Laser Diodes

Laser Diodes are semiconductor lasers and are available in many different shapes and sizes with laser powers ranging from a few mW to hundreds of watts. The emitted wavelength depends mainly on the semiconductor material of the laser diode cavity and laser diodes are produced to cover the full visible spectrum from blue to red, and even beyond, with some emitting in the infrared.

The laser diodes distributed by Schäfter+Kirchhoff cover the whole wavelength range from 370 nm to 2300 nm.

Temperature and Power Dependence

The emitted spectrum is influenced by the diode temperature and diode current, as well as the geometry of the laser cavity. The front face and the end face serve as a Fabry-Perot cavity allowing multiple longitudinal modes. When operated just over the threshold, the diodes have a wavelength spectrum with equidistant peaks (longitudinally multimode). On increasing the diode current (to produce a higher power output), one of the longitudinal modes is usually favored and the diode emits in (longitudinally) singlemode. Unfortunately, the gain profile and the refractive index of the semiconductor material are temperature dependent and, so, other longitudinal modes can be amplified and the output wavelength changes rapidly, by up to a few nanometers, resulting in mode hopping.

For a non-stabilized singlemode diode, mode hopping occurs stochastically and the emitted wavelength and output power can change erratically by as much as 3%. For a temperature range of 20 to 30°C, the center wavelength can drift by 2.5–3 nm (GaAs).

Since changing the diode current changes the diode temperature, the current/power output dependence of the laser diode is only nominal. When the laser power is increased from the threshold up to the nominal power then the wavelength increases by 2–4 nm.

Astigmatism

The non-uniform gain profile within the active layer of the laser diode means that some laser diodes show astigmatism. Here, the laser radiation emitted parallel and perpendicular to the active layer does not emerge from one point at the cavity end, but appears to be emerging from two different positions. The distance between these is called the astigmatic difference ΔA and is between 3–40 μm. Astigmatism can be corrected by using anamorphic optics (SAN-...).

Coherence

The particular application determines whether a long coherence $L_c$ (here given for a Gaussian spectrum) or a short coherence is desirable. Non-stabilized singlemode lasers with stochastic changes of the wavelength also exhibit such changes in coherence behavior.

Superluminescent diodes use incoherent spontaneous emission to provide short coherence. For interferometry or spectroscopy, a long (or sufficient) coherence is essential, a feature of DFB, DBR VCSEL diodes with integrated or external thermo-electric cooling (TEC).

Wavelength Constancy

The emitted wavelength can be kept constant in a number of ways. External temperature control is possible using integrated or external Peltier elements and temperature sensors (see GTTE SOT-...). Most laser diodes also have an integrated monitor photodiode, providing feedback for control of the laser power.

The use of DFB (distributed feedback) or DBR diodes (distributed Bragg reflector) with their spectrally very narrow lines can be advantageous. With the help of a grid structure, only one longitudinal Fabry-Perot mode is amplified (stable singlemode) and mode hopping is suppressed.

VCSEL diodes use DBR structures to produce very narrow lines. The temperature dependence remains, however, and a constant wavelength can only be provided by using an integrated or external temperature control system with integrated monitoring photodiode.

Lifetime and Low Noise Operation

Laser diodes are very sensitive, especially when exposed to an electrostatic discharge. Surges in the current or voltage can damage a diode severely, making extremely stable power sources a necessity. The life expectancy of the diode is increased at lower diode temperatures and power outputs, making it very important to operate the diode below its maximum current.

Faraday Isolators (48FI-5-...) can effectively prevent back-reflection into the diode 2. Back-reflections can cause mode hopping 1 and instabilities in the diode wavelength as well as the power output that, in turn, result in faster degradation of the performance and to disturbance of the polarization.
Laser Collimation and Overview of Laser Diodes

Laser Collimation

Collimation optics transform a divergent beam with the divergence $\theta_c \times \theta_l$ into a collimated beam, retaining both its Gaussian intensity distribution and elliptical beam profile with diameters $\phi_1$ and $\phi_2$. The beam diameter $\phi_1$ at the collimator is also given at the 1/e²-level and is defined by the focal length $f$ of the collimating lens and the divergence $\theta_{l,\text{FWHM}}$ of the laser diode.

These differing definitions are responsible for the factor 1.7 in the equations above.

\[
\phi_1 = 2 \cdot f \cdot \sin \left( \frac{1}{2} \theta_{l,\text{FWHM}} \cdot 1.7 \right) \quad f = \text{focal length of collimating lens} \quad \phi_2 = \text{beam diameter (13.5%-level)} \\
\theta_{l,\text{FWHM}} = \text{laser diode beam divergence (50%-level)}
\]

