Industrial markets beckon for high-power diode lasers

Changes in the design and manufacture of laser diodes are seeding fundamental shifts in the way that we think about the cost and reliability of high brightness laser systems. **Robert Martinsen** of nLight Corporation tells *OLE* more.

Industrial markets for material processing set some of the most stringent benchmarks for cost, performance and reliability and to date, diode lasers have seen only modest penetration into this space. At nLight, we believe that this will all change over the next couple of years.

Today, the fundamental difference is the collective progress that is being made in metrics that we usually consider to be opposing or competing. For example, new products are being introduced that scale power and brightness significantly in configurations with unprecedented durability, longer lifetimes and lower costs.

The collective impact of these improvements will not only strengthen the value of direct-diode solutions over legacy technologies, but should also accelerate the adoption of solid-state and fibre laser systems as the cost, performance and reliability of the diodes improve.

Equally important are the changes about to happen within the manufacturing infrastructure for high-power diodes. New opportunities will require an order of magnitude expansion of today's production capacities to supply millions of units per year, forcing increased automation and process control reminiscent of the silicon industry.

Industrial markets will benefit greatly from such an increase in volume of diodes as costs fall to potentially disruptive levels and quality standards are made stricter. Laser-based material processing will then become faster, better and cheaper than conventional technologies.

Cost-performance trends

The "Moore's Law" of the high-power semiconductor laser industry follows the dollar per watt trend for a centimetre-bar. Figure 2 shows the exponential decline in average selling price (ASP) over the past 20 years and its correlation with increases in rated power over the same period (a commercially available product with a minimum expected lifetime of 10 000 h is implied). If the past trend continues, an 808 nm bar will reduce to half of the current ASP within 4–5 years.

Perhaps more relevant to high-growth markets is the power scaling that we expect to see from the single emitters that are used to pump high-beam-quality fibre lasers, end-pumped solid-state and compact disk lasers. The thirst for greater power in a fundamental mode beam will continue and broad-area single emitters with stripe widths from 50 to 500 µm will fuel much of the growth.

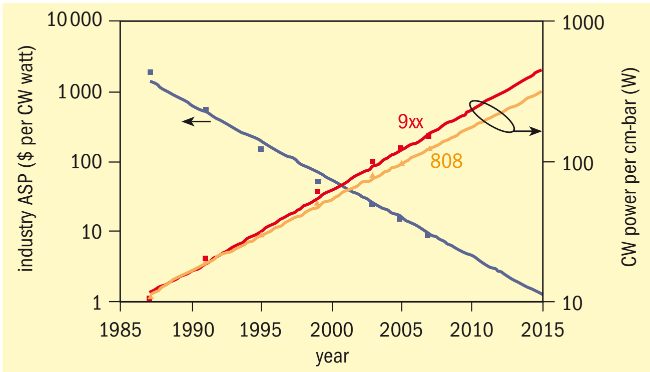
High-brightness, single-emitter packages that can efficiently aggregate power to kilowatt levels are beginning to roll out with free space and fibre-coupled options. This approach to scaling power, brightness and reliability in a small, low-cost, conduction-cooled format will likely refocus our Moore's Law to the true demands of the marketplace, such as dollar per efficient, bright watt per hour of expected lifetime.

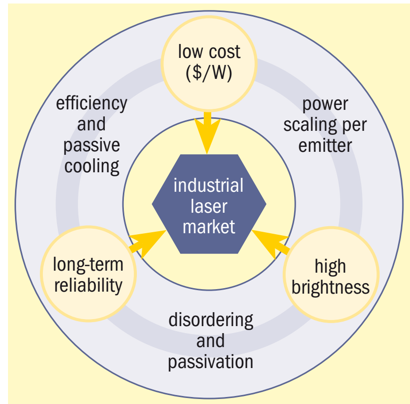
Performance and reliability

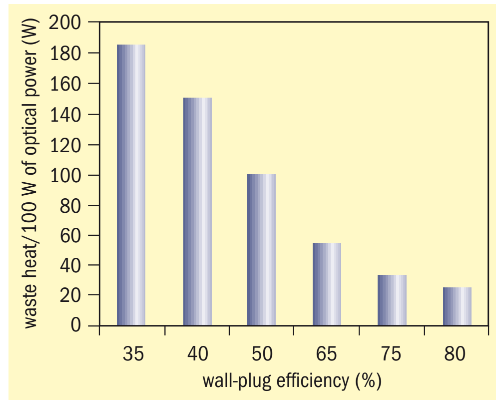
What is making this power scaling possible? Higher device efficiencies and packaging with improved heat transfer characteristics are critical, but certainly not the only factor.

