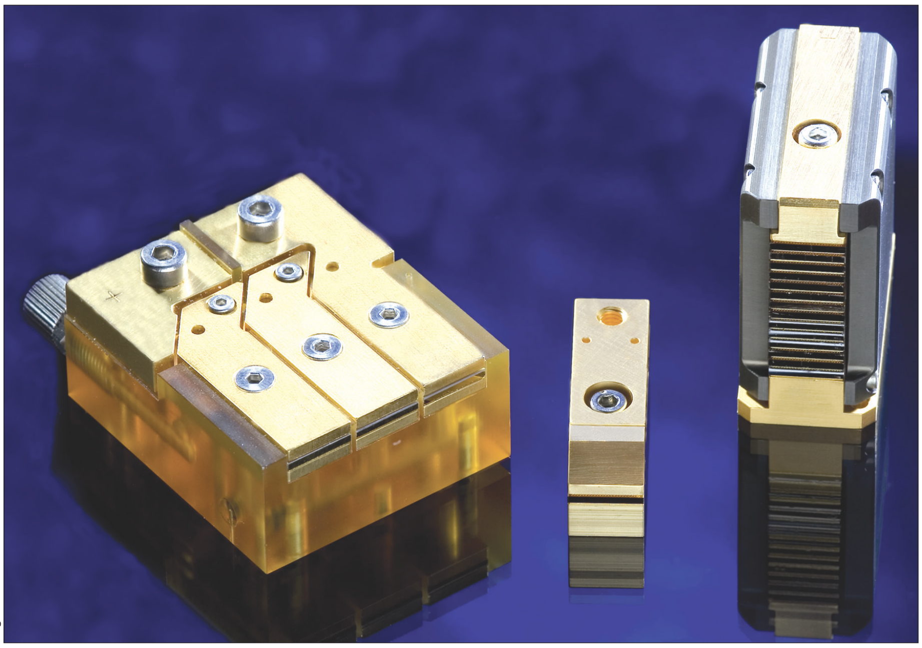
PRODUCT GUIDE

High-power diode lasers offer efficient answer

High-power diode bars that are highly efficient and boast output powers of hundreds of watts are now commercially available. **Merrill Apter** gives a tutorial on the technology.

It is widely recognized that high-power diode lasers (HPDLs) are compact, portable and highly reliable. Recent advances in their output power and the efficiency of their electrical-to-optical power conversion (more than 50%) are making them increasingly attractive for a wide range of industrial applications.

The main focus of this article will be diode-laser bars, which are made from broad-area edge-emitting semiconductor chips, and generate high-power continuous-wave (CW) or quasi-CW light. The aim is to provide new users of HPDLs with an understanding of their basic technical aspects and guidance on how to specify devices when purchasing them. Commonly used rules of thumb within the industry are also presented.



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An HPDL mounted on a heatsink to remove waste heat that is generated during high-power operation.

The basics explained

HPDLs are designed for three distinct modes of operation: classical CW; quasi-CW; and pulsed or high peak-power. Their typical operational characteristics are defined in the box (right). HPDLs can be constructed as single-emitter devices, 1D arrays (called bars), or 2D arrays of stacked bars.

An HPDL bar consists of a thin piece of semiconductor that features multiple broad-area emitters arranged in a line, with a small gap between each one. Bar dimensions are typically 140 μm high by 1 mm deep by 10 mm wide, and contain between 10 and 60 emitters precisely spaced along the bar.

The laser light is actually generated within a small (less than 1 μm high by 150 μm wide) active region in each emitter called the diode junction, and exits through the edge of the semiconductor. The result is that an array of small parallel light beams called "beamlets" are generated by the emitters and propagate away from the bar.

An important factor in bar design is its fill-factor. This describes the percentage of the bar that is occupied by emitters, and equals the width of one emitter divided by the centre-to-centre spacing between emitters. A typical bar might have 19 emitters, each 150 μm wide, on 500 μm centres, resulting in a 30% fill-factor. Commercially available conduction-cooled bars with a 30% fill-factor and 1 mm-long cavity can produce up to 40 W of total CW power, while water-cooled versions with an 80% fill-factor can provide up to 100 W CW.

