1.47–1.49-μm InGaAsP/InP diode laser arrays

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Continuous-wave power of 25 W at 1.47-μm was obtained from a 20-element, 1-cm-wide, one-dimensional diode laser array mounted in a microchannel water-cooled heat sink. The coolant temperature was 16 °C. A two-dimensional array comprising four laser bars achieved a quasi-cw output of 110 W at a wavelength of 1.49 μm, with an 8–9-nm full width at half-maximum spectrum width. The coolant temperature was 18 °C. We developed a theoretical model that describes array heating. Thermal resistances of 0.56, 0.4, and 0.34 K/W were experimentally and theoretically determined for arrays with fill factors of 10%, 20%, and 40%, respectively. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1596379]

Replacing flash-lamps with efficient, narrow-band diode laser pumping sources significantly increases the maximum available power and extends the application area of solid-state lasers. In recent years, there has been an increased interest in the development of high-energy, Q-switched solid-state sources operating in eye-safe wavelength range. Erbium-doped crystalline hosts offer great potential as efficient, pulsed, eye-safe laser sources with applications in range finding, target identification, and Lidar. Direct resonant pumping of erbium lasers performed in absorption bands near 1.47 and 1.54 μm eliminates the need for sensitizer ions, and the crystalline matrix provides good thermal, spectral, and mechanical properties for high-energy, high-repetition-rate applications.[1]

This letter describes the operational characteristics of 1.47–1.49-μm one-dimensional (1D) and two-dimensional (2D) InP-based diode laser arrays designed for high-duty-cycle (HDC) operation. 1D arrays output 25 W cw at a coolant temperature of 16 °C. In quasi-cw (q-cw) operation 2D arrays output 110 W at a coolant temperature of 18 °C. The dependence of active layer temperature on dissipated power as a function of the array fill factor was experimentally and analytically investigated.

The InGaAsP/InP heterostructures were grown by organometallic chemical vapor deposition. The active region consisted of three 6-nm-thick compressively strained quantum wells incorporated into a two-step graded index waveguide with a total thickness of 710 nm. Zn doping of the 1.5-μm-thick *p*-cladding exhibited optical losses as low as 2–3 cm^{-1}.[2,3] The laser facets were high-reflection/antireflection coated with reflection coefficients of 95% and 3%, respectively. A single 100-μm-wide, 1-mm-long laser had a threshold current density of 480 A/cm^2 and a differential efficiency of 60%. Over the temperature range from 18 to 60 °C, the threshold characteristic temperature T_0 was 54 K and the slope-efficiency characteristic temperature T_1 was 160 K.

We used 1-cm-long laser bars containing twenty 100-μm-wide emitters equally spaced 500 μm center-to-center, yielding a fill factor of 20%. The laser cavities were 1 mm long to fit the standard heat sink. 1D and 2D arrays were fabricated by mounting the bar (1D) or bars (2D) in metallized grooves in BeO blocks, which were bonded on water-cooled microchannel heat sinks. This arrangement removes heat from both sides of the laser bar.

Figure 1 shows the current dependencies of the cw and q-cw (5-ms pulse duration, 20-Hz pulse repetition frequency) output power and the wall-plug efficiency for a 1D diode array at a coolant temperature of 16 °C. The output power was recorded by a 50-mm-diameter thermopile detector. The slope efficiency of 0.5 W/A remained constant in q-cw mode up to the measured output power of 27 W. The power rollover in cw mode was observed when the drive current exceeded 40 A. The maximum wall-plug efficiency was 37% at

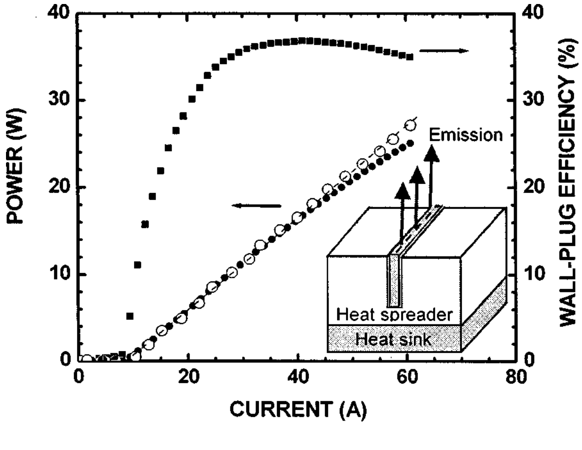

FIG. 1. Output power (circles) and wall-plug efficiency (squares) of a 1.47-μm 1D array operated in q-cw (open symbols) and cw (closed symbols) modes at a coolant temperature of 16 °C. Schematic diagram of a 1D diode laser array is shown in the inset.