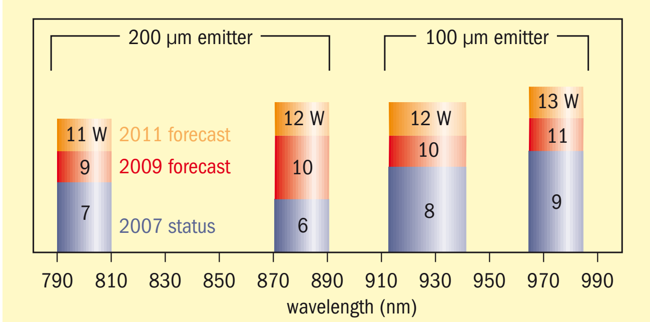
The challenge of realizing a 200 W, 808 nm bar product rests primarily with the required reliability advancements. Electrically isolated coolers that do not require de-ionized water; strain-balanced material systems that allow for bar-bonding with hard solders; and fluids that can leverage the latent heat exchange associated with mixed phase flows are among the key initiatives in roadmaps for higher power bars.

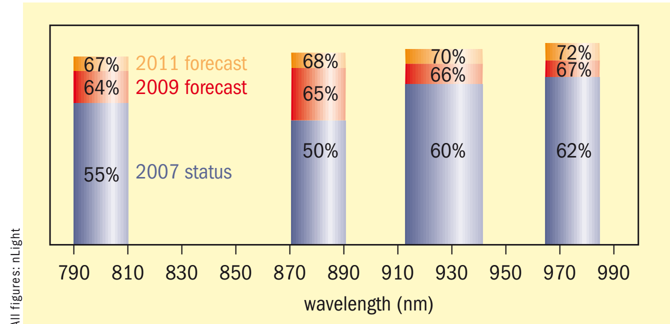
To ensure lifetimes of several tens of thousands of hours, facet protection to guard against catastrophic optical mirror damage (COMD) became mandatory when facet intensities exceeded 30 mW/µm of emitting aperture at 808 nm. Impurity-induced disordering and epitaxial passivation have proven effective by creating high-bandgap, non-absorbing regions (windows) at the facets. Large waveguides and long cavity lengths offer additional means to combat COMD by reducing optical field intensities, current densities and junction temperatures.











All figures: nLight

Fig. 1 (top middle): Initiatives driving semiconductor laser roadmaps are in strong alignment with the industrial market needs for material processing. Fig. 2 (top left): Price-performance trend for high-power centimetre-bars at 808 nm and 9xx nm wavelengths. Fig. 3 (middle left): Brightness of high-power laser diodes for direct material processing and pumping wavelengths between 800 and 980 nm. Fig. 4 (bottom left): Efficiency outlook for high-power laser diodes with wavelengths between 800 and 980 nm. Fig. 5 (top right): Waste heat reduction with efficiency advancements and improved thermal management.

Pulsed operation

Lasers for material processing are typically modulated rather than operated continuous wave (CW). Pulse formats are tailored to a specific application and can have virtually any combination of short or long pulses (microseconds to seconds) with low to high duty factors (1–50%).

Pulsed operation has been a major hurdle blocking the diode laser's entry into industrial markets because of fundamental material compatibility issues, namely, the strain mismatch between GaAs and copper. High-power diode-laser packaging has historically relied on indium solder to accommodate the high thermal performance of copper heat sinks and, under CW and limited pulsed operation, bar products have demonstrated over 30 000 h of expected lifetime with such packaging.

