Laser Sources for Metrology and Machine Vision

Laser diode based light sources are widely used for high precision measurement and inspection systems

Best of Applications
OPTIK & PHOTONIK
Invited Article

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The laser sources shown in Fig. 1 combine a laser diode with refractive and sometimes diffractive optics to achieve the required beam shape. The form and shape of the beams reflect the broad variety of their application. Even within the basic groupings of laser line, laser spot or pattern, there are variants that differ widely in their physical characteristics.

Fig. 1 Laser beam sources for 3D measuring and process control applications: laser lines are ideal for triangulation and laser light sectioning, telecentric beams predestined for laser diffraction and laser spots for particle counting and sizing.

Laser triangulation, also called laser light sectioning, is the most common application of a laser line. It is a 3D measuring technique for determining a profile at a predefined incident section (Fig. 2). The imaging camera is mounted directly perpendicular to the scanned object. It measures the lateral displacement and distortion of the incident laser line projected at an angle onto the object. The recorded camera image contains all of the height information obtained from the section defined by the incident laser beam, which is then decoded to provide the 3D height profile as the object passes through the laser line camera detection system.

The depth of the measuring area and its resolution are determined by the triangulation angle between the planes of the dissecting laser line and the optical axis of the camera lens, with deeper angles of the dissecting incident laser line producing the greatest range in recordable height variations.

Particle counting and measuring is another important application which uses laser lines or laser spots. In the most simple setup a detector registers the light reflected by a particle passing through the laser beam.

Other applications make use of the smallness of a laser diode emitter. With a typical emitter size of 1 µm × 3 µm, single mode laser diodes combined with long focal optics result in large laser beams with very small divergence (typical 0.03 mrad). These laser sources are used for width and gap measurements, using simply the shadow, or in more sophisticated cases the diffraction pattern of the object placed into the beam.

Beam characterization

Laser lines, e.g., are primarily characterized by their length, width and working distance. The measurement resolution is often determined by the line width and can be limited by laser speckle. A sufficient depth of focus has to be taken into account when measuring objects of variable height. The fan angle of the laser can also be decisive in the choice of laser line. A large fan angle is required for long lines at short distances.

A so-called semi-telecentric laser line, with zero fan angle, might be appropriate in case of a glossy surface and a reflection based measurement technique.

In addition, there are other important parameters, like wavelength, coherence length, output power, and power noise, which have to be considered before a laser source is selected for a specific measurement task. Some of these aspects are subsequently discussed in more detail.

Wavelength

Laser sources based on laser diodes are available in wavelengths from 375 nm in the near UV to over 2300 nm in the

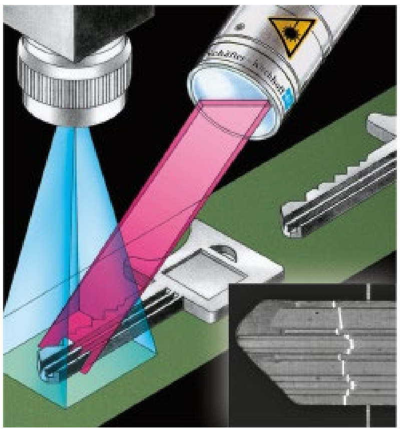

Fig. 2 Profiling an object with laser triangulation. Insert: the image obtained from the camera. The relative displacement of the laser line provides information about the object height at that point.

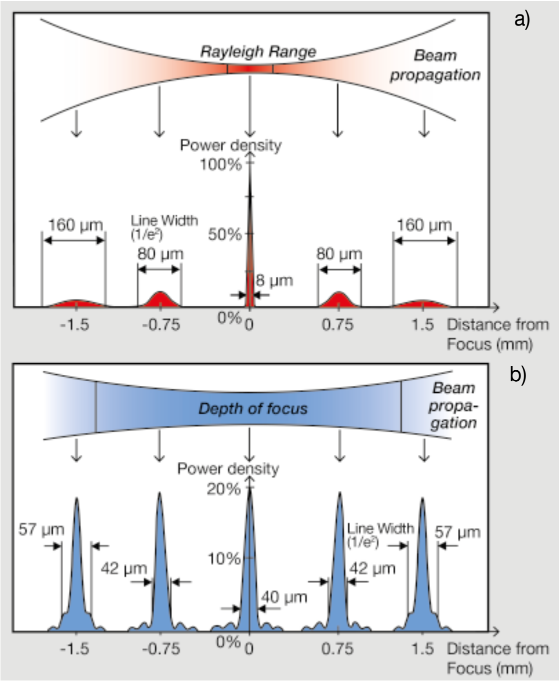

Fig. 3 Micro lines (a) exhibit a high power density at the focus, but line width increases and power density decreases considerably outside this point. Macro lines (b) have a lower power density but an extended depth of focus (approx. 7 – 40 times larger).

