High-power (>10 W) continuous-wave operation from 100-μm-aperture 0.97-μm-emitting Al-free diode lasers

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By incorporating a broad transverse waveguide (1.3 μm) in 0.97-μm-emitting InGaAs(P)/InGaP/GaAs separate-confinement-heterostructure quantum-well diode-laser structures we obtain record-high continuous-wave (cw) output powers for any type of InGaAs-active diode lasers: 10.6–11.0 W from 100-μm-wide-aperture devices at 10 °C heatsink temperature, mounted *on* either diamond or Cu heatsinks. Built-in discrimination against the second-order transverse mode allows pure fundamental-transverse-mode operation ($\theta_\perp = 36°$) to at least 20-W-peak pulsed power, at 68×threshold. The internal optical power density at catastrophic optical mirror damage (COMD) $\bar{P}_{COMD}$ is found to be 18–18.5 MW/cm^2 for these conventionally facet-passivated diodes. The lasers are 2-mm-long with 5%/95% reflectivity for front/back facet coating. A low internal loss coefficient ($\alpha_i = 1$ cm^{-1}) allows for high external differential quantum efficiency η_d (85%). The characteristic temperatures for the threshold current T_0 and the differential quantum efficiency T_1 are 210 and 1800 K, respectively. Low differential series resistance R_s: 26 mΩ; leads to electrical-to-optical power conversion efficiencies in excess of 40% from 1 W up to 10.6 W cw output power, and as much as 50% higher than those of 0.97-μm-emitting Al-containing devices. © *1998 American Institute of Physics.* [S0003-6951(98)03335-X]

Broad-stripe, InGaAs-active diode lasers (λ=0.89–1.06 μm) are routinely used for pumping solid-state fiber lasers, frequency doubling, and for numerous medical applications. Al-free devices (i.e., InGaAs/InGaP/GaAs structures) have superior ''wallplug'' efficiency compared with conventional Al-containing devices[1] due to their low differential series resistance.[1,2] Furthermore, the low oxidation rate of InGaP permits high-quality epitaxial regrowths over gratings for longitudinal-mode control (i.e., distributed-feedback lasers)[3,4] or over etched structures for lateral-mode control.[5–9] Thus, the Al-free material system is highly desirable for both broad-stripe spatially incoherent devices as well as for temporally and/or spatially coherent index-guided diode lasers.

Recently, we have reported[10] continuous-wave (cw) output powers of 8 W from 0.98-μm-emitting InGaAs/InGaP/GaP lasers of a 100-μm-wide stripe, 4-mm-long cavity, 1-μm-thick transverse waveguide, and mounted *on* Cu heatsinks. Such broad-waveguide (BW) devices also demonstrated fundamental-transverse-mode operation to high drive levels,[11] as expected since the cutoff thickness for the second-order transverse mode is 1.05 μm. BW devices with a waveguide thickness of 1.3 μm exhibited lasing in both the fundamental and the second-order transverse modes.[12]

We report here maximum cw output powers of 10.6–11 W, record-high values for any type of InGaAs-active-region diode lasers. The devices show pure fundamental-transverse-mode operation to at least 20 W peak pulsed power. We achieve these results using a 1.3-μm-waveguide structure, designed to suppress oscillation of the second-order transverse mode.

The InGaAs(P)/InGaP/GaAs laser structure used is shown in Fig. 1. It was grown by low-pressure metal–organic chemical vapor deposition in an Aixtron A-200 system on exact-oriented (100) GaAs substrates.[13] The structure

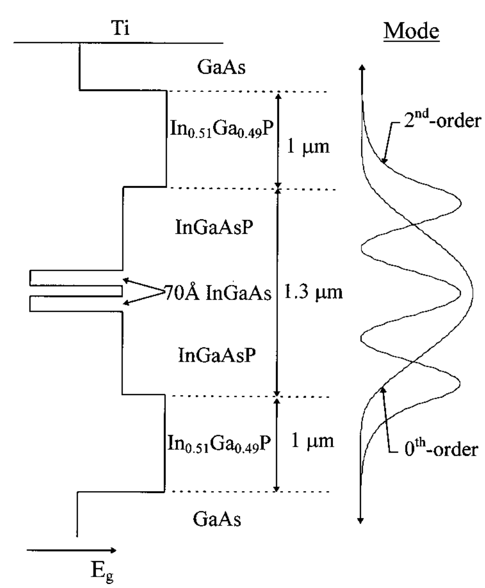

FIG. 1. Schematic representation of Al-free, broad-waveguide 0.97-μm-emitting diode laser. The field intensity profiles for the fundamental- and second-order-transverse modes are shown on the right side. The first-order transverse mode is not shown since it has negligible field overlap Γ with the active region (i.e., the two quantum wells).

