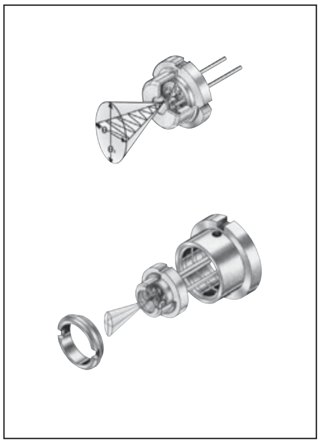
Physics Fundamentals: Laser Diode Characteristics

Laser Diodes

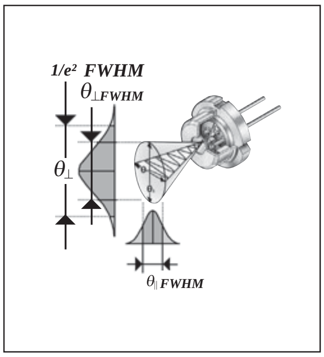


Laser Diodes are semiconductor lasers and are available in many different shapes and sizes with laser powers ranging from a few mW to hundreds of watts.

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.

Divergence and Polarization

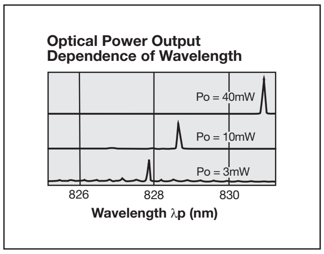


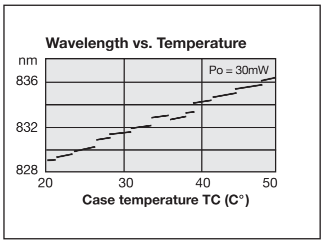
The microscopic cross-section of the laser diode active area of 1 x 3 µm results in emitted radiation that is divergent. Most laser diodes have a cone of divergent radiation with an elliptical cross-section and an approximately Gaussian intensity distribution. The ellipticity can be overcome with the help of anamorphic optics.

Some diodes (e.g. **VCSEL** or **Circular Laser**) are designed to produce a circular beam profile.

The polarization of the emitted radiation is linear and is parallel to the active area of the diode. The degree of polarization varies with the diode current and is lowest at the threshold.

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.

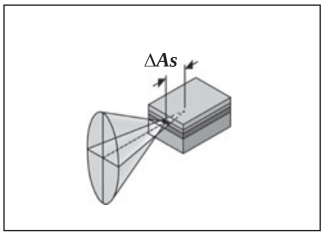
When operated just over the threshold, the diodes have a wavelength spectrum with equidistant peaks (longitudinally **multimode**). On increasing the diode current (to produce a higher power output), one of the longitudinal modes is usually favored and the diode emits in (longitudinally) **singlemode**.

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).

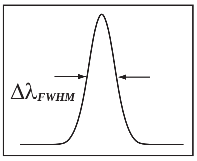
Since changing the diode current changes the diode temperature, the current/power output dependence of the laser diode is only nominal. When the laser power is increased from the threshold up to the nominal power then the wavelength increases by 2–4 nm.

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 ΔAs and is between 3–40 µm. Astigmatism can be corrected by using anamorphic optics (**5AN-...**).

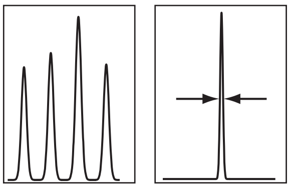
Coherence



$$L_c = \frac{\lambda^2}{\Delta\lambda_{FWHM}}$$

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 stochastic 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



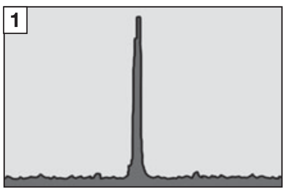
Non-stabilized singlemode diode | Narrow tunable DFB spectrum

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 **48TE SOT-...**). Most laser diodes also have an integrated monitor photodiode, providing feedback for control of the laser power.