IR. For most inspection systems, the usable wavelengths are limited by the sensitivity of the camera to the visual spectrum range 400 – 700 nm plus the shorter end of the near infrared (up to about 1000 nm). Within the visual range, the wavelength is further limited to the wavelengths available from laser diodes. There are still some gaps in the spectrum, on the market are violet (405 – 410 nm), blue (415 – 488 nm), green (515 – 520 nm), and red (635 – 690 nm) laser diodes.

Company

Schäfter+Kirchhoff
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Schäfter+Kirchhoff has accumulated substantial experience in the development of opto-mechanical and opto-electronic systems for use in research, aviation and in space, as well as for demanding medical and industrial applications. Schäfter+Kirchhoff designs and manufactures their own line scan camera systems, laser sources, beam-shaping optics and fiber-optic components, including laser beam couplers, fiber collimators and fiber port clusters for customers worldwide.

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Violet or blue are often used when very thin lines or small spots are required, and depth of focus is not important. Most other applications still work with red lasers, where the price-performance ratio is optimal.

Micro and macro laser lines

Thin laser lines are often preferred in order to maximize the signal intensity at the sensor. Sometimes they are even necessary if the required resolution is small compared to the width of standard laser lines. If a laser line is very near to the diffraction limited ideal of a focused Gaussian beam, we call it a micro laser line. The line width still depends on parameters like wavelength and working distance, but these lines provide for each case the smallest possible line width within the laws of physics.

But thin laser lines are limited by their small depth of focus. The line width increases and the power density falls drastically when the line is out of focus (Fig. 3a). 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.

For a micro laser line of width B and wavelength λ it is given by the so called Rayleigh range (twice the Rayleigh length z_R), defined by

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

For a 660 nm (red) laser line with 10 µm line width, e.g., the Rayleigh range is only 0.15 mm. This is definitely not suitable if, e.g., height variations of 1 mm are to be measured with laser triangulation.

So-called macro laser lines have an extended depth of focus. Within the depth of focus range, the intensity profile across the laser line is approximately Gaussian, the side lobes caused by diffraction remain below the 13.5 % intensity level within the depth of focus range (Fig. 3b). For a macro laser line with width B and wavelength λ, the depth of focus $2\,z_M$ is defined as

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

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 macro lines are 2 – 5 times wider than micro lines, leading to a depth of focus extended by a factor of approx. 7 – 40.

Laser speckle

Laser speckle arise from multiple interference, caused by, e.g., diffuse reflection of laser radiation on optically rough surfaces (height variations > $\lambda/4$).

A laser beam observed directly with, e.g., the camera of a beam profiling system, appears smooth. If the same beam is directed to a rough surface and then imaged onto the camera sensor, the typical speckle intensity pattern appears.

The speckle contrast and size generally depends on the spot size and the size of the aperture of the optics as well as the measurement geometry. In case of a laser line, laser speckle disturbs the 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 more homogeneous image (see Fig. 4a), whereas the speckles are more granular and particularly disturbing when using a larger *f*-number (i.e. smaller aperture, see Fig. 4b).

The generation of laser speckle in most cases cannot be avoided. 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 can be achieved by:

- choosing large lens apertures (small *f*-numbers) for the objective lens, which reduces speckle size, at the expense of a reduced depth of focus (Fig. 4),

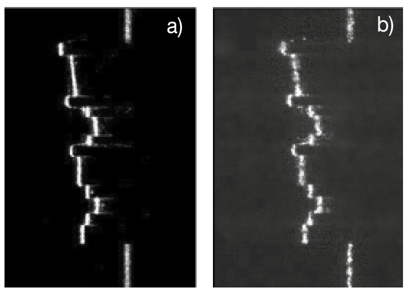


Fig. 4 Laser speckle behavior imaged with a small *f*-number k = 2.8 (a) and with a large *f*-number k = 22 (b).

- using a laser beam source with decreased coherence length, such as a superluminescent diode or a laser of the LNC-Series.

Laser diode modules with low noise and reduced coherence

Conventional singlemode laser diodes are semiconductor lasers and usually operate on one favored longitudinal mode. However, the semiconductor laser material exhibits a temperature dependency, which alters the gain profile and refractive index so that the diode jumps between different longitudinal modes. This mode hopping causes the output wavelength to jump rapidly by a few picometers. For single mode diodes that are not temperature stabilized, the output power can change erratically by as much as 3 %.

