Beam Properties and Quality Factor of VCSELs

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In this article, the concept of laser beam propagation and beam quality factor (M^2 factor) is described. We discuss different relations between real laser beams and the ideal Gaussian beam in terms of the M^2 factor. Measurement methods are presented which help to determine the quality factor and other beam parameters of VCSELs, such as divergence angle, Rayleigh length, and beam waist.

1. Introduction

For many industrial and scientific laser applications, such as materials processing, fiber coupling, beam collimation, and beam focusing, it is necessary to have a good laser beam quality. In general, propagating laser beams deviate from an ideal Gaussian intensity distribution. The degree of deviation can be conveniently quantified by a quality factor M^2 (called the "M-squared" factor or the "times diffraction limit number"). This factor has been defined such that $M^2 = 1$ for an ideal Gaussian beam. Real laser beams have factors greater than one. For example helium neon lasers have typically an M^2 factor of less than 1.1. The M^2 factor of single-mode laser diodes is in the range of 1.1 to 1.5. For multi-mode lasers, M^2 can be as high as 20 and more. Therefore, the beam quality is important for many laser measurements and optical designs, where the M^2 factor cannot be neglected.

2. Real Beam Propagation and M^2 Concept

Laser beam propagation can be described using the Gaussian equation

$$w(z) = w_0\sqrt{1+\left(\frac{z-z_0}{z_\mathrm{R}}\right)^2} \tag{1}$$

with

$$z_\mathrm{R} = \pi w_0^2/\lambda \ , \tag{2}$$

where $w(z)$ is the beam radius, w_0 the radius of the beam waist, z_0 the beam waist location, and z_R the Rayleigh length. When propagating a distance z_R from the waist,

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the beam radius expands by a factor of $\sqrt{2}$. This distance defines the beginning of the far-field region where the beam propagates with the constant divergence angle

$$\vartheta \approx \tan\vartheta = \frac{w_0}{z_\mathrm{R}} \,, \tag{3}$$

where the approximation is valid for small angles ϑ. The product of beam waist and divergence angle

$$w_0 \cdot \vartheta = \frac{\lambda}{\pi} \tag{4}$$

is a lower fundamental limit which can only be approached by an ideal Gaussian beam. To describe real laser beams, the M^2 factor should be considered and included in the product of beam waist and divergence angle as

$$W_0 \cdot \Theta = \frac{\lambda}{\pi} M^2 \,. \tag{5}$$

To distinguish between the ideal Gaussian beam and real beams, we use lower case symbols that refer to the former and upper case symbols for the latter. For the Rayleigh length we obtain

$$Z_\mathrm{R} = \frac{\pi W_0^2}{M^2 \lambda} \,. \tag{6}$$

Both, divergence angle as well as beam waist, must be known to obtain an accurate result for the M^2 factor. Measuring only one parameter, e.g. the divergence angle without determining the actual waist size and location, leads to different M^2 factors as seen in the theoretical plots in Fig. 1. Real laser beams of the same divergence angle as an ideal Gaussian beam have a beam waist which is enlarged by the factor M^2 (Fig. 1, left), namely for the beam waist–divergence product we may write

$$W_0 \cdot \Theta = M^2 w_0 \cdot \vartheta \implies W_0 \propto M^2. \tag{7}$$

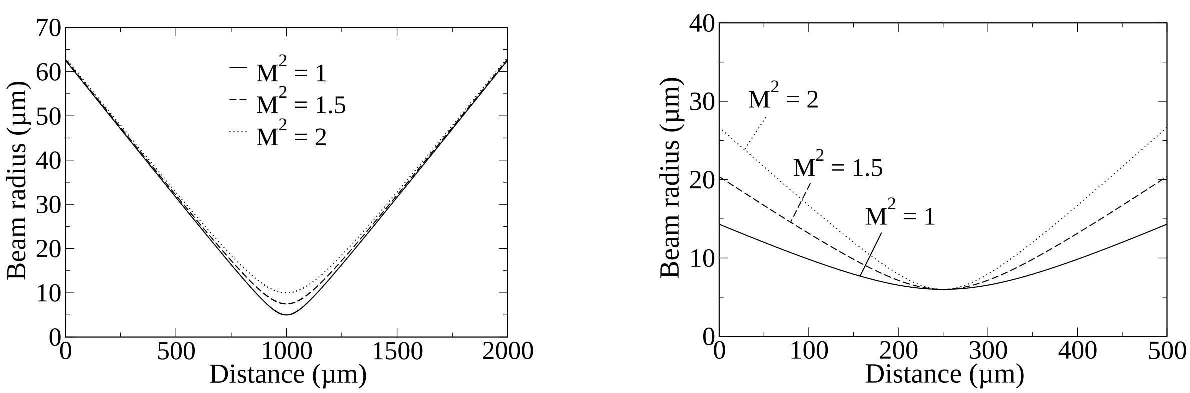

Fig. 1: Laser beams of constant divergence angle (left) and constant beam waist (right) for different M^2 factors.