Operational characteristics

Mode of operation	CW	Quasi-CW	Pulsed
Pulse width	n/a	hundreds of μs	hundreds of ns
Duty cycle	100%	less than 5%	1 kHz
Rated output power from a conduction-cooled package	50 W	100 W peak power/bar	30–50W peak-power device

When output powers of more than about 100 W are required, bars can be stacked in a 2D array. In this case, bar pitch refers to the centre-to-centre spacing between bars along horizontal spacing or a vertical stacking direction. These 2D arrays potentially emit incredible amounts of CW power from a very compact package. For example, a 10-bar 2D vertical stack array with a pitch of 1.8 mm might have an emission region measuring 16.2 × 10 mm. If each bar consists of 64 emitters generating 100 W, then the 2D array will have 640 emitters and a total power of 1 kW CW.

Beam characteristics

To describe the beam characteristics of a diode bar, it is useful to visualize the beam propagating in the z-direction, with the height of the active region along the y-axis and its width along the x-axis. Owing to the asymmetric shape of each emitter's active region (typically 1 μm high by 150 μm wide), the output beam from a bar is elliptical and ▷

astigmatic (beam-waist occurs at different locations in the x- and y-axes).

The beam in the y-axis is usually single-transverse-mode or diffraction-limited. As the height of the active region is so small, beam-divergence is usually very high – up to 30–40° full-angle at half-maximum power points. For this reason, the y-axis is also often called the fast axis of beam divergence.

In contrast, the beam in the x-axis is highly multimode, i.e. it has many transverse modes, and usually has a smaller beam-divergence of about 10° FWHM. The divergence is reduced because the width of the active region is so much larger than its height. Owing to the reduced beam-divergence, this axis is often referred to as the slow axis of beam divergence.

How to specify HPDLs

Wavelength: One of the first questions to consider when purchasing an HPDL is the wavelength of operation. Devices are commercially available with wavelengths spanning the 635–1600 nm range, but with some gaps in coverage. Semiconductor material systems include:

- AlGaInP/GaAs (635–700 nm)
- AlInGaAsP/GaAs (780–1000 nm)
- InGaAsP/InP (1250–1700 nm).

However, it is important to specify not just the desired centre-wavelength, but also the acceptable tolerance, as this strongly influences price. A useful rule of thumb is that the broader the centre-wavelength tolerance, the lower the price of the HPDL as the production yield increases. A standard tolerance on peak wavelength might be:

- ±3 nm for an 800 nm laser
- ±5 nm for a 900–980 nm laser and red diode laser
- ±10 nm for a 1400 nm or longer-wavelength diode laser.

When emission bandwidth is important, one may specify the full-width-at-half-maximum (FWHM) of the output beam. This is the spectral width, in nanometres, of the laser at the 50%-of-peak-power points. Alternatively, one might specify the full-width at 10% of peak, or the $1/e^2$ width, which is the full-width at 13.5%-of-peak-power points.

High-power bars at 6xx, 8xx and 9xx nm usually have spectral widths of 2–3 nm FWHM, while the spectral width in the 14xx nm and longer range is considerably broader, sometimes by a factor of 5–8.

Lifetime: Another important parameter is the lifetime of the diode laser. This is a measure of its reliability and describes how long a typical device will operate before it fails.

Today, the latest high-quality manufacturing techniques ensure that most manufacturers quote figures of tens of thousands of hours. However, it is important to remember that these lifetime figures are only valid for a particular set of operating conditions, which specify drive current, device temperature and output power. Deviations from the specified values are possible without catastrophically damaging the laser, but usually reduce its lifetime.

A further rule of thumb is that diode-laser lifetime halves for each 10 °C increase in case temperature above room temperature. Conversely, diode-laser lifetime can be increased by reducing the drive current, output power and temperature. Don't cool the device too much as condensation forming on the mirror facets could adversely affect the laser operation.