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consists of two 70-Å-thick $In_{0.2}Ga_{0.8}As$ quantum wells, a 1.3-μm-thick InGaAsP ($E_g = 1.6$ eV) waveguide region, 1.0-μm-thick $In_{0.51}Ga_{0.49}P$ cladding layers, and a 0.2-μm-thick p^+-GaAs cap layer.

Fabry–Perot lasers with 100-μm-wide metal contact stripes were fabricated by using conventional oxide-defined window-stripe processing. The *p*- and *n*-side metal contacts were Ti/Pt/Au and Ge/AuGe/Ni/Au, respectively. The lasing wavelength was 0.97 μm at 15 °C.

The structures used here are similar to previous structures,[10–12] except for a notable difference in the thickness of the InGaP cladding layers: it has been reduced from 1.5 to 1.0 μm. This reduction has no effect on the fundamental mode. The first-order mode cannot lase since it has negligible (transverse) optical field overlap Γ with the quantum wells. The second-order mode, however, is strongly influenced by thinning the cladding layers. That is, the second-order mode suffers both (transverse) radiation losses to the substrate as well as absorption loss in the *p*-side metal contact. The first layer in the *p*-side metal contact, Ti, has a refractive index at $\lambda = 0.98$ μm (i.e., $n = 3.3 + i.3.26$), which gives a light penetration depth of 240 Å (i.e., only 60% of its actual thickness), and thus, can be considered semi-infinite. The second-order mode loss is then found to increase from 2.2 to 37.4 cm^{-1} as the cladding layers' thickness decreases from 1.5 to 1.0 μm. In turn, using an experimentally determined[1] logarithmic gain versus threshold-current density J_{th} relationship, with 2.1% and 1.35% values for the Γ's of the fundamental and second-order mode, respectively, we estimate that the second-order mode has a J_{th} value 11.8 times that for the fundamental mode. As a result, the device operates in the fundamental transverse mode [Fig. 2(a)] to 20-W-peak pulsed power (0.5-μs-wide pulses, 200-Hz repetition rate) at a drive current of 27 A (i.e., 68×threshold) in a virtual Gaussian beam pattern ($\theta_{\perp,1/2} = 36°$, $\theta_{\perp,1/e^2} = 62.5°$) identical to that predicted by theory [Fig. 2(b)]. (The peak output power was limited by the maximum drive current of our power supply.)

It should be noted that for 1.5-μm-thick cladding layers the J_{th} of the second-order mode is only 1.6 times higher than that for the fundamental mode, solely based on the different Γ values for the two modes. Since in broad-stripe devices uniform lasing does not occur over the whole aperture until the drive current reaches ~2 times the threshold current, it is quite likely that at 1.6 J_{th} unused gain is available for lasing to start in the second-order transverse mode. As a result, one obtains in the far field a combination of the fundamental and second-order transverse modes,[12] as shown by the dashed curve in Fig. 2(b). For the case shown in Fig. 2(b) the beamwidth at $1/e^2$ points in intensity is 20% larger than theory predicts, which can be easily shown to mean that ~16% of the energy is emitted in the second-order mode. (The $\theta_{1/2}$ value is virtually unaffected, since the second-order-mode beam pattern has intensity nulls at ±16.5°.)

The use of a broad-waveguide structure results in an optical-field distribution almost entirely confined to the nominally undoped waveguide region. As a result, a low internal loss coefficient $\alpha_i = 1$ cm^{-1} is obtained, which in turn provides a relatively high value for the external differential quantum efficiency $\eta_d = 85\%$ for 2-mm-long, 5%/95%

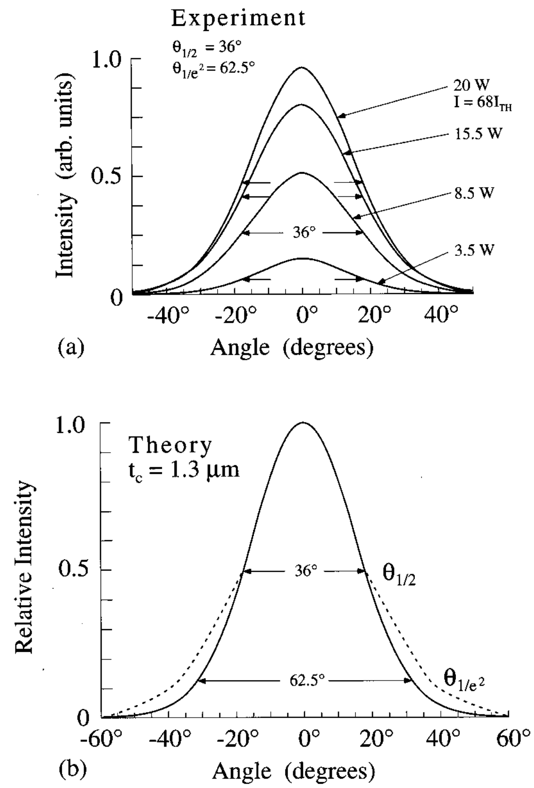

FIG. 2. (a) Transverse far-field patterns at various peak output powers in pulsed operation (0.5 μs pulse width, 200 Hz repetition rate) for the device shown in Fig. 1. I_{th} is the threshold current and has a value of 0.4 A for 100 μm×2 mm contact devices. (b) Theoretical far-field pattern for the device shown in Fig. 1 and typical experimental far-field pattern for 1.5-μm-thick cladding-layer devices (Ref. 12) (dashed curve).