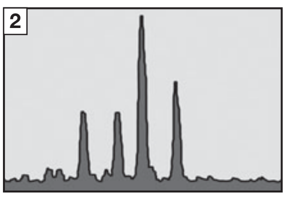
The use of **DFB (distributed feedback)** or **DBR diodes (distributed Bragg reflector)** with their spectrally very narrow lines can be advantageous. With the help of a grid structure, only one longitudinal Fabry-Perot mode is amplified (stable singlemode) and mode hopping is suppressed.

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



Faraday isolator prevents back-reflection and the diode spectrum is undisturbed



Mode hopping from destabilization of the diode by back-reflections

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 [1].

Back-reflections can cause mode hopping [2] 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.

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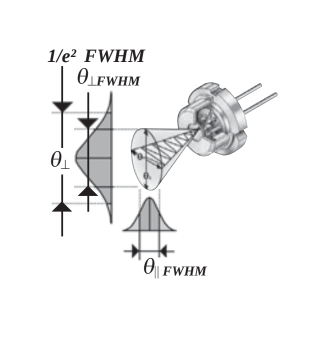
Laser Collimation and Overview of Laser Diodes

Laser Collimation



The beam can be characterized by the divergence $\theta_\perp$ x $\theta_\parallel$ measured perpendicular and parallel to the active surface area at the 1/e²-level (= 13.5%).
Beam characteristics can also be described at the 50% intensity level and are then defined by the divergence $\theta_{\perp FWHM}$ x $\theta_{\parallel FWHM}$ (FWHM: full-width at half-maximum).

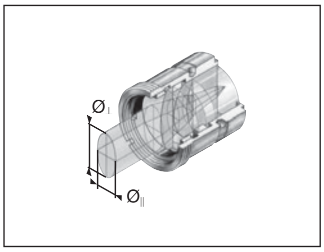
For laser diodes, the parameters $\theta_{\perp FWHM}$ x $\theta_{\parallel FWHM}$ are usually specified and for a collimated beam, a description at the 1/e²-level is more suitable.

Collimation optics transform a divergent beam with the divergence $\theta_\perp$ x $\theta_\parallel$ into a collimated beam, retaining both its Gaussian intensity distribution and elliptical beam profile with diameters $\varnothing_\perp$ x $\varnothing_\parallel$. The beam diameter $\varnothing_{\perp,\parallel}$ 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 $\theta_{\perp,\parallel FWHM}$ of the laser diode.
These differing definitions are responsible for the factor 1.7 in the equations above.

$$\varnothing_\parallel = 2\cdot f\cdot \sin\left(\frac{1}{2}\cdot\theta_{\parallel FWHM}\cdot 1.7\right)$$

$$\varnothing_\perp = 2\cdot f\cdot \sin\left(\frac{1}{2}\cdot\theta_{\perp FWHM}\cdot 1.7\right)$$

f = focal length of collimating lens
$\varnothing_{\perp,\parallel}$ = beam diameter (13.5%-level)
$\theta_{\perp,\parallel\, FWHM}$ = laser diode beam divergence (50%-level)



Even a collimated beam exhibits minimal divergence, since the beam diameter varies (for large distances) with the distance A from the laser diode collimator. The resulting beam divergences of the collimated beam $\vartheta_\perp$ and $\vartheta_\parallel$ depend on the respective beam diameters at the collimator $\varnothing_\perp$ and $\varnothing_\parallel$ and on the wavelength λ of the emitted radiation. For an ideal Gaussian beam (M² = 1):

$$\vartheta_{\perp/\parallel} = \frac{2\cdot\lambda}{\pi\cdot\varnothing_{\perp/\parallel}}$$

$\vartheta_{\perp,\parallel}$ = beam divergence of the collimated beam
$\varnothing_{\perp,\parallel}$ = beam diameter (13.5%-level)
λ = wavelength

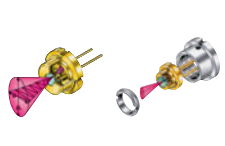
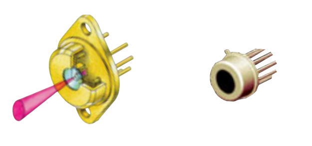
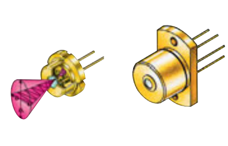
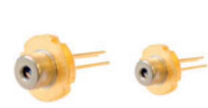
Collimating Lenses

The collimating lenses from **Schäfter+Kirchhoff** are manufactured from high quality glass. Beam collimation and beam shape are up to 30x more stable in comparison with plastic lenses, which exhibit variations in refractive index and shape with changes in temperature.