If both beams have the same waist size, real beams will diverge faster by the factor M^2 (Fig. 1, right), as seen from

$$W_0 \cdot \Theta = w_0 \cdot M^2 \vartheta \implies \Theta \propto M^2. \tag{8}$$

Another relationship between real beams and the Gaussian beam is the so-called embedded Gaussian beam, illustrated in Fig. 2. This relationship [1] describes the propagation of multi-mode laser beams such that both their beam waist and divergence angle are increased over those of an ideal beam by a factor $M = \sqrt{M^2}$. Here, the product

$$W_0 \cdot \Theta = M w_0 \cdot M \vartheta \tag{9}$$

leads to the same result as in the previous relationships (7), (8) and as shown before in (5).

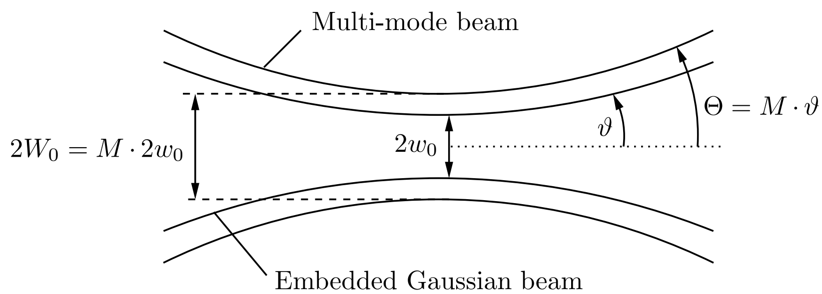

Fig. 2: The embedded Gaussian beam. It represents the relationship between the fundamental and higher order modes of a geometrically stable laser resonator.

3. Measurement Method and Setup

Figure 3 shows the experimental setup for the beam quality characterization. The laser beam of a mounted VCSEL is transformed through a lens such as to form a beam waist in the output beam. Two detectors with slits of 45° and −45° orientation scan the beam and measure the intensity profiles in x-direction for different propagation distances. According to a procedure defined by the ISO [2], ten measurements along the propagation axis must be at least performed, where half of them should be within the Rayleigh length on both sides of the beam waist. The detector head used in the measurement setup is part of the beam analyzer *BeamScope* [3], which provides a complete M^2 measurement. In our setup only the detectors have been used to measure the intensity distribution. Other commercial instruments, e.g. the *ModeMaster* [4] use the knife-edge technique to determine the M^2 factor. In Fig. 4, intensity profiles of a multi-mode laser are shown. For Gaussian beams, the $1/e^2$ beam diameter definition is used. The beam diameter of multi-mode lasers is calculated using the second-moment definition

$$\sigma^2 = \frac{\sum y \cdot (x - \bar{x})^2}{\sum y} \quad \text{with} \quad \bar{x} = \frac{\sum y \cdot x}{\sum y} \ , \tag{10}$$

where the beam width is four times the standard deviation σ of the intensity distribution $y(x)$. Calculated beam diameters are plotted versus the propagation distance and then fitted according to (1) (while replacing z_R with Z_R from (6)) to determine the M^2 factor and other beam parameters. Another M^2 measurement method described in [5] uses just four beam diameter measurements to determine the M^2 factor.

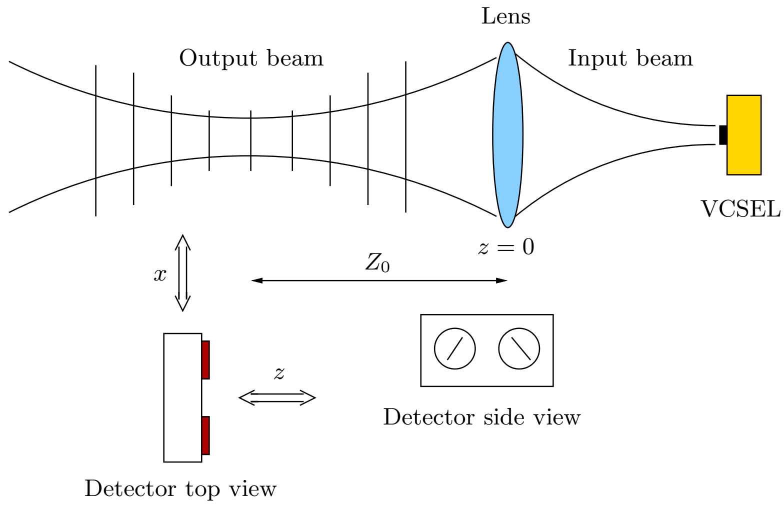

Fig. 3: Setup for the measurement of the beam quality of VCSELs.

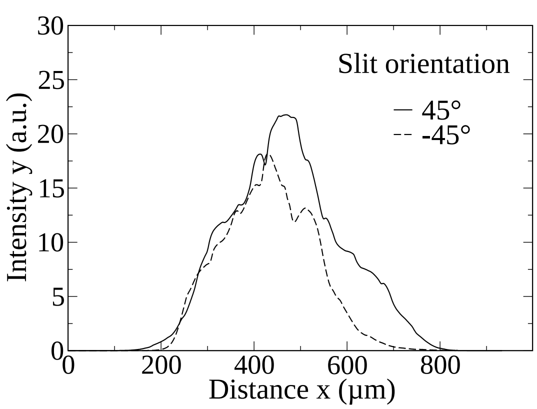

Fig. 4: Intensity profiles of a multi-mode laser. The active diameter of the VCSEL is about 36 μm.

