

Spatial and Spectral properties of Laser Beams

Transversal Multimode and TEM₀₀ Intensity Distribution

All lasers can be sorted into two main categories by their transversal beam characteristics: Multimode or TEM₀₀ (transversal electromagnetic mode 00). Another measure for the quality of the profile is the M² value. A M² value of 1 is the ideal Gaussian profile. An increasing value of M² represents a mode structure with more and more transversal modes.

1. TEM₀₀ Distribution (transversal singlemode, transversal monomode):

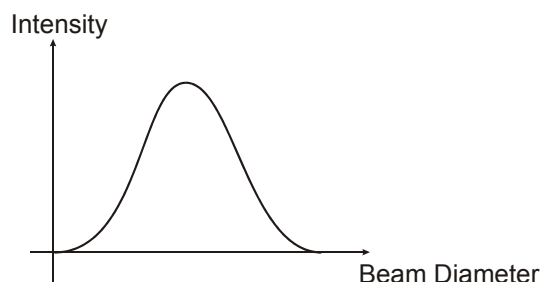
“Transversal” means orthogonal to the propagation direction of the light. “00” stands for the lowest order transversal mode which results in a Gaussian intensity distribution. In practical applications, this distribution determines how well the laser can be focused to a spot. The theoretical value for the minimum spot size is determined by the wavelength. It is half the wavelength. A laser with 1030 nm wavelength can therefore be focused down to a spot with 515 nm diameter (in real life, the optics will not be perfect). A general guideline is to use the wavelength as minimum value for further considerations.

Depending on the industry and the application, a spatial TEM₀₀ profile is also called monomode or singlemode. In this sense, singlemode means only one transversal mode is present. This is primarily true for telecom products, but the term is also used to describe the beam characteristics of fiber lasers.

In the scientific world, however, the description singlemode means a laser with only one longitudinal mode. A laser like this has also a Gaussian spatial intensity distribution but operates with a substantially reduced linewidth. A laser with a single longitudinal mode is also called single frequency laser. A true single frequency laser typically has a linewidth of a few Megahertz. A so-called single mode fiber laser has a linewidth of several nm (equivalent to a few Terahertz).

The quality of the intensity distribution is also described by the M² value. A M² values of 1 is equivalent to a perfect Gaussian distribution. Values up to 1.2 are still considered to be TEM₀₀.

Spatial TEM₀₀ distribution:



Disclaimer

This article does not attempt to cover all aspects of laser beams. All references and numbers are typical. Scientific literature dealing with these aspects is readily available. A list of articles and books can be provided upon request.

2. Multimode distribution (transversal multimode):

Multimode lasers have a different transversal distribution than TEM₀₀. Multimode behaviour starts approximately at a 1.3 M² value. The intensity distribution across the beam is no longer Gaussian shaped. For lasers with a high order multimode structure, the cross intensity of the beam can be almost rectangular. Multimode lasers can be focused down to a spot with an approximate diameter of 50 μm (typical are diameters of > 100 μm). These lasers are mostly used for welding, cutting, marking and other industrial applications.

Some examples for multimode distribution:

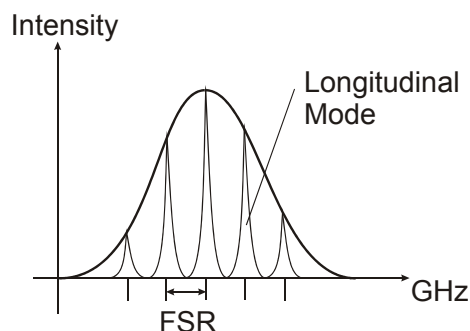


3. Spectral properties

Depending on the lasing material, lasers have a specific linewidth. The intensity distribution of the linewidth of a TEM₀₀ laser over the frequency or wavelength has again a Gaussian shape. This is also called the gain profile. Frequencies in the center will have a higher amplification than frequencies on the border.

A closer look to this gain profile with a scanning Fabry Perot interferometer reveals that various longitudinal modes are present. These are standing waves in the optical resonator of the laser. Their spacing is determined by the effective optical length of the resonator. The condition for this is that multiples of half a wave must fit into the length of the linear resonator (for ring resonators it is a complete wave). This distance from one frequency to the next is called mode spacing or Free Spectral Range (FSR).

Frequency Distribution of a standard TEM₀₀ laser:



Mode spacing FSR (Free Spectral Range) $FSR = \frac{c}{2 l_e}$

l_e = Effective optical length of resonator

This exhibit shows a laser with a perfect Gaussian gain curve and several longitudinal modes.

Disclaimer

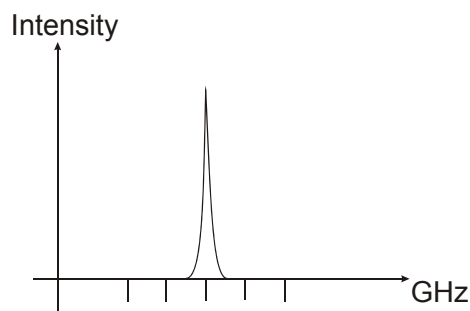
This article does not attempt to cover all aspects of laser beams. All references and numbers are typical. Scientific literature dealing with these aspects is readily available. A list of articles and books can be provided upon request.

