Introduction to Diode Laser Assemblies

Diode laser assemblies comprise, at a minimum, a semiconductor diode laser and beam-conditioning optics. In addition to these two basic elements, assemblies may include thermoelectric coolers (TECs), dc power supplies, and ac/dc converters, along with a variety of other options and accessories. To understand why these additional components are needed, it is necessary to understand the basic characteristics of the diode laser itself.

OUTPUT POWER

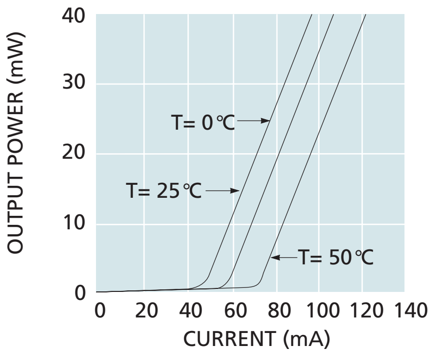
The output power from a diode laser is a function of both the current supplied to the diode junction and the temperature of the junction itself. Since the current through the diode generates heat at the junction, these two factors are highly interrelated. Typical relationships for output power, forward current, and junction temperature are shown for a generic diode laser in the accompanying figure.

AVAILABLE WAVELENGTHS

The basic diode lasers used in our assemblies are available in a wide range of wavelengths and output powers, ranging from 408 nm to 1550 nm and from 1 mW to 100 mW, depending on wavelength. Only the most popular lasers we offer are listed in this catalog. If you have a special OEM requirement, do not hesitate to call your nearest CVI Melles Griot sales office.

TEMPERATURE DEPENDENCE

In addition to the dependence of output power on junction temperature, wavelength exhibits a marked temperature dependence and can vary by several nanometers over a 20°C change in temperature, as can be seen in the figure on the next page. Wavelength variation is not a smooth function of temperature but occurs in abrupt jumps, called mode hops. Between mode hops, wavelength change can be as little as 0.05 nm/°C, with an average change in wavelength of 0.3 nm/°C over a large temperature range. The marked dependence of both power and wavelength on junction temperature illuminates the importance of either maintaining a constant junction temperature through thermoelectric cooling or maintaining output power with automatic power control (APC).



Output power vs current at constant temperature

TRANSVERSE MODE AND EMISSION ANGLES

The emission from a diode laser generally is TEM_{00} (Gaussian), but the emission angles are typically 10 degrees and 30 degrees parallel and perpendicular to the laser junction, respectively—with variability up to 25 percent from component to component. This illustrates the importance, when making an assembly, of matching collimating optics to each individual diode.

LONGITUDINAL MODE STRUCTURE

Below a defined threshold point, the diode laser will usually exhibit a spectral width of several nanometers with several longitudinal modes operating simultaneously—similar to a light-emitting diode (LED). Above threshold, spectral width is reduced to a fraction of a nanometer with a single longitudinal mode. If multimode behavior persists above threshold, the most common cause is optical feedback from light reflected back into the diode laser.

POLARIZATION

Diode lasers are linearly polarized with a nominal 100:1 extinction ratio typically in the direction parallel to their junction. This ratio varies with operating current, proximity to threshold, and the f-number of the collimating lens.

LIFETIME

Lifetimes in excess of 50,000 hours at room temperature are not uncommon for most low-power visible and near-infrared diode lasers. In general, operating life doubles for every 10°C reduction in operating temperature and halves for every 10°C increase. Current transients caused by inappropriate drive circuitry and electrostatic discharge (ESD) are the two primary causes of diode laser mortality.

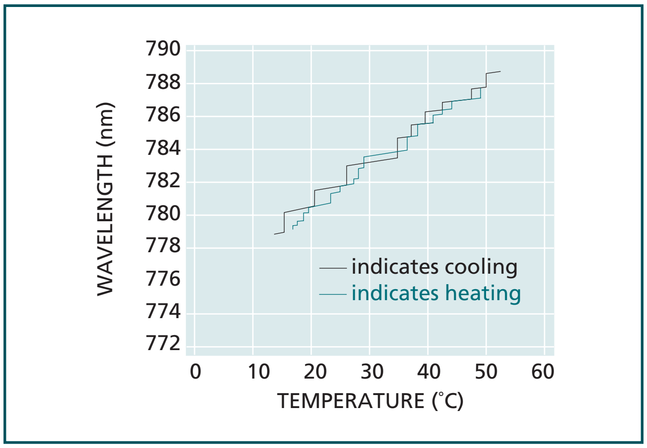
BEAM-DELIVERY METHODS

The two most common methods of delivering a diode laser beam are free-space optics (conventional lenses) and optical fibers. The free-space approach has been used extensively for scientific and industrial applications, because single-element or multielement glass lenses and molded plastic optics provide relatively good optical performance at a reasonable price.

Fiber-coupled diode laser assemblies, however, result in an optical beam quality that is far superior to that produced by bulk collimating and beam-shaping optical systems. Transmission through the fiber can eliminate high-order spatial modes and result in a diffraction-limited, circular output that is truly Gaussian and free from astigmatism. A drawback of these assemblies is optical efficiency. Single-mode fibers typically transmit from 20 to 40 percent of the available light for visible wavelengths and up to 75 percent for infrared wavelengths. Multimode fiber bundles can transmit more than 70 percent of the available visible light, but with a reduction in mode quality.

