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INTERNATIONAL STANDARD

colour inside

Display lighting unit –
Part 2-4: Electro-optical measuring methods of laser module

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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DISPLAY LIGHTING UNIT –

Part 2-4: Electro-optical measuring methods of laser module

FOREWORD

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International Standard IEC 62595-2-4 has been prepared by IEC technical committee 110: Electronic displays.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
110/1224/FDIS	110/1246/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62595 series, published under the general title *Display lighting unit*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Laser modules, in general, have been used widely for various applications such as, optical communications, laser beam machining, bar-code reading, optical disc drives and so on. The laser module in this document is limited to display applications. It is a key light source for laser displays, laser backlight/front light units for liquid crystal displays (LCDs), holographic displays and so on. A typical laser module for display applications comprises multiple laser devices, electrical inputs and an optical output combining the outputs of the laser diodes (LDs). The laser device used in the laser module here is an edge-emitting laser diode (LD), a vertical cavity surface-emitting laser diode (VCSEL), or a photon up-conversion laser including second-harmonic generation (SHG).

The optical output is usually provided out of an optical component such as a pigtail fibre, a fibre with a connector, a waveguide, a light guide, or a lens unit for the convenience of users.

In advanced display applications, not only visible laser diodes but also near infrared (near IR) laser diodes are included in the module for sensor applications such as the LiDAR system (light detection and ranging, or laser image detection and ranging).

Therefore, the wavelength range for display applications covers all the visible wavelengths from 380 nm to 780 nm, including the laser diodes for pumping phosphors. That is, a violet laser diode emitting at 405 nm is included. Photometric and colorimetric measurements are the primary focus of this document. The near IR LD for a LiDAR system included in the module can be measured as a monochromatic light output using the light measuring device (LMD) covering the IR wavelength region. However, the measurements of IR lasers are out of the scope of this document.

It is important for the designing of the above display systems and devices to standardise the electro-optical measuring methods of the laser modules. Photometric and colorimetric measurements are particularly important for display applications because each LD has different electrical and optical performances, such as threshold currents, efficiency, spectrum, far field pattern (FFP) of the output laser beam, speckle-related behaviours and their temperature dependence.

Particularly for the colour speckle of the output laser beam, the measured speckle data are very useful to predict the visual quality of laser displays and to design speckle reducing devices.

DISPLAY LIGHTING UNIT –

Part 2-4: Electro-optical measuring methods of laser module

1 Scope

This part of IEC 62595 specifies the electro-optical measuring methods of laser modules with multiple laser devices and an optical output for various displays and display lighting applications which require photometric and colorimetric measurements, covering the wavelength range of 380 nm to 780 nm. The module has multiple laser devices such as edge-emitting laser diodes (LDs), vertical cavity surface-emitting laser diodes (VCSELs), or photon up-conversion laser devices including second-harmonic generation (SHG). The module has an optical output such as an optical fibre, waveguide, light guide, lens unit, or other optics, emitting a laser beam combining the output of the multiple laser devices.

NOTE See 3.1.1 for a definition of a laser device inside the laser module.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

IEC 62906-5-2, *Laser display devices – Part 5-2: Optical measuring methods of speckle contrast*

IEC 62906-5-4, *Laser display devices – Part 5-4: Optical measuring methods of colour speckle*

3 Terms, definitions, abbreviated terms, and letter symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
laser device
<of display lighting unit> semiconductor-based or compactly assembled solid-state up-conversion laser

EXAMPLE Edge-emitting laser diode, vertical cavity surface-emitting laser diode, or photon up-conversion laser including second-harmonic generation (SHG), or third-harmonic generation (THG).

Note 1 to entry: See Annex A.

3.1.2
laser module
<of display lighting unit> display light source with an optical output combining the emitted lights of multiple laser devices

3.1.3
monochromatic laser module
<of display lighting unit> display light source with an optical output combining the emitted lights of multiple laser devices within the wavelength range of 10 nm

Note 1 to entry: See Figure B.1 in Annex B.

3.1.4
multi-colour laser module
<of display lighting unit> display light source with an optical output combining the emitted lights of multiple laser devices emitting at different monochromatic wavelengths

3.1.5
RGB laser module
<of display lighting unit> display light source with an optical output combining the emitted lights of red, green, blue monochromatic laser devices

Note 1 to entry: See Figure B.2 and Figure B.3 in Annex B.

3.1.6
laser display
display using a laser or lasers, based on stimulated emission

Note 1 to entry: This term is specified as "laser display device (LDD)" in IEC 62906-1-2. However, the term "laser display" covers more widely and appropriately than "laser display device".