Overview of Laser Diodes

<table>
<thead>
<tr>
<th>Component</th>
<th>Type of diode</th>
<th>Fabry Perot</th>
<th>DFB / DBR</th>
<th>Integrated TEC/NTC</th>
<th>VCSEL</th>
<th>Circular Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case type</td>
<td>Ø9</td>
<td>Ø5.6</td>
<td>TO3</td>
<td>TO5</td>
<td>Ø9</td>
</tr>
<tr>
<td>Integrated TEC/NTC</td>
<td>without</td>
<td>without</td>
<td>with and without</td>
<td>without</td>
<td>with</td>
<td>with and without</td>
</tr>
<tr>
<td>Description</td>
<td>Fabry-Perot laser diodes possess a good price-performance ratio because they are one of the commonest types of laser diode and they have a simple edge-emitting structure.</td>
<td>Distributed feedback (DFB) laser diodes have an integrated grating within the active medium while the grating structure for DBR diodes is outside of the active area. The emission bandwidth is narrow since the emission wavelength can be tuned by modifying either the applied current or the diode temperature.</td>
<td>Superluminescent diodes are characterized by spontaneous emission, producing a larger emission bandwidth with lower coherence length.</td>
<td>Vertical cavity surface-emitting laser diodes are inexpensive to produce. The beam profile is circular and the emission bandwidth narrow.</td>
<td>Circular Laser diodes have integrated internal beam-correcting (anamorphic) optics that produce a circular beam profile.</td>
<td></td>
</tr>
<tr>
<td>Wavelengths</td>
<td>390 – 515 nm</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>633 – 700 nm</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>700 – 1100 nm</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>1100 – 2300 nm</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Emission bandwidth</td>
<td>narrow</td>
<td>narrow</td>
<td>very narrow</td>
<td>very narrow</td>
<td>broad</td>
<td>very narrow</td>
</tr>
<tr>
<td>Coherence</td>
<td>varying</td>
<td>varying</td>
<td>long</td>
<td>long</td>
<td>short</td>
<td>long</td>
</tr>
<tr>
<td>Beam and spot profile</td>
<td>elliptical</td>
<td>elliptical</td>
<td>elliptical</td>
<td>elliptical</td>
<td>elliptical</td>
<td>circular</td>
</tr>
</tbody>
</table>

Even a collimated beam exhibits minimal divergence, since the beam diameter varies (for large distances) with the distance $\lambda$ from the laser diode collimator. The resulting beam divergences of the collimated beam $\phi_1$ and $\phi_2$ depend on the respective beam diameters at the collimator $\phi_1$ and $\phi_2$ and on the wavelength $\lambda$ of the emitted radiation. For an ideal Gaussian beam ($M^2 = 1$):

\[
\phi_1 = 2 \cdot \frac{\lambda}{\pi} \cdot \frac{\theta_1,\text{FWHM}}{\phi_1} = \text{beam divergence of the collimated beam} \\
\phi_2 = \frac{\lambda}{\pi} \cdot \theta_{l,\text{FWHM}} = \text{beam diameter (13.5%-level)} \\
\lambda = \text{wavelength}
\]
Laser lines are primarily characterized by their length and their working distance, with other parameters becoming relevant depending on the measuring task. The measurement resolution is determined by the line width and can be limited by speckle. A sufficient depth of focus has to be taken into account when measuring objects of variable height.

The Schäfter+Kirchhoff laser line generators were developed to satisfy these differing measurement requirements – providing laser micro lines for fine line widths and laser macro lines for extended depth of focus.

The fan angle can also be decisive in the choice of laser line and, for objects with glossy surfaces, Schäfter+Kirchhoff supplies laser line generators that are semi-telecentric.

The Schäfter+Kirchhoff laser spot generators are also differentiated in the same manner, with micro focus generators producing small spot sizes and macro focus generators providing extended depth of focus.

Line Width

Ideally, a thin laser line is used in order to maximize the signal intensity at the sensor. Measurement accuracy can be improved by using sub-pixel algorithms with thicker laser lines, assuming any disturbances caused by laser speckle (see below) are small enough.

For both micro and macro line generators, the width of the laser line is proportional to the working distance and the power density decreases for deviations from the specified working distance and line width. The relationship between the square of the line width and depth of focus means that the depth of focus of a laser line required by an application effectively limits the minimum laser line width that can be used and, thereby, the signal intensity at the sensor.

Adjustment of the collimating lens generates a convergent beam. At distance $A$ relative to the fiber collimator, a beam propagation with width $B$ is formed.

$$B = \frac{4 \cdot \lambda \cdot A}{\pi \cdot \mathcal{O}}$$

where

- $B$ = line width [mm]
- $A$ = working distance [mm]
- $\lambda$ = wavelength of the laser emission [mm]
- $\mathcal{O}$ = cross-section [mm$^2$] of the collimated laser beam at the 1/e$^2$ level parallel to the active diode strip

Correction factor $F$

The beam properties of the laser line/focus generators are presented for a collimator using a diode example, the diode M26 with a wavelength of 660 nm and its distinct divergence angle; these diode characteristics determine the actual line width/spot size and Rayleigh range/depth of focus available for use. Thus, for laser diode choices other than M26 with 660 nm the line width/spot size and Rayleigh range/depth of focus values must be recalculated using the correction factor $F$ provided for each diode in the outmost right column of the right table. The other beam parameters remain the same.