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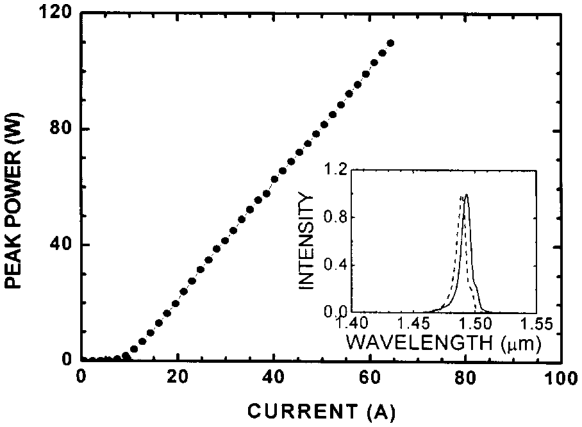

FIG. 2. Output power of a 2D array operated in the q-cw mode at 18 °C. Inset demonstrates integrated emission spectra of a 2D array at a coolant temperatures of 18 °C (dashed line) and 25 °C (solid line) measured in q-cw mode.

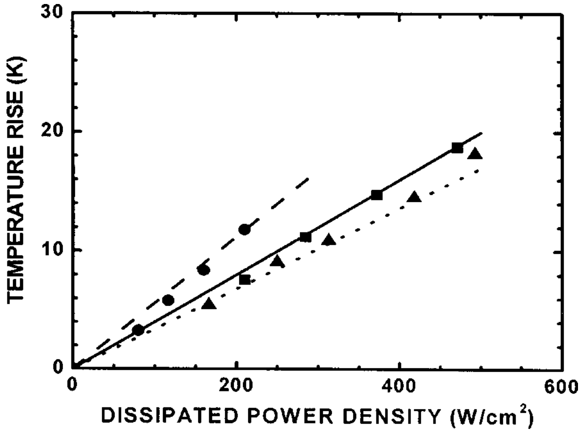

FIG. 3. The experimentally measured active-region temperature rise as a function of dissipated power is shown for 10% (circles), 20% (squares), and 40% (triangles) fill-factor arrays. The analytical result is displayed using dashed (10%), solid (20%), and dotted (40%) lines.

40 A, and was better than 34% up to the maximum drive current of 60 A.

To estimate the heating of the laser active region caused by power dissipation, we measured the emission spectrum redshift with increasing drive current using an integrating sphere and an optical spectrum analyzer. To correlate wavelength shift to temperature change, a calibration factor of 0.55 nm/K was obtained by measuring the spectral shift under low-duty cycle (LDC) (0.02%), narrow-pulse-width (200 ns) excitation at a variety of heat-sink-coolant temperatures. To estimate the contribution of factors related to current change, we fixed the temperature of the heat sink and increased the current in LDC pulsed-mode operation. The spectral shift due to current under LDC pulsed-mode operation was insignificant. We conclude that the observed redshift under cw and q-cw operation was caused by the heating of the active region. At 60-A drive current, the active-region temperature rise was 18 K in the cw mode and 13 K in the q-cw mode.

A series connected four-bar 2D array with a bar-to-bar pitch of 3.2 mm was fabricated. A q-CW output power of 110 W was achieved at a current of 60 A, as shown in Fig. 2. The 2D array's integrated emission spectra were measured at a current of 30 A in q-CW mode at 18 and at 25 °C as shown in the inset in Fig. 2. The spectrum shifted with temperature, while the full width at half maximum spectral width remained at about 8–9 nm.

The temperature of the active region is a critical factor in the operational lifetime of the array. Previous results indicate that the lifetime is exponentially dependent on the active region temperature.[4] The main factors determining the temperature of the active region are the power dissipation in the active area, the series resistance of the cladding layers, and the mutual heating of adjacent emitters. To find the influence of bar design on heating, we investigated the effect of fill factor on thermal resistance. We fabricated arrays with fill factors of 10%, 20%, and 40% and found the dependence of the active region temperature on dissipated power. The dissipated power is defined as the difference of input power and output optical power. As can be seen in Fig. 3, the active-region temperature depends linearly on dissipated power, with thermal resistance as the coefficient of proportionality.