3.1.7
fibre output power
<of laser module> optical output power of the optical fibre facet equipped with the laser module

3.1.8
wall-plug efficiency
WPE
<of laser module> power efficiency of the optical output power by the electrical input power of the laser module

3.1.9
threshold current
<of laser module> current input level of a laser module at which an optical output of the laser module, combining the emitted lights of multiple laser devices, starts laser oscillation

3.1.10
near field pattern
NFP
<of laser module> output power distribution on the output aperture of the laser module

3.1.11
far field pattern
FFP
monochromatic FFP
<of laser module> output power distribution measured on the plane at a distance which is significantly greater than W^2 / λ, where λ is the wavelength and W is the largest dimension in the output aperture

3.1.12
colorimetric far field pattern
colorimetric FFP
colour FFP
<of laser module> output chromaticity distribution measured on the plane at a distance which is significantly greater than W^2 / λ, where λ is the wavelength and W is the largest dimension in the output aperture

3.1.13
XYZ filters, pl.
set of optical filters which will produce an optical measuring device that approximately has the spectral responsivity of colour matching functions $\bar{x}$, $\bar{y}$, $\bar{z}$ in the CIE 1931 standard colorimetric system when used together with the intended lens, sensors, and other components

3.1.14
laser multi-meter
light measuring device for measuring centroid wavelengths and radiometric quantities of laser light sources with very narrow spectral linewidths using non-spectrometric methods, also deriving colorimetric and photometric quantities using the colour-matching functions

Note 1 to entry: See [1][1].

3.2 Abbreviated terms and letter symbols

3.2.1 Abbreviated terms

ACC	automatic current control
APC	automatic power control
BW	bandwidth
CW	continuous wave
DBR	distributed Bragg reflector
DUT	device under test
FFP	far field pattern
FWHM	full width at half maximum
IR	infrared
LCD	liquid crystal display
LD	laser diode
LiDAR	light detection and ranging (or laser image detection and ranging)
LMD	light-measuring device
MMF	multi-mode fibre
MTF	modulation transfer function
NA	numerical aperture
ND	neutral density
NFP	near field pattern
NRZ	non-return-to-zero
PCB	printed circuit board
PD	photodiode

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[1] Numbers in square brackets refer to the Bibliography.

PPG pulse pattern generator
PRBS pseudo-random binary (or bit) sequence
PWM pulse width modulation
QPM quasi-phase-matching
RGB red, green, blue
RMS root mean square
RT room temperature
SHG second harmonic generation
SLM spatial light modulator
SMF single-mode fibre
SHG second-harmonic generation
TE transverse electric
TEC Thermo-electric cooler
THG third harmonic generation
TM transverse magnetic
VCSEL vertical cavity surface-emitting laser diode
WPE wall-plug efficiency

3.2.2 Letter symbols

The letter symbols for a laser module are shown in Table 1.

Table 1 – Letter symbols (quantity symbols/unit symbols)

Definition	Symbol	Unit
Electrical		
Current	I	A
Threshold current	I_{th}	A
Voltage	V	V
Input electrical power	IV, P_i	W

Definition	Symbol	Unit
Optical output		
Optical output power	P_o	W
Output of red power	P_R	W
Output of green power	P_G	W
Output of blue power	P_B	W
Wall-plug efficiency optical output (W) / electrical input (W)	P_o / P_i	-
Slope efficiency	η_s	W/A
Size of output aperture	W	nm
Wavelength	λ	nm
Centroid wavelength	λ_c	nm
Peak wavelength	λ_p	nm
Spectral power density	$S(\lambda)$	W/nm
CIE 1931 chromaticity	x, y	-
CIE 1976 chromaticity	u', v'	-
Rise/fall time of output waveform	t_r, t_f	s
Delay time of output waveform	t_d	s
Period of output waveform	T	s
Direct measurement setup		
Distance from DUT output to measurement plane along z	L	m
Azimuth angle	ϕ	degree
Zenith angle	θ	degree
Screen measurement setup (speckle measurement)		
Distance from DUT output to screen centre	L_s	m
Distance from LMD to screen centre	D_s	m
Angle between LMD and DUT	θ_s	degree
Speckle		
Speckle contrast	C_s	-
Speckle contrast for red colour	$C_{s\text{-}R}$	-
Speckle contrast for green colour	$C_{s\text{-}G}$	-
Speckle contrast for blue colour	$C_{s\text{-}B}$	-
Photometric speckle contrast	C_{ps}	-
u'-variance of CIE 1976 chromaticity distribution of colour speckle	$\sigma_{u'}$	-
v'-variance of CIE 1976 chromaticity distribution of colour speckle	$\sigma_{v'}$	-
Covariance of CIE 1976 chromaticity distribution of colour speckle	$\mu_{u'v'}$	-