For correction of:

- line width/spot size: multiply by $F$
- Rayleigh range/depth of focus: multiply by $F^2 \cdot 660 / \lambda$ (in nm)

Line Length and Line Width Extrapolation

The rule of propagation provides the equation for the extrapolation of line width and length. With the values $L_1$, $B_1$, and $L_2$, $B_2$ for two working distances $A_1$ and $A_2$, then the line length $L$ and line width $B$ for the desired working distance $A$ can be calculated from:

$$L = L_1 + \frac{L_2 - L_1}{A_1 - A_2} (A - A_1)$$

$$B = B_1 + \frac{B_2 - B_1}{A_1 - A_2} (A - A_1)$$

Example: Length L and Width B of 13LR25-S250 at A = 300 mm

Look up values in Table 1.1a (Page 22):

- $A_1 = 248$ mm
- $A_2 = 496$ mm
- $L_1 = 109$ mm
- $L_2 = 217$ mm
- $B_1 = 0.063$ mm
- $B_2 = 0.126$ mm

Insert into the formulas above

- $L = 132$ mm
- $B = 0.076$ mm at $A = 300$ mm for 13LR25-S250

Laser Speckle

Laser speckle is interference caused by stochastic lateral displacement of the coherent laser radiation upon reflection from a rough surface. Laser speckle disturbs the edge sharpness and homogeneity of the imaged laser line.

The granularity of the laser speckle depends on the aperture setting of the objective used to image the laser line. With a small f-number / large aperture, the generated speckles have a high spatial frequency and produce a distinct image (see Figure 1B), whereas the speckles are more granular and particularly disturbing when using a larger f-number/smaller aperture (see Figure 1C).

The generation of laser speckle cannot be avoided as the principle of laser light-sectioning relies upon the imaged surface being roughly textured and diffusely reflecting optically.

A substantial reduction in the speckle effect is achieved by:

- choosing large lens apertures/small aperture numbers for the objective, which improves depth discrimination but at the expense of depth of focus,
- altering the distance between the object and the sensor, which is most convenient when a scanning measurement is being performed anyway, such as profile measurement of railroad tracks while the train is moving,
- using a laser beam source with decreased coherence length, such as a superluminescent diode or laser of the LNC-Series (p. 49f).

Figure 1: 3D profiling by use of laser light sectioning

- Improvement of laser speckling with larger aperture objectives

  - A: Measured object with generated laser lines X1 and X2 at an incident angle of 60° and with an additional dome illumination of the object.
  - B: Object imaged with a large aperture, f/# 2.8. The imaging lens acts as a spatial frequency filter, restricting the measurement to a shallower dissecting plane and minimizing the speckle effect.
  - C: Object imaged with a small aperture, f/# 22, which increases speckle and granularity, bringing uncertainty in the contour of the line.
Physics Fundamentals: Micro and Macro Laser Lines or Spots

Laser Micro Line Generators and Laser Micro Focus Generators

- Narrow laser line widths or small laser spots
- High power density in the focal plane
- Gaussian intensity profile across the laser line or laser spot

Laser Macro Line Generators and Laser Macro Focus Generators

- Larger, almost constant laser line widths or spot sizes with lower power density
- Extended depth of focus (7 to 35-times greater)
- Approx. Gaussian intensity profile across the laser line or laser spot

Depth of Focus of a Laser Line

The laser lines are focussed at a defined working distance and attempts at focussing outside of this narrow range produces line broadening and power intensity reductions. The range around the nominal working distance, in which the laser line does not increase by more than a factor 1.41, is usually specified as the depth of focus of that laser line and is specified differently for the two types of laser line generator.

Laser Micro Line Generators (see Figure 2) produce narrow laser lines with a high power density and a Gaussian intensity profile across the laser line.

For a laser line with line width \( B \) (at the 13.5% level) and wavelength \( \lambda \), the depth of focus is defined as the Rayleigh range \( 2z_R \):

\[
2z_R = \frac{\pi B^2}{2\lambda}
\]

Laser Macro Line Generators generate laser lines with an extended depth of focus. Within the depth of the focus range, the intensity profile across the laser line is approximately Gaussian and the side lobes caused by diffraction remain below the 13.5% intensity level within the depth of focus range (Figure 3).

Laser Micro Focus Generators produce laser spots with high power density and a Gaussian intensity profile. The line width \( B \) is replaced by the spot diameter in the formula to reveal the Rayleigh range.

Applications for Laser Micro Line/Focus Generators:
- Scattered light measurements
- Photometry
- Laser triangulation / 3D-Profiling: with narrow laser lines for detecting small changes within a small height range

Laser Macro Focus Generators generate laser spots with lower power density and an extended depth of focus. The intensity profile is approximately Gaussian. The line width \( B \) is replaced by the spot diameter in the formula to reveal the depth of focus.

Applications for Laser Macro Line/Focus Generators:
- Machine vision
- Laser triangulation / 3D profiling: with larger laser line widths for detecting over a large height measurement range