Hard solder packaging

It is not surprising to find that indium is being phased out as a solder for laser-die attach. The high fatigue strength and low creep characteristics of eutectic gold-tin (AuSn 80/20) solder, for example, offers a superior lifetime under pulsed conditions, long-term stability of wavelength and polarization, as well as high temperature operation.

The conundrum is that GaAs lasers cannot tolerate being AuSn-soldered to copper heat sinks as the strain mismatch would far exceed the stress fracture limit of the laser. The high modulus, shear strength and solidification temperature of eutectic AuSn requires a GaAs die to be mated with an expansion-matched heat-sink material.

Given today's material choices, this means losing approximately half of the thermal conductivity you once had with copper in the critical zone immediately under the chip (where most of the thermal resistance is accounted for). Therefore, devices tend to be "hard soldered" to relatively thin, lower conductivity, expansion-matched submounts such as CuW, AlN, CuMo or BeO, which in turn are bonded to a copper heat sink. While this approach reduces the thermal resistance penalty for pulsed reliability, today's sub-mount materials can result in around a 50% higher junction temperature compared with traditional indium-on-copper packaging for the same device.

Solutions to this dilemma include diamond-metal matrix and nanoparticle composites that are well matched to the expansion coefficient of GaAs, and have equivalent, or better, thermal conductivity compared with copper. A great deal of material science research has still to be done. While the prospects are compelling, a number of practical considerations still need to be resolved.

Success depends on how well the composite material suppliers address the demanding and peculiar requirements for p-side-down laser die bonding. This interface is critical to maintaining junction temperatures consistent with several tens of thousands of hours of lifetime in the presence of extraordinary heat flux ($>2\,kW/cm^2$) and high-temperature environments.

Since the thermal and mechanical requirements of high-power diode lasers far exceed those for microelectronics, the semiconductor laser industry will have to drive this innovation and develop the supply chain rather than be a follower of advanced thermal management technologies.

The importance of high efficiency

In order to improve the overall system reliability at higher power and with lower cost, efficiency improvements become key. It is worth noting that a strategy of simply using larger chip sizes can also lower junction temperatures by increasing the thermal footprint with the heat sink, but inevitably leads to higher costs (dollar per watt) given fewer available chips per wafer and reduced packaging yields.

Reducing the waste heat load has enormous implications. Less internal heat generation leads to lower junction temperatures and longer lifetimes, but also the cost and complexity of thermal management becomes more consistent with large markets.

When high-efficiency diode lasers are then used to pump low quantum defect brightness converters such as Yb-doped fibre lasers, disk lasers and upper laser level excited solid-state Nd lasers, a new generation of high-brightness technology unfolds. Compact, air-cooled, near-diffraction-limited industrial lasers in the 100 W to kilowatt-class not only become a distinct possibility, they are already being offered as fibre laser heads for less than $40/W.

What's next

Nothing creates momentum in innovation like high-volume opportunities. Entirely new markets for high-power diode lasers are emerging because critical thresholds for performance, reliability and cost are being reached. These ramps in production are driving the initiatives that are vitally important to industrial lasers.

By examining the timing of these multiple volume markets and tracking the progress in semiconductor laser brightness, efficiency and cost over the past 10 years, the following five projections seem reasonable for the next four years:

- AuSn-bonded centimetre-bars will continue to serve high-power, low-brightness applications in direct-diode material processing and side-pumping;
- Fibre-coupled lasers at the important wavelengths for pumping and direct material processing will have wall-plug efficiencies exceeding 65%, simplifying thermal management dramatically;
- Single-emitter-based packages will drive the lowest available cost per bright, reliable watt – a more meaningful figure of merit for industrial applications;
- Facet passivation and disordering technologies will continue to promote the scaling of single-emitter brightness to >60 mW/µm at 808 nm and >80 mW/µm at 9xx nm;
- Reliability and cost considerations for industrial applications will favour distributed, fault-tolerant, single-emitter-based packages, shedding their reliance on high-current drivers and sophisticated cooling.

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