Definition	Symbol	Unit
Temperature/Thermal		
Atmospheric temperature	T_a	°C
Case temperature	T_c	°C
Junction temperature (LD)	T_j	°C
Characteristic temperature of I_{th} (LD)	T_0	°C
Characteristic temperature of η_s (LD)	T^*_0	°C
Thermal resistance (LD)	R_{th}	K/W
Series resistance (LD)	R_s	Ω
Others		
Critical angle (fibre)	θ_c	degree
Maximum incident angle to fibre	θ_{max}	degree
Wavelength accuracy of LMD	$\pm\delta$	nm
Reference wavelength	λ_r	nm
Spectral bandwidth of LMD	$\Delta\lambda$	nm
CIE 1931 chromaticity differences	Δx, Δy	-
CIE 1976 chromaticity differences	$\Delta u'$, $\Delta v'$	-

4 Standard measuring conditions

4.1 Standard measuring environmental conditions

Measurements shall be carried out under the following standard environmental conditions:

– temperature: 25 °C ± 3 °C
– relative humidity: 25 % to 85 %
– pressure: 86 kPa to 106 kPa

When different environmental conditions are used, they shall be reported.

4.2 Standard measuring dark-room conditions

The background illuminance of the standard dark-room shall be less than 0,01 lx except when the DUT and the LMD are covered under the same dark-room conditions or when both are fibre-connected.

4.3 Safety requirements

The DUT and the measurement conditions shall be strictly in accordance with the safety requirements of IEC 60825-1.

Laser modules are mostly intermediate (B2B) products. Some of the high-power laser modules are categorized as class 4. The measurements shall be carried out carefully in the laser- controlled area, by putting on laser protection glasses, so that the maximum permissible exposure levels in IEC 60825-1 are not exceeded by persons in the area. That is, the laser safety class label on the DUT shall be confirmed, and the measurement of environmental conditions shall be kept as specified in IEC 60825-1, depending on the DUT laser class.

4.4 Standard DUT conditions

The position for measuring the case temperature T_c shall be determined depending on the laser module type and its structure. It should be determined usually at the surface closest to the heatsink of the internal LD assembly.

The accuracy of standard case temperature T_c shall be ±0,5 °C.

The measurements shall be started after the DUT and the LMD have achieved stability. Regarding the DUT, the stability shall be achieved when the output power of the DUT varies within ±3 % over the entire measurement timeframe.

Most laser modules for display applications are usually operated in ACC (automatic current control). The current level (CW) or the time-averaged current level (PWM) for the measurements shall be noted in the report.

The DUT shall be operated under the current conditions less than the absolute maximum rating, both for CW and PWM (pulse peak) operations. The PWM operation for LDs is explained in detail in 5.2.3. If the laser module manufacturer provides the driver circuitry or module, it should be used.

If the laser module includes a thermo-control function, e.g., TEC (thermo-electric cooler), the thermo-control capability in the specifications shall be noted in the report.

4.5 Standard LMD requirements

The LMD performance for CW operation shall be as follows.

When an LMD with a different performance is used, its specifications shall be noted in the report.

a) ampere meter
   1) current range: zero to the absolute maximum rating
   2) accuracy: ±2 %
b) voltmeter
   1) voltage range: zero to the absolute maximum rating
   2) accuracy: ±2 %
c) optical power meter/laser power meter
   1) power range: from zero to the absolute maximum rating. A calibrated ND filter may be used if the power meter cannot cover the maximum rating
   2) accuracy: ±4,5 %
   3) spectral range: covering at least the wavelengths of the laser module
   4) launch condition: underfilled launch for total optical power measurement, overfilled launch for optical power density measurement
d) spectral irradiance meter
   1) irradiance range: from zero to the absolute maximum rating. A calibrated ND filter may be used if the power meter cannot cover the maximum rating
   2) wavelength accuracy: ±0,3 nm
   3) spectral range: covering at least the wavelengths of the laser module
   4) spectral bandwidth: ≦ 5 nm
e) luminance meter/illuminance meter (using a $v(\lambda)$ filter)
   1) shall be calibrated by the spectral radiance / Irradiance meter