coated devices. High cw output powers are attained by taking advantage of the relatively large equivalent transverse spot size,[10] d/Γ: 0.66 μm; where *d* is the quantum-well(s) thickness. Cw output power as high as 10.6 W [Fig. 3(a)] is achieved from 2-mm-long, 100-μm-wide aperture devices at 10 °C heatsink temperature and mounted on diamond submounts. Two other devices reached 10.5 and 10 W cw output power. The internal optical power density at catastrophic optical-mirror damage (COMD),[10] $\bar{P}_{COMD}$, is ≃18 MW/cm^2, a value quite similar to the 19 MW/cm^2 obtained[15] from InGaAs/AlGaAs high-power devices mounted on Cu heatsinks; proving that when the maximum cw power is limited by COMD (rather than due to thermal considerations), the chip thermal resistance is low due to large contact area, and η_d is relatively temperature insensitive (i.e. high T_1 values),[13] the use of diamond or Cu heatsinks makes *no* difference. More recently, we obtained[14] 11 W cw at 10 °C, from identical devices mounted *on* Cu heatsinks, thus further confirming the above conclusion. The 10.6–11.0 W cw power levels are, to the best of our knowledge, the highest cw powers reported from any type of semiconductor lasers with an InGaAs active region.

The threshold-current density J_{th} and the differential quantum efficiency η_d were measured in pulsed operation as the heatsink temperature was varied from 20 to 80 °C. A best-fit analysis gives characteristic temperatures for the threshold current T_0 and the external differential quantum efficiency[13] T_1 of 210 and 1800 K, respectively. That is, η_d

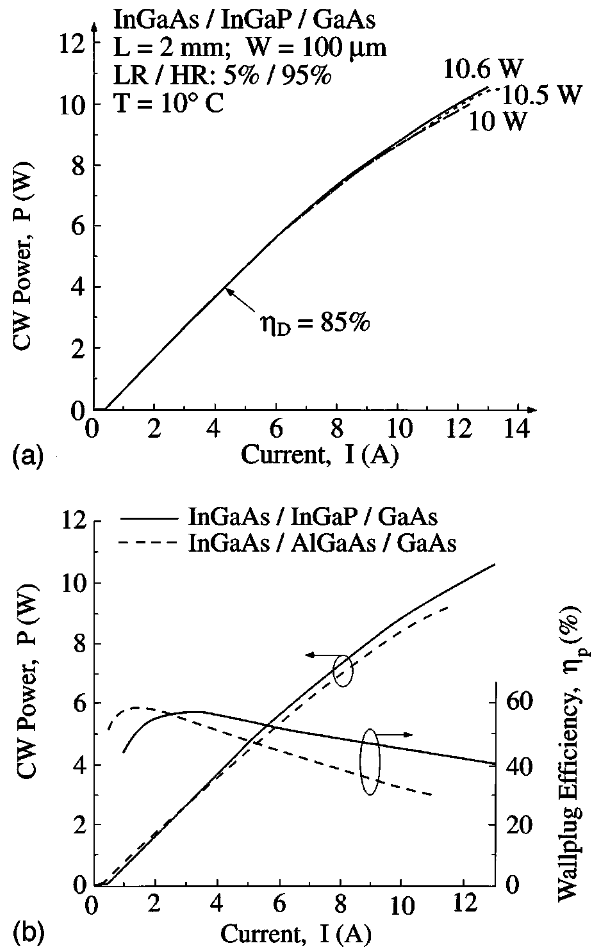

FIG. 3. (a) Cw light-current characteristics for three typical 0.97-μm-emitting diodes at 10 °C heatsink temperature. (b) Cw light-current characteristics and ''wallplug'' efficiency curves at 10 °C for 100-μm-stripe, 2-mm-long, 0.97-μm-emitting lasers. Solid lines: Al-free structure shown in Fig. 1. Dashed lines: InGaAs/AlGaAs/GaAs device (Ref. 15).

decreases by only 3% between 20 and 80 °C. The relatively high values obtained for T_0 and T_1 reflect excellent carrier confinement. By comparison, the T_0 and T_1 values for 0.97-μm-emitting, high-power AlGaAs-cladding devices[15] of the same dimensions are significantly lower: 150 and 760 K, respectively; even though the temperature range is narrower (15–60 °C).