Bi-asphere lenses are used for collimating monochromatic radiation and exhibit the same correction and imaging quality as microscope lenses with three or four elements. The particular manufacturing process produces micro structures on the lens surface, which are manifest in the collimated beam but not in a focussed spot. Triplet lenses are three lens systems of spherical elements with high quality surfaces that provide a substantial level of spherical correction and a high numerical aperture.

In the wavelength range 370–2300 nm, lenses are provided with an individual anti-reflex coating that cover a few hundred nm of bandwidth.

Overview of Laser Diodes

Component									
Type of diode	Fabry Perot		DFB / DBR		**Integrated TEC/NTC**		VCSEL	Circular Laser	
Case type	Ø9	Ø5.6	TO3	TO5	Ø9	TOW 2	TO46	Ø9	Ø5.6
Integrated TEC/NTC	without	without	with and without	with and without	without	with	with and without	without	
Description	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.		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.		Superluminescent diodes are characterized by spontaneous emission, producing a larger emission bandwidth with lower coherence length.		Vertical cavity surface-emitting laser diodes are inexpensive to produce. The beam profile is circular and the emission band-width narrow.	Circular Laser diodes have integrated internal beam-correcting (anamorphic) optics that produce a circular beam profile.	
Wavelengths									
390 – 515 nm	x	x							
633 – 700 nm	x	x			x	x	x	x	x
700 – 1100 nm	x	x	x	x	x	x	x	x	x
1100 – 2300 nm			x	x			x		
Emission bandwidth	narrow	narrow	very narrow	very narrow	broad	broad	very narrow	narrow	narrow
Coherence	varying	varying	long	long	short	short	long	varying	varying
Beam and spot profile	elliptical	elliptical	elliptical	elliptical	elliptical	elliptical	circular	circular	circular

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Physics Fundamentals: Structured Laser Illumination

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.

$$B = \frac{4 \cdot \lambda \cdot A}{\pi \cdot \varnothing_{\parallel}}$$

B = line width [mm]
A = working distance [mm]
λ = wavelength of the laser emission [mm]
$\varnothing_{\parallel}$ = cross-section [mm] 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:

$$L = L_1 + \frac{L_2 - L_1}{A_2 - A_1} \cdot (A - A_1) \qquad B = B_1 + \frac{B_2 - B_1}{A_2 - A_1} \cdot (A - A_1)$$

Example: Length L and Width B of 13LR25-S250 at A = 300 mm
Look up values in Table 1.1a (Page 22):

A1 = 248 mm A2 = 496 mm L1 = 109 mm L2 = 217 mm
B1 = 0.063 mm B2 = 0.126 mm and 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 homogeneous 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 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).

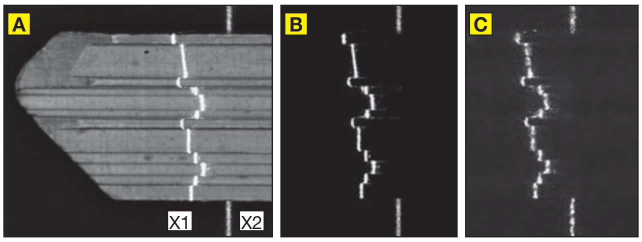


Figure 1: 3D profiling by use of laser light sectioning Improvement of laser speckling with larger aperture objectives