f) colorimeter (using XYZ filters)
   1) shall be calibrated by spectrometric LMD
g) wavelength meter
   1) spectral range: covering at least the wavelengths of the laser module
   2) power range: zero to the absolute maximum rating. A calibrated ND filter may be used if the power meter does not cover the maximum rating
   3) wavelength accuracy: ±0,3 nm
h) spectrum analyser
   1) wavelength range: covering at least the wavelengths of the laser module
   2) power range: zero to the absolute maximum rating. A calibrated ND filter may be used if the power meter does not cover the maximum rating
   3) wavelength accuracy: ±0,3 nm
   4) spectral bandwidth: ≦ 1 nm
i) laser multi-meter
   1) wavelength range: covering the wavelengths of the laser module
   2) power range: zero to the absolute maximum rating
   3) wavelength accuracy: ±0,3 nm
j) speckle measurement equipment
   1) wavelength range: covering at least the wavelengths of the laser module
   2) the MTF of the optics shall be equivalent to that of the human eye

NOTE See [1], IEC 62906-5-2 and IEC 62906-5-4 regarding the MTF of optics (consisting of iris, lens, imaging devices and so on) inside the speckle measurement equipment.

For measuring laser modules operated in PWM, the RMS voltmeter and the time-averaged power meter shall be used. To keep the accuracy of the measurements, the measurement time (integrating time) shall be sufficiently longer than the period of the PWM as explained in 5.2.3.

The laser modules use laser devices as light sources. Their emission spectra are very narrow, and their chromaticity coordinates are plotted almost on the wavelength locus of the chromaticity diagram. Therefore, the chromaticity accuracy is very sensitive to wavelength because the curvature of the wavelength locus at the LD wavelength affects the chromaticity accuracy.

The wavelength accuracy of ±0,3 nm specified in d), g), h), and i) above, is a practical value mostly common to the conventional display measurements. Precise spectrometric methods should be the reference of the wavelength measurements.

If it is necessary to guarantee a specific value of chromaticity accuracy at a specific wavelength, the wavelength accuracy shall be evaluated. Examples of the wavelength accuracy curves with respect to visible wavelengths are shown in Annex D.

When multi-colour laser modules are measured, the LMDs shall not be wavelength-dependent, or shall be calibrated for their spectral responsivity for all the laser wavelengths for spectral radiant flux measurements.

The edge-emitting LDs operate in the TE-polarized (linearly polarized) mode explained in Annex A. The linearly polarized laser light incident to the isotropic optical fibres is converted into a circularly polarized light. That is, the output beam of the laser modules which is combined with multiple laser beams can include various polarization states depending on the output optics. The LMDs for direct measurements shall detect the optical power of a polarization state as is.

Therefore, the optics inside the LMD shall be polarization-independent. It is much easier for laser beams with a very narrow divergence to design polarization-independent optics because the beam incident normal to a multi-layered coated surface or total reflection surface is polarization-independent. For the case of relatively large beam divergence, the detector angular dependence regarding polarization should be described. A simple LMD structure with a photodiode only is much better than the complicated LMD with diffusers for laser beams with a very narrow beam divergence.

4.6 Standard measurement setup and coordinate system

The standard measurement setup is schematically illustrated in Figure 1. A spherical coordinate system in Figure 1 shall be used for direct beam evaluation. The optical output of the DUT is set at the origin of the coordinate system (0, 0, 0).

The spherical coordinate system has been widely used for measuring the FFP of LDs because their FFP is wider in the vertical direction (see Annex A). The FFP measurement units are usually equipped with an automated scan mechanism for the user's convenience. Various types of fixtures for LD chip carriers, LD packages, fibres, fibre ferrules, fibre connectors, and other guided structures are optionally available. They are designed to be mechanically aligned with the axis of the auto-scan system. Therefore, the direction of the guided structures of the optical output of the laser modules can be easily aligned mechanically with the optical axis. The optical misalignment inside the module or the guided structure can be evaluated by the mechanical alignment.

A Cartesian coordinate system shown in Figure 2 shall also be used for direct beam evaluation if the divergence of the output laser beam from the laser modules is narrow enough. For example, the NA (numerical aperture) of a typical silica MMF is usually around 0,22, which implies that the maximum divergence angle (half width) is around 12°. It should be noted that the measurement errors for larger optical misalignment inside the module or the guided structure can be larger when using the Cartesian coordinate system.

NOTE See Annex E for NA.

The virtual flat screen at (x, y, L) in the Cartesian coordinate system in Figure 2 is easier to set up. The formulae for converting the Cartesian coordinate system into the spherical system are shown in Annex F. For the above MMF, the position on the virtual screen at the beam edge of θ_{max} = 12° is only 2,2 % ($1/\cos\theta_{max}$) larger than the spherical coordinate system.