A comparison to 0.97-μm-emitting InGaAs/AlGaAs devices of the same geometry and driven under the same conditions: cw and 10 °C heatsink temperature; is shown in Fig. 3(b). The difference in maximum cw power simply reflects the smaller d/Γ value (i.e., 0.53 μm)[15] for the Al-containing devices. The most relevant and significant difference is in ''wallplug'' efficiency, η_p, due to the fact that InGaP-cladded devices have a series resistance $R_s = 26–28$ mΩ, about four times less than R_s values for the 0.97-μm-emitting, AlGaAs-cladded devices of the same contact geometry.[15] Although η_p reaches basically the same maximum value for both structures, for Al-free devices η_p is higher and decreases much more slowly with increasing drive current than it does for Al-containing devices. Thus, at the 9 W cw power level, η_p of Al-free devices is 50% higher (i.e., 45% versus 30%) than η_p of Al-containing devices. Higher wallplug efficiency coupled with significantly less Joule heating should permit Al-free devices to operate reliably at higher cw powers than Al-containing devices.

In conclusion, we report on 0.97-μm-emitting Al-free lasers with record-high cw output powers, 10.6–11.0 W, for InGaAs-active devices; low internal loss, $\alpha_i = 1$ cm^{-1}; and high characteristic temperatures, $T_0 = 210$ K, $T_1 = 1800$ K. Furthermore, built-in discrimination against the second-order transverse mode allows stable fundamental-transverse-mode operation to 20-W-peak pulsed power.

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[1] D. Botez, L. J. Mawst, A. Bhattacharya, J. Lopez, J. Li, T. F. Kuech, V. P. Iakovlev, G. I. Suruceanu, A. Caliman, and A. V. Syrbu, Electron. Lett. **32**, 2012 (1996).
[2] A. Al-Muhanna, L. J. Mawst, D. Botez, D. Z. Garbuzov, R. U. Martinelli, and J. Connolly, Appl. Phys. Lett. **71**, 1142 (1997).
[3] Y. K. Sin and M. Horikawa, Electron. Lett. **29**, 240 (1993).
[4] M. Nesnidal, T. Earles, L. J. Mawst, D. Botez, and J. Buus, Appl. Phys. Lett. **73**, 587 (1998).
[5] S. H. Groves, Z. L. Liau, S. C. Palmateer, and J. N. Walpole, Appl. Phys. Lett. **56**, 312 (1990).
[6] E. C. Vail, S. F. Lim, Y. A. Wu, D. A. Francis, C. J. Chang-Hasnain, R. Bhat, and C. Caneau, Appl. Phys. Lett. **63**, 2183 (1993).
[7] M. Sagawa, T. Toyonaka, K. Hiramoto, K. Shinoda, and K. Uomi, IEEE J. Sel. Top. Quantum Electron. **1**, 189 (1995).
[8] A. Bhattacharya, L. J. Mawst, M. Nesnidal, J. Lopez, and D. Botez, Electron. Lett. **32**, 657 (1996).
[9] H. Yang, L. J. Mawst, M. Nesnidal, J. Lopez, A. Bhattacharya, and D. Botez, Electron. Lett. **33**, 136 (1997).
[10] L. J. Mawst, A. Bhattacharya, J. Lopez, D. Botez, D. Z. Garbuzov, L. DeMarco, J. C. Connolly, M. Jansen, F. Fang, and R. F. Nabiev, Appl. Phys. Lett. **69**, 1532 (1996).
[11] D. Garbuzov, N. Morris, B. Odubanjo, R. Martinelli, J. C. Connolly, L. J. Mawst, A. Bhattacharya, D. Botez, C. Dries, and S. R. Forrest, *Tech. Dig. IEEE/OSA Conference on Lasers and Electro-Optics '97*, Baltimore, MD; **11**, 3 (1997).
[12] D. Garbuzov and J. C. Connolly (unpublished).
[13] L. J. Mawst, A. Bhattacharya, M. Nesnidal, J. Lopez, D. Botez, J. Morris, and P. Zory, Appl. Phys. Lett. **67**, 2901 (1995).
[14] D. Z. Garbuzov, M. G. Harvey, J. C. Connolly, M. A. Maiorov, A. Al-Muhanna, L. Mawst, and D. Botez (unpublished); and D. Z. Garbuzov, *Tech. Dig. IEEE/OSA Conference on Lasers and Electro-Optics '98*, San Francisco, CA, (1998), Vol. 6, p. 10.
[15] S. O'Brien, H. Zhao, A. Schoenfelder, and R. J. Lang, Electron. Lett. **33**, 1869 (1997).