The undesirable features of power noise and mode hopping are eliminated in the low noise laser diode module LNC-series by modulating the current of the laser diodes at a high frequency. This RF-modulation excites numerous longitudinal modes of emission while simultaneously lowering signal noise significantly, to < 0.1 % RMS. This induced broadening of the spectrum, in a controlled and stable way, has the added advantage of considerably reducing the coherence length of the laser beam which, in turn, reduces laser speckle contrast and prevents interference patterns.

The notable benefits of RF-modulated laser diodes become more evident when compared with the undesirable characteristics of a standard laser diode. The noise, spectrum, laser speckle as well as interference behaviour are all improved for the low noise laser diode module, Fig. 5, in comparison with a standard laser diode, Fig. 6.

Low noise

In Fig. 5a and 6a, the noise profiles (bandwidth of 1 MHz, period of 60 minutes) of the two diodes are compared. Peak noise values exceed 1 % for a standard laser diode while the RF-modulation of the low noise laser diode module reduces noise to < 0.1 %, a value close to the limit of detection.

No mode hopping

Without RF-modulation, the laser jumps stochastically between several emitting modes (Fig. 6b, different colors). Upon RF-modulation, numerous modes are excited within the gain profile of the resonator (Fig. 5b), producing a broad spectrum with about 1.5 nm FWHM (full-width at half-maximum).

Reduced laser speckle

The corresponding laser speckle behavior is shown in Fig. 5c and 6c.

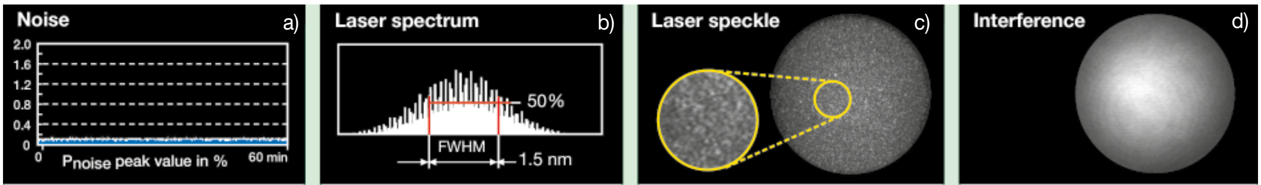
For thicker laser lines and larger laser spots when using a fully coherent laser source, the laser speckle contrast is 1 and there are areas of zero intensity within a laser spot.

The emission from multiple laser modes results in the coherence length of a low noise laser diode being reduced, to < 300 µm, and the speckle contrast and size are also less (compare Fig. 5c with Fig. 6c).

It should be noted that this benefit is less relevant for thinner laser lines and smaller laser spots. With a thin laser line of e.g. 10 µm, there is not much coherence length required for laser speckle to appear.

Less interference

Another effect of a reduced coherence length can be observed in Fig. 5d and 6d. The recording of a collimated laser beam reveals a disturbing interference pattern when using a standard laser diode (Fig. 6d), as a result of internal reflection within the protective glass window of the detector in an area scan camera. Since the coherence length of a low noise laser diode module is less than the



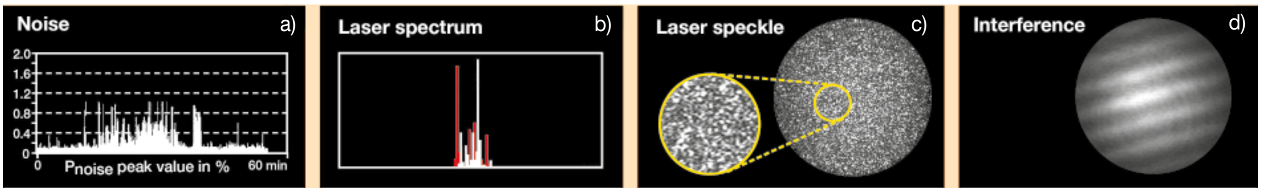
The RF-modulation results in a constant mean laser power. Power noise <0.1 % RMS (<1MHz).

Broadened spectrum (~1.5 nm FWHM) with reduced coherence length (~0.3 mm) as a result of using RF-modulation.

Low speckle contrast due to reduced coherence length. Note that speckle contrast and size generally depend on factors such as spot size and the aperture of the optics.

Intensity distribution of a laser spot at a camera sensor. No interference patterns, despite the sensor protection window.

Fig. 5 Advantages of the low noise laser diode beam source with lower noise (a), spectral broadening (b), reduced laser speckle (c), and less interference (d).