Experimental data presented in Fig. 3 (symbols) are described well by a theoretical model (lines). In this thermal model, we simulated the real geometry (see inset Fig. 1) with a structure in which the laser bar, the BeO layer, and the ideal heat sink are coplanar (see inset in Fig. 4). The 830-μm thickness of the BeO layer was determined by comparing the temperature distribution within the slotted-BeO geometry with the corresponding data calculated for the planar model. The specific requirement for both geometries was the equivalence of the maximum bar temperature with 100% fill factor. Figure 4 presents the temperature distribution along the laser bar for fill factors of 10%, 20%, and 40%. The thermal resistance, defined as the ratio of the average temperature across a separate emitter (direction parallel to the laser facets) to dissipated power, was found to be 0.56, 0.4, and 0.34 K/W for fill factors of 10%, 20%, and 40%, correspondingly.

The dependence of the thermal resistance on the fill factor results from a nonuniform temperature distribution in the bar (Fig. 4). The larger the temperature of a region in the bar, the larger the heat flux that goes from this region to the heat sink. That is, the main heat flux to the heat sink goes from the regions with high temperature. The temperature is higher

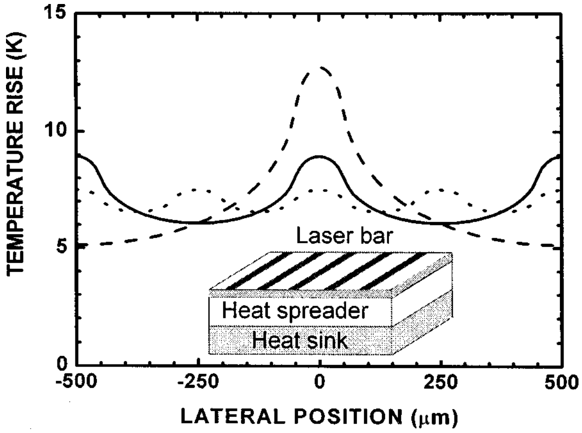

FIG. 4. Active-region temperature distribution at 1 mm of the 1-cm-long laser bar at the total dissipated power of 21 W. At a fill factor of 10% (dashed line), the heat from just one laser stripe is evident. As the fill factor increases to 20% (solid line) and 40% (dotted line), the heat from more laser stripes comes into view. The inset illustrates the planar geometry used in calculation of the temperature distribution.

in the regions close to the emitters and lower between them, so that the larger the fill factor, the larger the heat flux, given the temperature at the emitters. Thus, larger power can be dissipated and transferred to the heat sink without temperature increase. Therefore the thermal resistance decreases with the fill factor.

In agreement with Ref. 5, our calculations show that a further fill-factor increase does not lead to significant reduction of thermal resistance. Good agreement between the theoretical and experimental data in Fig. 3 shows that we can use our planar model to calculate the dependence of the laser active-region temperature on the fill factor. Moreover, the model allows calculation of the temperature at any point of a laser bar and its heat sink.

In conclusion, we report on the development of high-power diode arrays operating near 1.5 μm. A 25-W cw output power was obtained from a 1D array at 16 °C, and 110-W q-cw power was obtained from a 2D array at 18 °C. The thermal resistances of 0.56, 0.4, and 0.34 K/W were experimentally and theoretically determined for 10%, 20%, and 40% fill-factor arrays, respectively. The agreement of the theoretical and experimental results shows that a simple plane geometry is adequate to determine the temperature distribution in the arrays.

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[1] S. D. Setzler, P. A. Budni, and E. P. Chicklis, OSA Trends Opt. Photonics Ser. **50**, 309 (2001).

[2] L. Shterengas, R. Menna, C. W. Trussell, D. Donetsky, G. Belenky, J. Connolly, D. Garbuzov, J. Appl. Phys. **88**, 2211 (2000).

[3] G. Belenky, L. Shterengas, C. W. Trussell, C. L. Reynolds, M. S. Hybertsen, R. Menna, *Future Trends in Microelectronics*, edited by S. Luryi, J. Xu, and A. Zaslavsky (IEEE, New York, 2002), p. 230.

[4] M. Voss, C. Lier, U. Menzel, A. Barwolff, and T. Elsaesser, J. Appl. Phys. **79**, 1170 (1996).

[5] R. Puchert, A. Barwolff, M. Voss, U. Menzel, J. W. Tomm, and J. Luft, IEEE Trans. Compon., Packag. Manuf. Technol., Part A **23**, 95 (2000).