High-Power, Reliable Diode Lasers and Arrays

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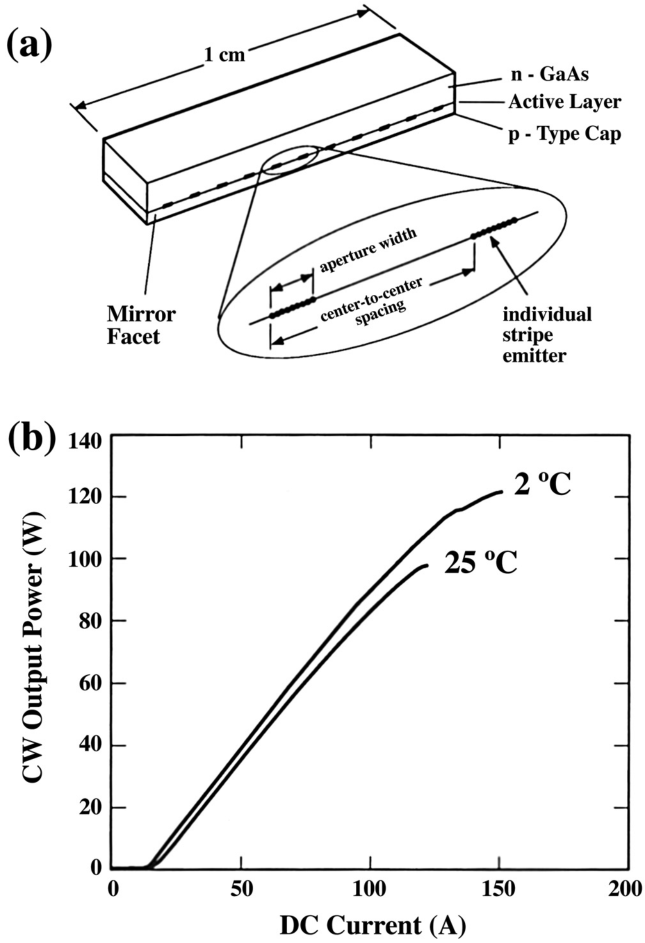
The long-lived diode lasers demonstrated at Bell Laboratories in 1977 produced only a couple of milliwatts (mWs), good enough for fiber-optical communications and later for compact disc reading. Other applications, such as high-speed optical recording, required quasi-continuous-wave (CW) powers in the 50–100-mW range delivered reliably in a single spatial mode.

Since the reliable power is closely related to the optical power density that can damage the emitting facet, designs were needed for enlarging the laser spot size both transversely (i.e., in a direction perpendicular to the plane of the grown layers) and laterally, while maintaining a single spatial mode. In conventional double-heterojunction devices, for which single transverse optical-mode operation is ensured, the main challenge was to create single-mode structures of large lateral spot size. This was realized by introducing mode-dependent radiation losses in so-called antiguided structures, in either the lateral or the transverse directions, on both sides of the defined lateral waveguide. Laterally antiguided diode lasers [1] emitting single-mode peak powers in the 50–80-mW range at 20%–50% duty cycle enabled RCA Laboratories in 1980 to realize high-speed optical recording. At about the same time, Hitachi Central Research Laboratory reported single-mode CW powers as high as 40 mW employing optimized transversely antiguided double-heterojunction devices [2].

In 1980 a breakthrough occurred in high-power diode-laser design with the implementation of the large-optical-cavity concept for increased spot size in the transverse direction [1]. These structures provided transverse spot sizes about 60% larger than in double-heterojunction devices, enabling record-high reliable powers [1]. As a result, the constricted double-heterojunction, large-optical-cavity laser became the most powerful single-mode commercially available diode laser between 1981 and 1986.

In the 1980s the maximum reliable CW power was only about 25% of the maximum achievable power set by catastrophic optical-mirror damage. Mirror damage in diode lasers is caused by thermal runaway at the mirror facets due to increased light absorption and nonradiative recombination with increased drive current [3]. Solutions to suppressing damage required nonabsorbing regions at the mirror facets. As early as 1978 researchers from NEC Laboratories showed that Zn diffusion provides nonabsorbing regions at the mirror facets. This led to a fourfold increase in the maximum achievable CW output power. Then, in 1984 researchers from RCA Laboratories demonstrated mirror-damage suppression by creating, via a single etch-and-regrowth cycle, two-dimensional (2D) waveguiding structures at the mirror facets that were transparent to the laser light. Those devices [3] provided peak output powers of 1.5 W, a fourfold increase over the highest previously reported. However, the early nonabsorbing-mirror approaches were impractical to implement. It took over five years before practical nonabsorbing-mirror lasers were developed and became commercially available.

