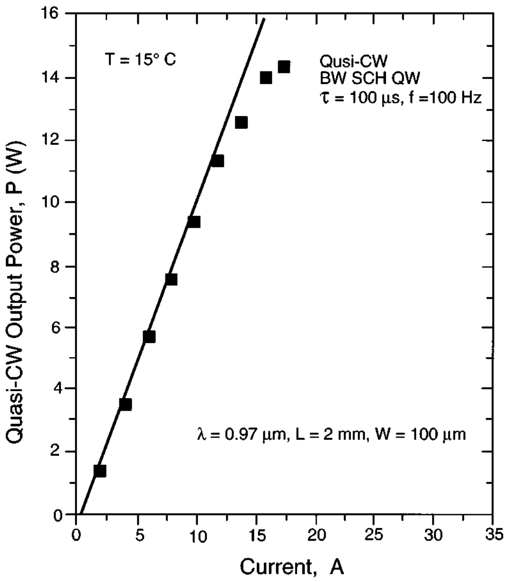

FIG. 2. Quasi-cw output power characteristics for a 0.97 μm BW-SCH-QW laser of 2 mm cavity length and 100 μm stripe width, measured with 100 μs pulses at 100 Hz repetition rate.

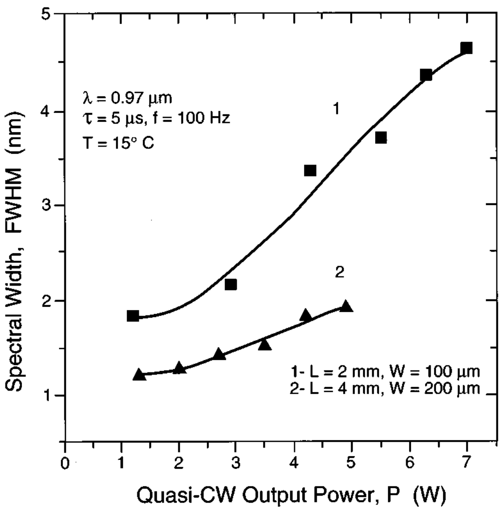

FIG. 3. The dependence of the spectral FWHM on output power for two 0.97 μm lasers measured with 5 μs pulses at repetition rate of 200 Hz. Curve 1 refers to the laser with a cavity length of 2 mm and 100 μm aperture. Curve 2 refers to a 4-mm-long, 200 μm aperture laser.

lateral far-field pattern increases from about 9° near threshold to about 12° at maximum output power. These results suggest that filamentation is not an issue in these devices throughout the whole range of operating current. In the transverse direction the beam pattern FWHM is 36°, basically corresponding to the fundamental mode, over the whole range of drive current.[7]

Figure 2 shows the power-current characteristics measured with 100 μs current pulses at a repetition rate of 100 Hz. For a laser with $L = 2$ mm and $W = 100$ μm an output power of 14.3 W is obtained at 17.5 A. At a slightly higher current the laser failed catastrophically. Since the equivalent (transverse) spot size[3] is 0.64 μm, the catastrophic optical mirror damage (COMD) power density is 22.5 MW/cm^2; that is ~40% higher than the COMD power density in cw operation of 0.97 μm×100 μm stripe devices.[1,3] The series resistance, R_s, is 0.03 Ω, that is 3–4 times less than Al-containing devices of the same contact geometry. Similarly low R_s values have been reported[8] for 0.81 μm emitting Al-free diode lasers of 200 μm×2 mm stripe geometry. The differential efficiency in the linear portion of the power-current characteristics is 86% (see Fig. 2). The peak power represents the highest QCW value obtained to date for any type of wide-stripe diode lasers. By comparison, the previously highest reported QCW powers are[5]: 8 and 11 W from 100 and 200 μm stripe 0.87 μm emitting devices, respectively.

Studies of the laser radiation spectra demonstrate considerable changes with increasing peak-pulse current. An analysis of the spectral data shows that two different regimes of spectral behavior can be identified. The first regime is current-drive dependent, and is revealed by using driving current pulses of duration, τ, less than 10 μs. In this regime, the spectral shape does not depend on τ even at the highest driving currents. By contrast, for $\tau > 10$ μs an additional long-wavelength shift and broadening of the spectra occur with increasing τ. This second regime of spectral behavior is caused by submount overheating and can be eliminated by using a more massive submount to increase cooling capacity.

Under the conditions of our experiments (small portable submount), even in the case of highest currents, the mount temperature can be considered constant if 1 μs$<\tau<$10 μs. Thus steady-state temperature for the diode is obtained for times shorter than 10 μs. Using $\tau = 5$ μs, we were able to study the dependence of the steady-state laser spectra as a function of current-pulse amplitude. The spectra demonstrate both long-wavelength shifts of the spectral-emission peak as well as broadening of the spectra as the current-pulse amplitude increases. The rate of the shift of the spectral-emission peak depends on the device contact area, decreasing with increasing contact area. For 100 μm×2 mm stripe devices, this rate was about 0.6 nm/W. Comparing this data with the position of lasing spectral-emission peak at different mount temperature allows one to find the diode's active-region temperature relative to the submount temperature. At the driving currents necessary to reach 10 W, the temperature rise of the active regions is estimated to be in the range of 10–20 °C. For practical applications, a change of heatsink temperature can easily compensate for these 10–20 °C temperature increases.

The spectral broadening with increasing pulse width, so-called chirp, can create serious problems for applications involving solid-state or fiber-laser pumping with diode lasers. Figure 3 shows the spectral FWHM as a function of the output power for two 0.97 μm lasers: one with a relatively small stripe (2 mm×100 μm, curve 1) and the other with a large stripe (4 mm×200 μm, curve 2). These measurements were made using 5 μs current pulses. An increase of the FWHM from 1.8 to 4.5 nm, that is a factor of 2.5, was observed for the small-stripe laser when the peak output power increased from 1.3 to 7 W. The increase of heatsink temperature at a given pulsed current leads to ≤10% increase in the emission FWHM, and thus the diode temperature rise cannot be the reason for the spectral broadening with increasing current. As shown by curve 2 in Fig. 3, spectral broadening for the large-stripe device starts at much higher output power and its rate of increase with increasing drive current is ~3 times less than that for the small-stripe device. This result confirms that spectral broadening in multi-mode lasers is a strong function of the driving current density, and thus long-cavity devices are preferable for reducing spectral broadening.

In conclusion, we have demonstrated a broad-waveguide 0.97 μm SCH-QW laser with record quasi-cw output power of 14.3 W. This laser has very low internal loss ($\sim 1\ \mathrm{cm}^{-1}$) and high differential efficiency (86% for 2 mm cavity length), and exhibits only a 10–20 °C active-region temperature rise in QCW operation to ~10 W. It is also shown that long cavity, large-stripe devices have significantly reduced spectral broadening with increasing output power.

The authors gratefully acknowledge the support of the Phillips Laboratory, Albuquerque, N.M. under Contract No. F29601-96-C-0140, as well as the technical assistance of M. Harvey, D. Capewell, R. Farkas, L. DiMarco, and R. Materese.

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