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

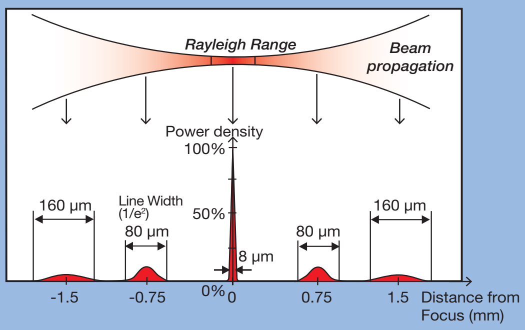


Figure 2: Micro line intensity profile and line width characteristics

- **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

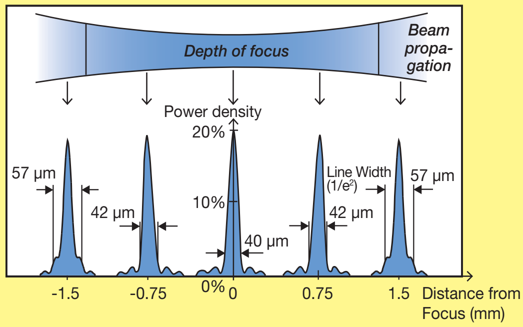


Figure 3: Macro line intensity profile and line width characteristics

- **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.

Which Laser Line/Focus Generator: Micro or Macro?

Micro lines/spots have a high power density close to their focus but the line width increases and the power density falls drastically when out of focus. In comparison, the power density of a macro line/spot is lower but does not change significantly over a larger range.

A compromise must be found for each application between either the benefits of a larger depth of focus, comparatively large line width/ spot size with a lower power density, or narrower lines/smaller spots with a high power density and a smaller depth of focus.

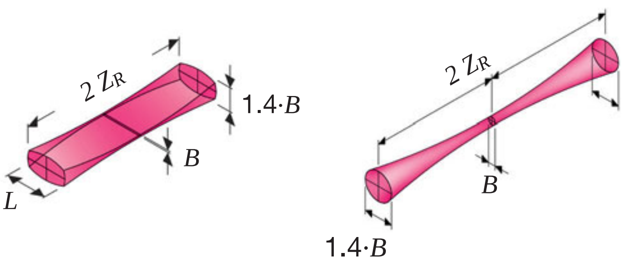
Laser Micro Line Generators (see Figure 2) produce narrow laser lines with a high power density and a Gaussian intensity profile across the laser line.

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

Rayleigh range

B = line width [mm]
λ = laser wavelength [nm]

$$2z_R = \frac{\pi B^2}{2\lambda}$$



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:

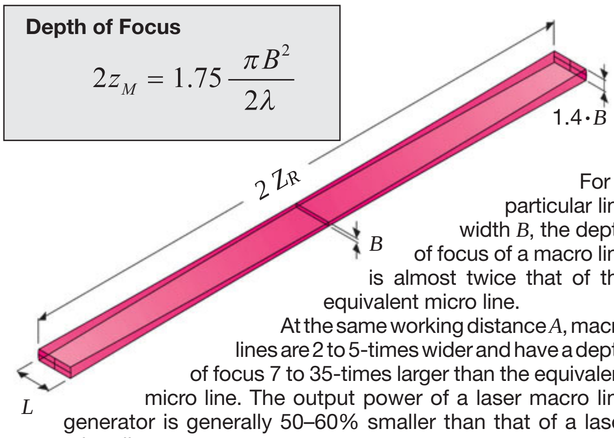
- Scattered light measurements
- Position sensing
- Photometry
- Machine vision
- Laser triangulation / 3D-Profiling: with narrow laser lines for detecting small changes within a small height range

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).

For a laser line with line width B (at the 13.5 % level) and wavelength λ, the depth of focus $2z_M$ is defined as:

Depth of Focus

$$2z_M = 1.75\,\frac{\pi B^2}{2\lambda}$$



For a particular line width B, the depth of focus of a macro line is almost twice that of the equivalent micro line.

At the same working distance A, macro lines are 2 to 5-times wider and have a depth of focus 7 to 35-times larger than the equivalent micro line. The output power of a laser macro line generator is generally 50–60% smaller than that of a laser micro line generator.

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 Micro Line/Focus Generators:

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

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