Output power: In general, output power scales linearly with increasing emitter width. For semiconductor materials that lase at 800 and 900 nm wavelengths, output power facet density is around 20–30 mW/µm of emitter width. Red diode lasers achieve about 5 mW/µm of emitter width, and lasers of 1400 nm or longer achieve 10–15 mW/µm. Lengthening the cavity of the emitter enhances its power output. Cavity lengths are typically in the ▷

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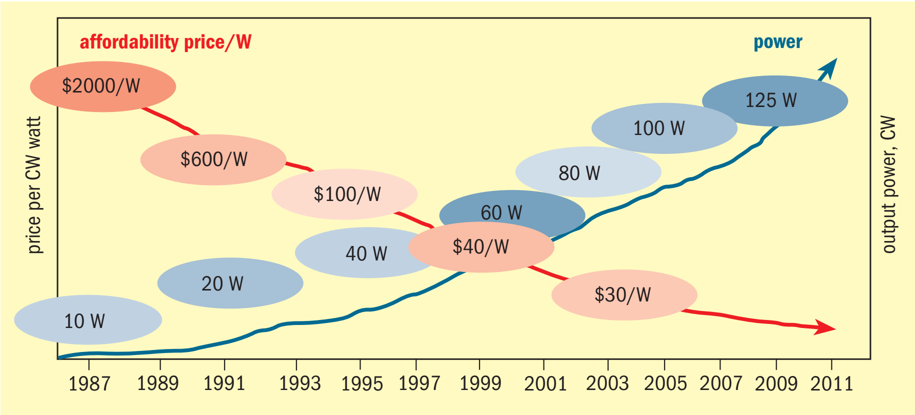
CS mount package for a laser-diode bar: the 1 cm-long bar is attached to a heatsink to remove waste heat and the package measures around 1 × 1 × 0.25 inches (above). A timeline of the affordability and output power of 1 cm laser-diode bar (below). Improvements have enabled the devices to become industrial tools.



0.6–1 mm range.

Polarization: A parameter that is often overlooked is the laser's emission polarization. Transverse-electric (TE) means that the emitted beam's electric-field polarization vector is parallel to the x-axis (plane of the diode junction). Transverse-magnetic (TM) means the magnetic-field vector is parallel to the diode junction plane, and the electric-field vector lies in a perpendicular direction along the y-axis.

Packaging and cooling: Conduction-cooled diode-laser bars are usually mounted on an open heatsink and can be enclosed in an environmentally sealed package to protect it and ease handling. Depending on the level of integration and sophistication, these enclosed packages can include internal thermoelectric coolers (a means to cool the diode) and thermistors (a means to measure and monitor the diode laser's case temperature). Water-cooled or actively cooled bars mounted on microchannel "coolers" can also be housed in the same types of sealed packages.

Low-power diode bars can also be conductively cooled using a CS package or something similar. A CS package is an industry-recognized package in which a single 1 cm × 1 mm diode bar is soldered to the heatsink or anode. A typical CS package measures 1 × 1 × 0.25 inches thick.

For higher-power bars emitting more than 50 W CW, water cooling is required to remove the heat that is generated. In this case, the solid copper block of the CS package is replaced by one with water channels that enable a turbulent flow of water to get close to the diode-bar junction and remove heat.

Water-cooled packages include copper macrochannel coolers (thermal resistance of ±0.5–0.6 °C/W) and copper microchannel coolers (0.2–0.3 °C/W). Silicon microchannel packages – not yet commercially available – replace the copper with a silicon mounting-plate, and have etched microchannels that bring waterflow to within 100 µm of the diode bar, to achieve thermal resistance of 0.1–0.15 °C/W.

The temperature of the diode laser may need to be actively stabilized to maximize its lifetime, or to stabilize its peak-emission wavelength. The emission wavelength shifts to longer wavelengths as the temperature rises. The shift is material-dependent and typical values are:

- 0.18 nm/°C for red diode-lasers.
- 0.28 nm/°C for 800 nm devices
- 0.34 nm/°C for 900 nm devices
- 0.4 nm/°C for 14xx nm devices

Optics/output options for diode bars

Microlens: Diode bars can be purchased with a microlens that is the same length as the bar and collimates all of the diverging beamlets in the fast-axis plane simultaneously. The diameter of the collimated beam roughly equals the focal length of the microlens and is usually 300–1000 µm FWHM.