Around 1982, interest arose in replacing flashlamps with diode-laser arrays as pumps for solid-state lasers. This drive picked up steam with the advent of quantum-well diode lasers since much lower threshold currents could be achieved than in standard double-heterojunction lasers. In early 1983 researchers from Xerox PARC reported very high (>2.5 W CW) CW power quantum-well lasers with optimized facet coatings [3]. Thus, they achieved an eightfold



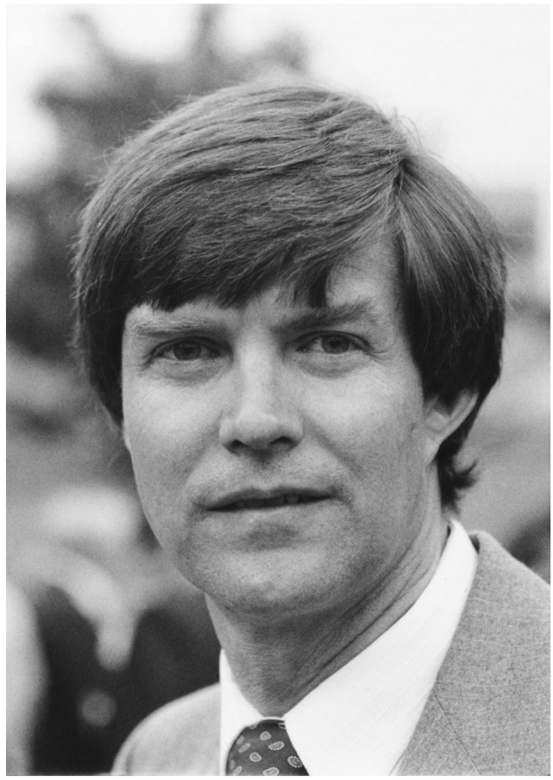
▲ **Fig. 1.** First diode-laser bar to emit 100-W CW power at room temperature: (a) schematic representation, (b) CW output as a function of drive current. (D. R. Scifres and H. H. Kung, "High-power diode laser arrays and their reliability," Chap. 7 in *Diode Laser Arrays*, D. Botez and D. R. Scifres, eds. [Cambridge University Press, 1994].)

increase over the maximum CW power reported from double-heterojunction lasers due both to the use of quantum wells and the use of low-reflectivity dielectric facet coatings. The facet coatings also prevented attack and erosion of the cleaved facets in air, enhancing device reliability [3]. By the mid-1980s large-aperture, high-power, reliable diodes lasting at least 10,000 hours became commercially available [3] from Spectra Diode Laboratories Inc., a start-up company spun off from Xerox PARC. Later that decade, quantum-well laser optimization employing a single, thin quantum well in a large-optical-cavity confinement structure resulted in front-facet, maximum CW wall-plug efficiency as high as 55%.

Quantum-well lasers turned out to offer a solution for practical nonabsorbing-mirror lasers. Researchers from the University of Illlinois at Urbana discovered that impurity diffusion causes lattice disordering of multi-quantum-well structures, leading to structures of higher bandgap energy than the energy of light generated in undisturbed multi-quantum-well structures [4]. In 1986, by using impurity-induced disordering, researchers from Xerox PARC and Spectra Diode Laboratories achieved nonabsorbing-mirror structures at the mirror facets [4]. This led to dramatic improvement in maximum CW power from large-aperture devices and was reflected in similar improvements in the reliable CW power output from single-mode devices. This approach led in 1990 to the first 100-mW CW commercially available single-mode diode laser. An alternative nonabsorbing-mirror approach was developed at IBM Zurich Laboratories [3,4]. This approach, called the E2 process, consisting of complete device-facet passivation via *in situ* bar cleaving in ultrahigh vacuum and deposition of a proprietary facet-passivation layer, led to reliable operation of single-mode AlGaAs lasers at 200-mW output power. Today these are the two main nonabsorbing-mirror approaches for multi-watt, reliable operation of both single-stripe lasers and laser bars.