Power noise from a laser diode module. Mode hopping increases the power noise.

Mode hopping: temporal jumps between modes. The short-term coherence of individual modes is >1 m, but effective coherence length is smaller.

A standard laser diode module produces a laser spot with speckle. Note that speckle contrast and size generally depend on factors such as spot size and the aperture of the optics.

The laser spot recorded directly using a camera sensor, with its protection window generating a disturbing pattern of interference.

Fig. 6 Characteristics of a standard laser diode beam source. High noise, mode hopping, laser speckle and unwanted interference can constrain the optical resolution.

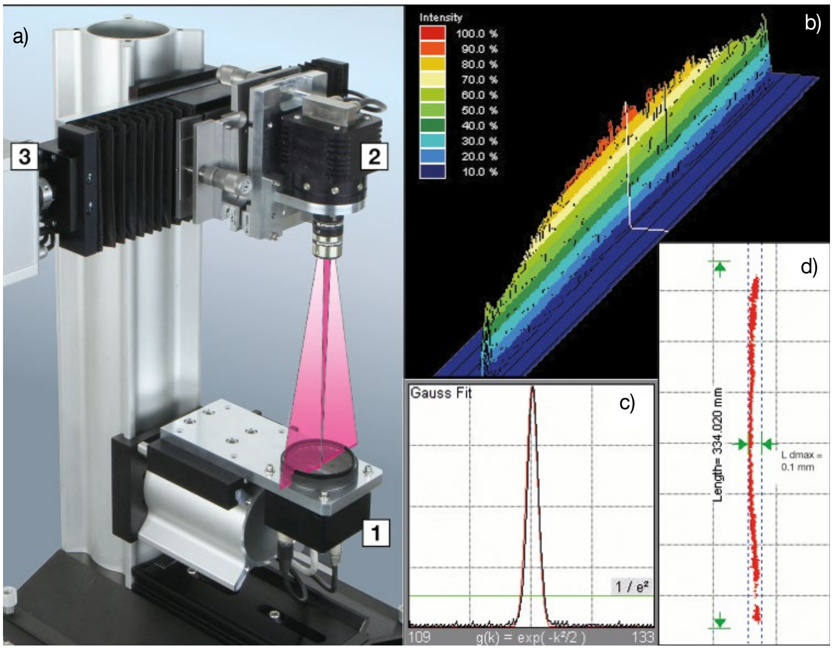


Fig. 7 Beam analysis setup (a) with line scan camera (1) and a laser line generator mounted on a translation stage (3). In b) an example 3D beam profile is shown. The Gaussian line profile is shown in c). The linearity of the laser line is also tested (d, please note the non-quadratic grid).

thickness of the glass, the interference is eliminated (Fig. 6d).

Laser beam analysis

Most laser diodes have a divergent radiation cone with an elliptical cross-section. A standard cylinder lens transforms it into a laser line by stretching the major semi-axis in relation to the minor semi-axis. The elliptical characteristics as well as the Gaussian intensity distribution along the line remain. A closer look at the laser line with the help of a camera reveals the elliptical character, characterized by a greater intensity and width at the center of the line. The useful range for, e.g., light-sectioning is restricted. Aspherical cylinder lenses and grid lenses are used to produce laser lines with constant line width and homogeneous intensity profile along the line, which improves the performance capabilities of light-sectioning considerably.

Fig. 7 shows how laser lines are evaluated and tested by Schäfter+Kirchhoff. A setup is used consisting of a Schäfter+Kirchhoff line scan camera, software for image acquisition and evaluation, and the laser line generator mounted in a *xyz*-adjustable console on a translation stage. The line scan camera sensor and the laser line axis are aligned perpendicular to one another, so that the camera acquires the cross-section of the laser line point for point. By moving the laser line generator on the translation stage, a scanned beam profile over the whole laser line is acquired. Line length, line width and the linearity of the laser line are evaluated.

Summary

Laser lines and laser spots are used for a large variety of applications, e.g., laser lines for 3D measurements.

Depending on the prerequisites for depth of focus of the laser line, either micro lines with a high power density and smaller depth of focus or macro lines with larger line width and increased depth of focus are appropriate. Special variants with low noise and reduced coherence length can improve the measurement results.

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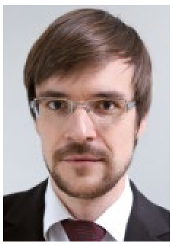

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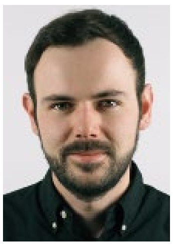

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