Benefits of free-space beam delivery

- High optical efficiency for greater output power
- Good beam quality—adequate for many high-volume applications
- Compact size for easy integration into most optical systems
- Low cost—an economical approach



Dependence of wavelength on temperature

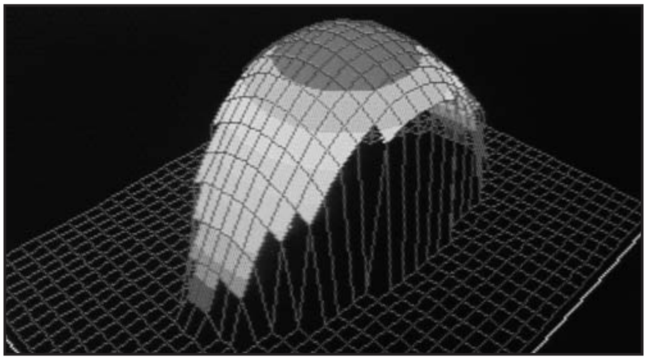
Benefits of fiber-coupled diode lasers

- Diffraction-limited, circular beam that is anastigmatic and can be focused to the theoretically smallest spot size or propagated over hundreds of meters while maintaining a clean, uniform beam shape
- Consistent beam size from unit to unit (traditional diode laser beams will vary by as much as 25 percent in size)
- Remote beam delivery over several meters possible without loss of optical power or degradation of beam quality

MODULATION

One inherent advantage of diode lasers over gas and diode-pumped solid-state (DPSS) laser sources is their ability to be directly modulated at a high data rate. The injection current to the laser diode, and thus the output power, can be rapidly changed by applying an analog or digital signal to the laser assembly. The speed of modulation is limited by the drive electronics. Advantages of modulation include the following:

- Extended life: Direct modulation of the laser lowers the duty cycle and increases overall life
- Power control: The output power of the laser can track an analog dc signal applied to the modulation input
- Synchronous detection: A modulated laser assembly can be synchronized with external equipment using various detection schemes
- Reduced system cost: A modulated laser diode module can reduce system size and cost by eliminating expensive and bulky acousto-optic modulators and acousto-optic tunable filters



Typical elliptical diode laser wavefront profile

About Diode Lasers

SEMICONDUCTOR DIODE LASERS

The means of generating optical gain in a diode laser, the recombination of injected holes and electrons (and consequent emission of photons) in a forward-biased semiconductor pn junction, represents the direct conversion of electricity to light. This is a very efficient process, and practical diode laser devices reach a 50-percent electrical-to-optical power conversion rate, at least an order of magnitude larger than most other lasers. Over the past 20 years, the trend has been one of a gradual replacement of other laser types by diode laser based-solutions, as the considerable challenges to engineering with diode lasers have been met.

Construction of a Double-Heterostructure Diode Laser

In addition to a means to create optical gain, a laser requires a feedback mechanism, a pair of mirrors to repeatedly circulate the light through the gain medium to build up the resulting beam by stimulated emission. The stripe structures needed to make a laser diode chip are formed on a single crystal wafer using the standard photolithographic patterning techniques of the semiconductor industry. The substrate crystal axes are first oriented relative to the patterning such that, after fabrication, a natural cleavage plane is normal to the stripe direction, and cleaving both ends of the chip provides a pair of plane, aligned crystal surfaces that act as a Fabry-Perot resonator for optical feedback. These mirrors use either the Fresnel reflectivity of the facet (often sufficient because of the high gain of diode lasers), or they can be dielectric coated to other reflectivities. This might be desired, for instance, to protect against damage from the high irradiance at the facets. This geometry gives the familiar edge-emitting diode laser.

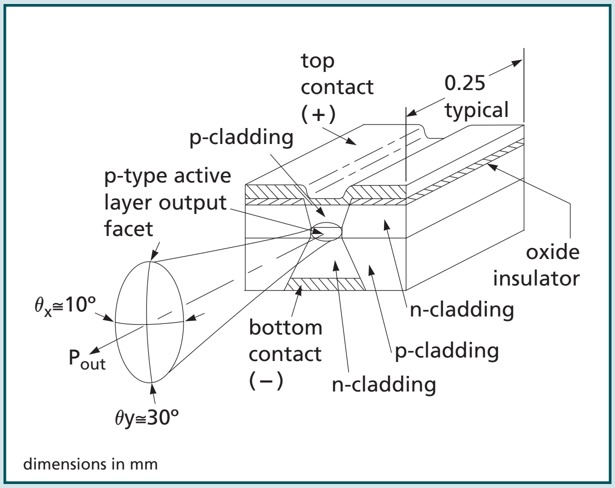
The semiconductor crystal must be defect free to avoid scattering of carriers and of light. To grow crystal layers without defects, commercial semiconductor lasers use III-V compounds, elements taken from those columns of the periodic table. These form varying alloys with the addition of dopants that can be lattice-matched to each other and to the initial crystal substrate. The band gap of the semiconductor chosen determines the lasing wavelength region. There are three main families: GaN-based lasers with UV-blue outputs, GaAs-based lasers with red-near infrared outputs, and InP-based lasers with infrared outputs. These base crystals are precisely doped with Ga, Al, In, As, and P to precisely control the band gap and index of refraction of the layers in the diode structure.