Residual divergence after collimation is typically 0.2–3° FWHM, depending on the type of microlens used and how accurately it is aligned. Microlenses are available in a variety of shapes, such as circular and aspheric cross-sections. Some manufacturers supply diode bars with micro-optics to collimate emission in the slow-axis plane as well, but this is less common.

Multimode fibre: It is possible to purchase diode bars with an attached multimode optical-fibre bundle. The individual fibres within the bundle (at the launch end) are arranged in a linear array to enable one-to-one butt-coupling to the diode emitters.

The delivery end of the fibre bundle usually has the fibres arranged in a close-packed hexagonal configuration that enables the output beam to be coupled into a single multimode optical fibre or other circular-shaped aperture. The fibre bundle may be terminated with an SMA or other fibre connector. For example, emission from the fibre bundle might have a diameter of 0.8 mm and a numerical aperture of 0.12 (full-angle beam-divergence of 14°). Using an appropriate lens, the light from the bundle can be coupled into a single multimode fibre with a core size of 0.4 mm and numerical aperture of 0.25.

Quasi-CW output: Although diode bars can also be operated in a CW or quasi-CW emission mode, the term quasi-CW is used most often in the context of 2D laser-diode arrays.

For quasi-CW emission, drive current to the diode array is modulated on and off in a repetitive fashion so that each "emission on" interval is followed by an "emission off" interval. The duty factor of the quasi-CW emission is the percentage of time that the emission is on.

For example, if the "on" time is 1 ms, and the "off" time is 4 ms, then the duty factor is 20%. Peak power refers to the emitted power level when emission is on, whereas average power refers to power averaged over many on/off cycles. Average power is calculated by simply multiplying the peak power by the duty factor.

2D diode-laser arrays designed for quasi-CW operation can generate much higher peak-power levels than those designed for CW operation. This comes from the use of diode bars with much higher fill-factors – 80–90% instead of the 30–50% fill-factors used for CW bars. The higher fill-factor roughly doubles the peak power compared with a CW array which uses the same number of bars.

Cost and pricing: Factors that influence the price of HPDLs include required lifetime, output power and brightness (W/unit emission area and per-unit solid-angle of beam-divergence), wavelength and wavelength tolerance, and the need for water-cooling. Purchase quantity is another very important cost factor. Per-unit pricing may be reduced by 30–50% when purchasing in volumes of 100–1000 units.

Packaged diode bars generally cost $1000–3000 (€770–2300), depending on output power, package design and the manufacturer. A 40 W bar usually costs $1500–2500, depending on volumes and specifications, while fibre-coupling can easily increase price by 50–100%.

The pricing of 2D arrays scales in terms of the number of bars. Copper microchannel-cooled arrays are priced at $1000–2000/bar. The good news for users is that, over the last decade, as manufacturing processes have become more robust, competition has grown and diode lasers have steadily reduced in price.

Today, there are many options for designing and specifying diode-laser bars. Although there is some standardization within the HPDL industry, it is more the exception than the rule. For the most part, every manufacturer provides a slight product variant which may not be obvious at first glance. Potential purchasers must make sure that they understand how a specification has been described and measured in order to get the best deal. □

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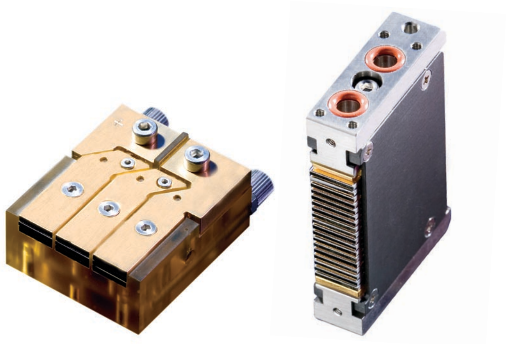

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