Single Frequency

The insertion of an etalon into the optical resonator selects one of the longitudinal modes. All other longitudinal modes are suppressed. Theoretically, the power of all of these suppressed modes is transferred into the selected mode. In reality, this etalon introduces some loss into the cavity. The output power is therefore lower than the power without etalon.

For a variety of applications, it is not enough to have a TEM₀₀ distribution (e. g. holography, interferometry, atomic traps and optical lattice). They require true single frequency operation. This means that only one longitudinal mode with a linewidth of a few MHz is generated by the laser.

Frequency Distribution of a single frequency laser:



For these applications, a long coherence length is essential. In the following table the relation between linewidth and coherence length is listed.

Typical characteristics of some laser types (all with TEM₀₀ profile)

Laser type	Linewidth TEM ₀₀	Coherence length TEM ₀₀	Linewidth Single Frequency	Coherence Length Single Frequency
Diode-pumped Nd:YAG	120 GHz	2.5 mm	n.a.	n. a.
Fiber Laser	> 300 GHz (1 nm)	< 1 mm	n. a.	n. a.
HeNe Laser	1.5 GHz	200 mm	n. a.	n. a.
Ar ⁺ /Kr ⁺ Laser	5 GHz	60 mm	50 MHz	6 m
VersaDisk Yb:YAG	1 GHz	300 mm	10 MHz	30 m

Disclaimer

This article does not attempt to cover all aspects of laser beams. All references and numbers are typical. Scientific literature dealing with these aspects is readily available. A list of articles and books can be provided upon request.

4.1 Focusing a TEM₀₀ Laser Beam

Assuming an ideal Gaussian laser beam and ideal focussing optics, the following equation is valid:

$$d_0 = \frac{4\lambda \cdot f}{\pi D}$$

d_0 = Diameter of the focus

λ = Wavelength

f = focal length of the optics

D = Diameter of the laser beam in the optics

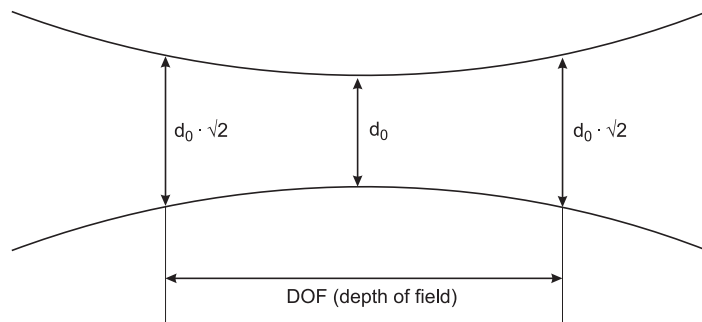
Example I: VersaDisk with an expanded collimated beam and an additional focussing lens.
Beam diameter $D = 15 \text{ mm}$, focal length $f = 75 \text{ mm}$

$$d_0 = \frac{4 \cdot 1030 \text{ nm} \cdot 75 \text{ mm}}{3,1415 \cdot 15 \text{ mm}}$$
$$= 6.56 \text{ } \mu\text{m}$$

4.2 DOF Depth of Field (or Depth of Focus)

In addition, the axial length of the beam waist is important. This describes the range in which the power density (Watt per cm²) is relatively uniform and does not change significantly.

The definition of the limits $d_0 \cdot \sqrt{2}$ is somewhat arbitrary, but reflects normal working conditions.



Under the same assumptions as 4.1, the following equation is valid:

$$\text{DOF} = \frac{8\lambda}{\pi} \cdot \left(\frac{f}{D}\right)^2$$

Disclaimer

This article does not attempt to cover all aspects of laser beams. All references and numbers are typical. Scientific literature dealing with these aspects is readily available. A list of articles and books can be provided upon request.

Continuing with Example I, we get:

$$\text{DOF} = \frac{8 \cdot 1030 \text{ nm}}{3,1415} \cdot \frac{75 \text{ nm}}{15 \text{ nm}} = 65.5 \text{ } \mu\text{m}$$

Within this range, the smallest beam waist is right in the middle. The diameter of the beam does not change more than + 40 % compared to this minimal beam waist. The power density varies by a factor of 2 at maximum.

4.3 Focussing a Multimode Laser Beam

Assuming a multi-mode laser beam and the same optics as described under 4.1, the following equation is valid:

$$d_M = \frac{4\lambda \cdot f}{\pi \cdot D} \cdot M^2$$

d_M = Diameter of the focus

λ = Wavelength

f = Focal length of the optics

D = Diameter of the laser beam in the optics

M^2 = Beam profile

Example II: CadiYAG with an expanded collimated beam and an additional focussing lens.

Beam diameter $D = 15 \text{ mm}$, focal length $f = 75 \text{ mm}$

$$d_0 = \frac{4 \cdot 1030 \text{ nm}}{3,1415} \cdot \frac{75 \text{ mm}}{15 \text{ mm}} \cdot 5$$

$$= 33.87 \text{ } \mu\text{m}$$

Disclaimer

This article does not attempt to cover all aspects of laser beams. All references and numbers are typical. Scientific literature dealing with these aspects is readily available. A list of articles and books can be provided upon request.