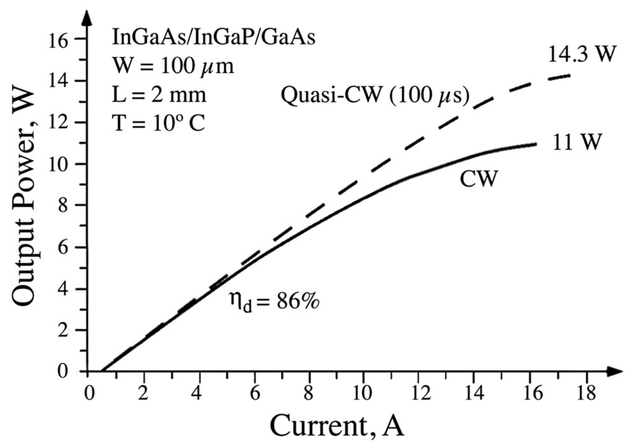
In the early 1990s single-stripe laser and laser-bar development for pumping solid-state lasers started in earnest. For single-stripe, facet-passivated devices of ~400-µm-wide aperture, Spectra Diode Laboratories reported maximum CW power of 11.4 W with reliable CW power of ~4 W [3]. Monolithic laser bars [Fig. 1(a)] composed of an array of 80 separate facet-passivated lasers emitted 100-W CW at room temperature [Fig. 1(b)] [3]. Laser-bar operation in quasi-CW mode at low duty cycles allowed effective heat removal; thus, permitting maximization of the energy per pulse and consequently quite suitable for pumping solid-state lasers. Researchers from Lawrence Livermore National Laboratories (LLNL) reported highly stable high-peak-power, quasi-CW operation after 1 billion shots from 1-cm-long bars [4]. Laser bars were further stacked in 2D arrays to deliver the high powers needed for effective solid-state-laser pumping. Heat removal was a challenging task, and several approaches were developed [3,4]. At the time, the most efficient way to remove heat from 2D arrays was the silicon-based micro-channel cooling technology developed at LLNL [4]. Using that technology LLNL demonstrated 41-bar stacks delivering 3.75-kW peak power [4]. By the end of the decade steady development led to significantly improved performance.

Spectra Diode Laboratories was at the forefront of commercializing high-power diode-laser bars. Donald R. Scifres, the CEO of Spectra Diode Laboratories, was recognized by The OSA in 1996, when he was the awarded the Edwin H. Land Medal for his pioneering scientific and entrepreneurial contributions to the field of high-power semiconductor lasers (Fig. 2). A year later, Dr. Scifres and his wife, Carol, endowed the OSA Nick Holonyak, Jr. Award, dedicated to recognize individuals who have made significant contributions to optics based on semiconductor-based optical devices and materials, including basic science and technological applications.



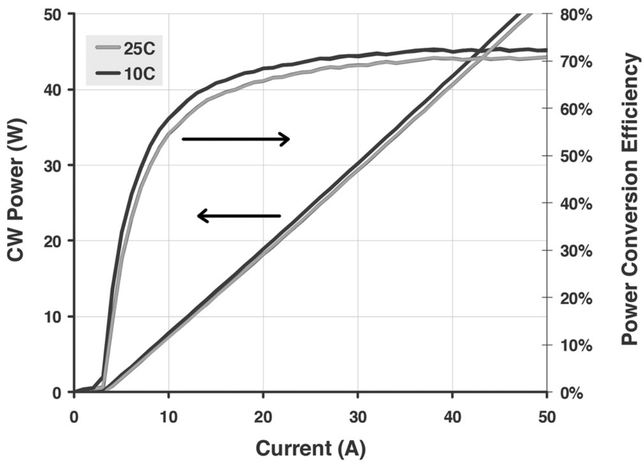
▲ **Fig. 2.** Donald R. Scifres, recipient of the 1996 Edwin Land Medal (at the time). (Courtesy of Dr. W. John Tomlinson, Princeton, New Jersey.)