4. Experimental Results

Beam properties of 980 nm oxide-confined multi-mode VCSELs have been investigated. In this section we present measurement results of the quality factor, waist size and divergence angle of a device with 36 μm active diameter. We started the characterization with a standard far-field measurement as shown in Fig. 5. The beam intensity of the device is plotted versus the divergence angle. The far-field angle Θ is about 5.7°, which is two times the calculated standard deviation.

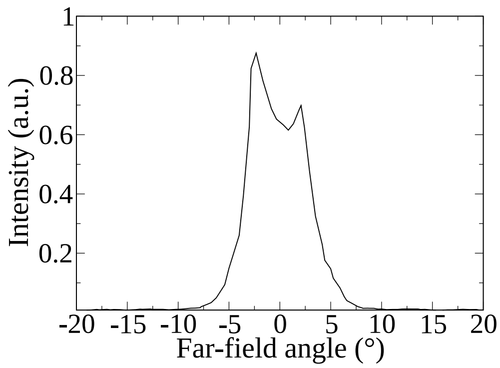

Fig. 5: Typical far-field intensity distribution of a 36 μm diameter multi-mode VCSEL emitting at 980 nm wavelength. Threshold current and driving current are ≈ 7 mA and 10 mA, respectively. The far-field angle Θ is about $5.7°$.

As previously described in Sect. 3, an M^2 measurement is performed on the same VCSEL device. The beam radii are plotted versus the propagation distance in Fig. 6. The hyperbolic form of the theoretical propagation curve (1) was used to fit the data points. The fit parameters and other beam properties are listed in Table 1. The magnification factor V is calculated using

$$V = \frac{Z_0 - f}{f}\,, \tag{11}$$

where Z_0 is the waist location (see Fig. 3) and $f = 14.5$ mm the focal length of the lens. The M^2 factor of the measured multi-mode VCSEL is about 6.3 and the divergence angle is approximately $5.4°$, which corresponds very well to the result of the far-field measurement. The results from both detectors show that the laser beam is not purely circular. The measured multi-mode device has an active radius of 18 μm, which is comparable to the calculated waist sizes of 18.0 μm and 20.7 μm, respectively.

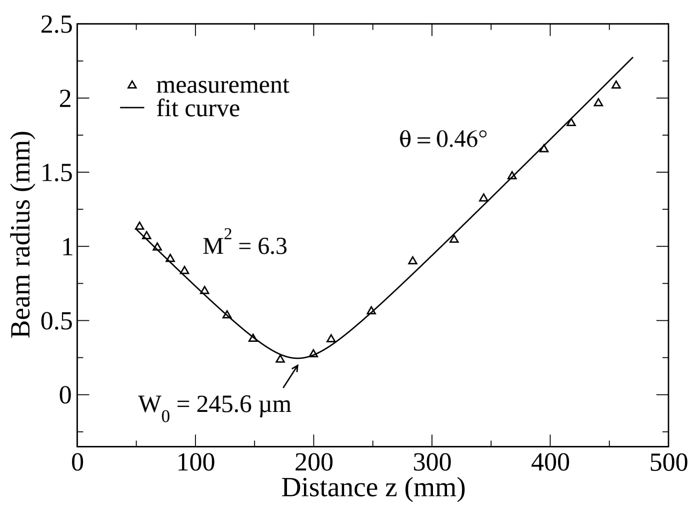

Fig. 6: Experimentally determined results of the beam radius versus propagation distance. The data points (detector at $45°$ position) of the 36 μm diameter multi-mode VCSEL (980 nm, $I = 10$ mA) were fitted to calculate the M^2 factor and other beam parameters.

Tab. 1: Beam parameters of a 36 μm diameter multi-mode VCSEL. The parameters in the input beam section (see Fig. 3) were calculated using the magnification factor V.

	Output beam		Input beam	
Slit orientation	45°	−45°	45°	−45°
W_0	245.6 μm	209.3 μm	20.7 μm	18.0 μm
Z_R	30.8 mm	25.5 mm	219.3 μm	189 μm
Θ	0.46°	0.47°	5.4°	5.45°
Z_0	186.4 mm	183 mm		
M^2	6.3	5.5		

5. Conclusion

We have investigated the beam properties of multi-mode VCSELs. Far-field and M^2 measurements have been performed to determine beam parameters such as the beam quality factor and the divergence angle. For a 36 μm diameter multi-mode device we have obtained an M^2 factor and a divergence angle of 6.3 and 5.4°, respectively.

References

[1] T.F. Johnston, Jr, "M^2 concept characterizes beam quality," *Laser Focus World*, pp. 173–183, May 1990.

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[5] T.F. Johnston, Jr, "Beam propagation (M^2) measurement made as easy as it gets: the four-cuts method," *Appl. Optics*, vol. 37, no. 21, pp. 4840–4850, 1998.