These compounds are direct band-gap semiconductors with efficient recombination of injected holes and electrons because no phonons (lattice vibrations) are required to conserve momentum in the recom-

Diode Laser Applications

Wavelength λ (nm)	Lattice Material*	Application
375	GaN	Biomedical fluorescence
405	GaN	Biomedical fluorescence, DVD mastering, direct-to-plate
440	GaN	Biomedical fluorescence, HeCd laser replacement
473	GaN	Biomedical fluorescence
488	GaN	Biomedical fluorescence
635–640	GaAs	Pointers, alignment, HeNe laser replacement
650–680	GaAs	Biomedical fluorescence, barcode scanners, pointers, alignment, surgical
780	GaAs	Audio CD readouts
785	GaAs	Raman spectroscopy
808	GaAs	Optical pumps for Nd:YAG lasers, thermal printing
940	InP	Optical pumps for Yb:YAG lasers
980	InP	Optical pumps for Er fiber telecom amplifiers
1310	InP	Input source for telecom short-wavelength channels, OCT
1455	InP	Optical pump for Raman gain in standard telecom fiber
1550	InP	Input source for telecom long-wavelength channels

*Ga, Al, In, P dopants are added to form the required layered strutures



Schematic of a double heterostructure index-guided diode laser

bination interaction. The injection layers surrounding the junction, the cladding layers, can be indirect band-gap semiconductors (where phonons are involved).

To make a planar waveguide that concentrates the light in the junction region (confinement between the top and bottom horizontal planes of the active region), the cladding layers are made of an alloy of lower refractive index (larger band gap) than the active junction region. This is then termed a double-heterostructure (DH) laser. The output power of the laser is horizontally polarized because the reflectivity of the planar waveguide is higher for the polarization direction parallel to the junction plane. Because the junction region is thin for efficient recombination (typically 0.1 μm), some light spreads into the cladding layers which are therefore made relatively thick (typically 1 μm) for adequate light confinement.

Gain Guiding and Index Guiding In Diode Lasers

To confine the light laterally (between planes perpendicular to the junction plane), two main methods are used. The first and simplest puts a narrow conductive stripe on the p-side of the device to limit the injected current to a line, giving a gain-guided laser. There is some spreading of current under the stripe, and the light is restricted only by absorption in the unpumped regions of the junction. The transverse mode of the laser light is therefore not tightly controlled. Many high-power diode lasers, used for instance in side-pumping another solid-state laser (where mode control is less critical), are gain guided.

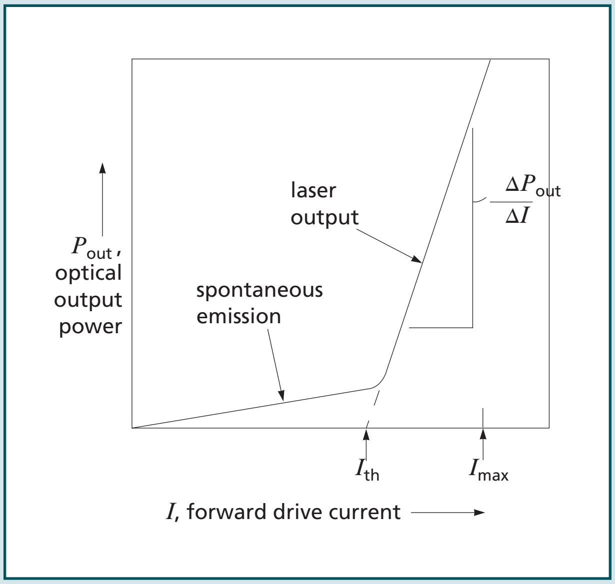
More efficient lateral laser mode control is achieved by fabricating, with multiple photolithographic, epitaxial, and etching steps, regions of low index of refraction on either side of the lasing stripe (the two lateral n-cladding regions in the upper half of the first figure). This confines the light by waveguiding between planes perpendicular to the junction plane as well giving an index-guided laser. These lasers produce a stable single transverse mode of lowest order.

Threshold Current and Slope Efficiency Definitions

Output power from a diode laser increases linearly with the drive current excess above the threshold current (see second figure). This steeply rising light output curve is extrapolated backward to the zero light output intercept to define the threshold current; the weak incoherent light emission for currents below threshold is due to the spontaneous recombination of carriers such as occurs in LEDs.

When divided by the drive voltage V, the slope of the output vs current curve yields the differential (above threshold) electrical-to-optical power conversion efficiency (also termed the slope or quantum efficiency) which ranges from 50 to 80 percent for various devices.

$$\text{Slope efficiency} = \frac{\Delta P_{out}}{V \Delta I} .$$



Definition of threshold current, I_{th}, and slope efficiency from the curve of light output, P_{out} vs drive current I