In the mid-1990s two major developments led to significant increases in the output powers of single-stripe diode lasers: the broad-waveguide-device concept and the use of Al-free, active-region structures. The broad-waveguide concept for asymmetric and symmetric structures involved a large-optical-cavity structure of large equivalent (transverse) spot size as well as low internal cavity loss [5]. The total thickness of the optical-confinement layer of the broad-waveguide structure is quite large, while making sure that lasing of high-order transverse modes is suppressed via losses to the metal contact [5]. Diodes capable of over 10-W CW power were achieved using active regions composed of Al-free, indium (In)-containing material with relatively high mirror-damage power density (see Fig. 3). Later it became clear that adding In to the active-region material significantly decreases the surface recombination velocity, which in turn increases the mirror-damage power density [4]. Indium had another highly beneficial effect with respect to laser-device reliability: it was found to suppress crystal-defect propagation in GaAs-based lasers [4]. That is why currently the most reliable 0.81-μm emitting devices have either InGaAsP or InAlGaAs active regions.



▲ **Fig. 3.** Light-current characteristics in CW and quasi-CW operation for the first single-stripe (100-μm-wide aperture) diode laser to emit over 10-W CW power. (Reproduced with permission from A. Al-Muhanna, L. J. Mawst, D. Botez, D. Z. Garbuzov, R. U. Martinelli, and J. C. Connolly, "High-power (>10 W) continuous-wave operation from 100-μm-aperture 0.97-μm-emitting Al-free diode lasers," Appl. Phys. Lett. **73**(9), 1182 [1998].)

Another key issue that was tackled in the mid-1990s was suppression of carrier leakage out of the lasers' active regions. Since carrier leakage is a thermally activated effect a substantial amount of it causes a significant decrease in the laser slope efficiency as the heat-sink temperature increases. This decrease in slope efficiency is characterized by a



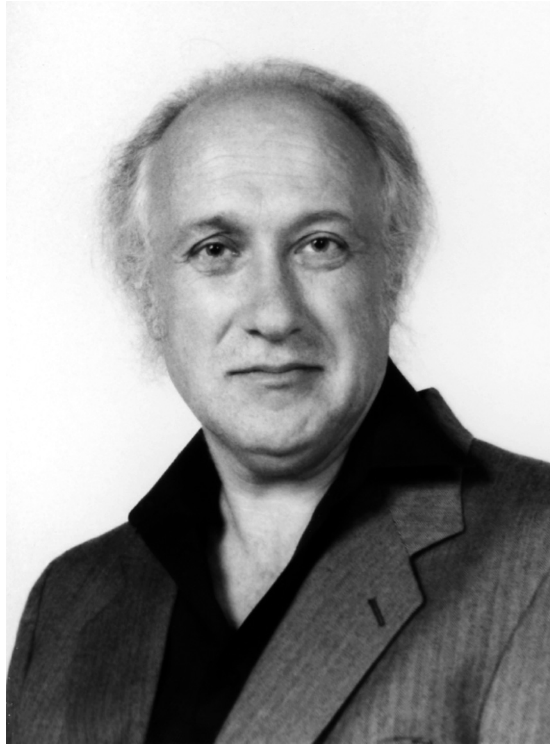
▲ **Fig. 4.** Light-current characteristics and wall-plug efficiency for the first diode-laser bar to emit with over 70% CW wall-plug efficiency at room temperature. (Reproduced by permission of the Institution of Engineering & Technology. Full acknowledgment to M. Kanskar, T. Earles, T. J. Goodnough, E. Stiers, D. Botez, and L. J. Mawst, "73% CW power conversion efficiency at 50 W from 970 nm diode laser bars," Electron. Lett. **41**(5), 245–247 [2005].)

temperature coefficient T_1 [5]. When carrier leakage is suppressed via bandgap engineering, the T_1 parameter has a high value, which reduces the active-region heating [5] and increases the maximum achievable CW power. A high T_1 value also leads to reduced mirror-facet heating; thus, it results in high mirror-damage power-density values [5] and subsequently long-term reliable operation at high CW power levels.

To minimize heating in diode lasers and decrease the heat load as well as improve the lasers' reliability in CW operation the value of the electrical-to-optical power conversion efficiency, the so-called wall-plug efficiency η_p needed to be increased. In 1996, by using broad-waveguide structures with suppressed carrier leakage [6], researchers at the University of Wisconsin–Madison achieved η_p as high as 66%. At the time it was noticed that the devices could not reach their ultimate maximum η_p value due to a built-in voltage differential in the laser structure. Efforts to increase η_p re-started in 2003. By 2005, reductions in the built-in voltage differential as well as laser-structure optimization led to CW wall-plug efficiencies of 73%–75% for laser bars from Alfalight, Inc., nLight Inc., and JDSU Corp. A typical result is shown in Fig. 4, which shows a 50-W CW output delivered with 73% wall-plug efficiency, at 0.97 μm from a 1-cm-wide laser bar [7]. The achievement of record-high wall-plug efficiency was quite a significant development in that it led the typical η_p of commercial laser bars to increase from ~45% to ~65%. Consequently, the dissipated heat that needed to be removed was reduced by more than a factor of 2, which is very important since thermal load management drives the packaged laser weight.

With the advent of the "telecom bubble," feverish activity started around 1999 to create single-spatial-mode, high-power (~1-W CW) 0.98-μm emitting diode lasers for use as pumps for erbium-doped fiber amplifiers to be employed as signal boosters in long-distance fiber-optical communications. Although many complex and elegant approaches were tried, in the end, facet-passivated, 4–5-μm-wide conventional ridge-guide devices prevailed [8]. Even though single-spatial-mode CW powers as high as 1 W are achievable, reliability limits output to ~0.7 W CW due to bulk degradation [8].

Attempts to achieve long-term, reliable operation at higher coherent CW powers by using unstable resonator or master oscillator–power amplifier semiconductor-based configurations have failed [2, 9]. Other approaches consisted of incorporating periodic features, such as distributed-feedback gratings, in the device structure to realize so-called photonic-crystal lasers. However, when using photonic-crystal distributed-feedback devices, the induced periodic refractive-index steps are so small that they are comparable to thermally induced index steps in quasi-CW or CW operation. In turn, these lasers perform well only in low-duty-cycle (≤1%) pulsed operation; thus they are impractical since most applications require high average powers. Only high-index-contrast photonic-crystal lasers that possess long-range coupling between the photonic-crystal sites [2, 9] appear, at present, as the solution to achieving multi-watt CW coherent power from monolithic semiconductor lasers. High-index-contrast, long-range coupling photonic-crystal lasers were realized [9] as early as 1989 in the form of laterally resonant, phase-locked arrays of antiguided lasers, so-called resonant-optical-waveguide arrays. The lateral resonance feature ensures strong coupling between all array elements, in spite of large built-in index steps [9]. In 1991 the resonant-optical-waveguide array became the first diode laser to demonstrate 1-W peak power in a diffraction-limited beam [9], and in 1992 it was theoretically shown to be equivalent to a lateral distributed-feedback structure for which both index and gain vary periodically [9]: that is, an *active* photonic-crystal laser structure. Thus, the resonant-optical-waveguide array did constitute the first photonic-crystal laser developed for high-power, single-mode operation from large-aperture semiconductor lasers. In 1999, resonant-optical-waveguide arrays of an index step more than an order of magnitude larger than in photonic-crystal distributed-feedback structures demonstrated 1.6-W CW power [10] in a nearly diffraction-limited beam from a 200-μm-wide aperture. In 2010, the OSA presented Dan Botez, Philip Dunham Reed Professor at the University of Wisconsin–Madison and co-founder of Alfalight Inc., the Nick Holonyak, Jr. Award for the achievement of active photonic-crystal semiconductor-laser structures for high-coherent-power generation (Fig. 5).



▲ **Fig. 5.** Dan Botez, recipient of the 2010 Nick Holonyak, Jr. Award (at the time). (OPN June 2010 Optical Society Awards.)

High-power, reliable diode-laser technology reached a high degree of maturity by about 2005. Single-stripe devices with 10-W reliable output power and wall-plug efficiencies of ~65% are available from diode-laser manufacturers for various applications including single-diode pumping of solid-state lasers and fiber lasers. Laser bars, used mostly for pumping solid-state lasers, are commercially available with 200-W CW output powers, ~65% wall-plug efficiency and are guaranteed to operate for 30,000 hours. Future developments may involve the commercial realization of active photonic-crystal lasers for watt-range coherent CW powers as well as the use of photonic-crystal structures for emission of the generated light through the substrate (i.e., surface emission) for even higher coherent powers delivered in a reliable fashion.

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