As explained in 5.5, the speckle measurement of the output laser beam shall remove the effects of FFP. Therefore, it is very convenient to measure the speckle and the FFP using a common standard diffusive screen (Cartesian coordinate system). An example of conversion between the two coordinate systems is also shown in 5.4.3.

An example of a high-power monochromatic laser module is given in Figure B.1, which shows the inside parts. All the nine monochromatic LDs are series-parallel connected for single input. The blue laser modules or violet (emitting around 405 nm) modules are used for pumping phosphors.

An example of a high-power RGB laser module is shown in Figure B.2. The RGB laser module has the R, G, B branches of three series-connected LDs emitting at the same wavelength. Each branch is driven independently by an electrical signal channel corresponding to the R, G, B colours. In this structure, the laser beams emitted out of the nine LDs (three LDs for each colour) are combined and collimated via the optics and coupled into a multi-mode fibre (MMF). The colour of the single output beam combining the output of the R, G, B LDs is tuneable by controlling the RGB power ratio.

The RGB laser module for lower power applications uses discrete or integrated RGB LDs and a single-mode fibre (SMF) for optical output (Figure B.3).

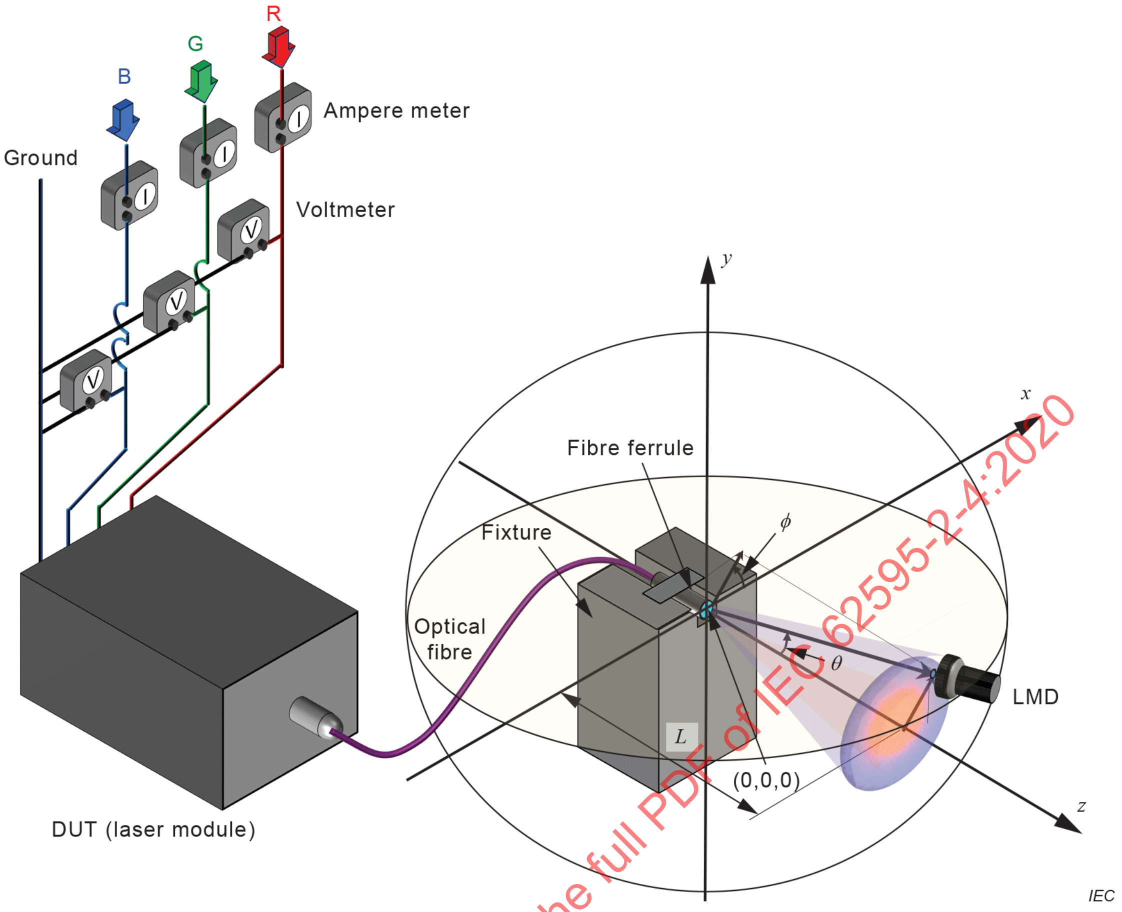


Figure 1 – Measurement setup and coordinate system (spherical)

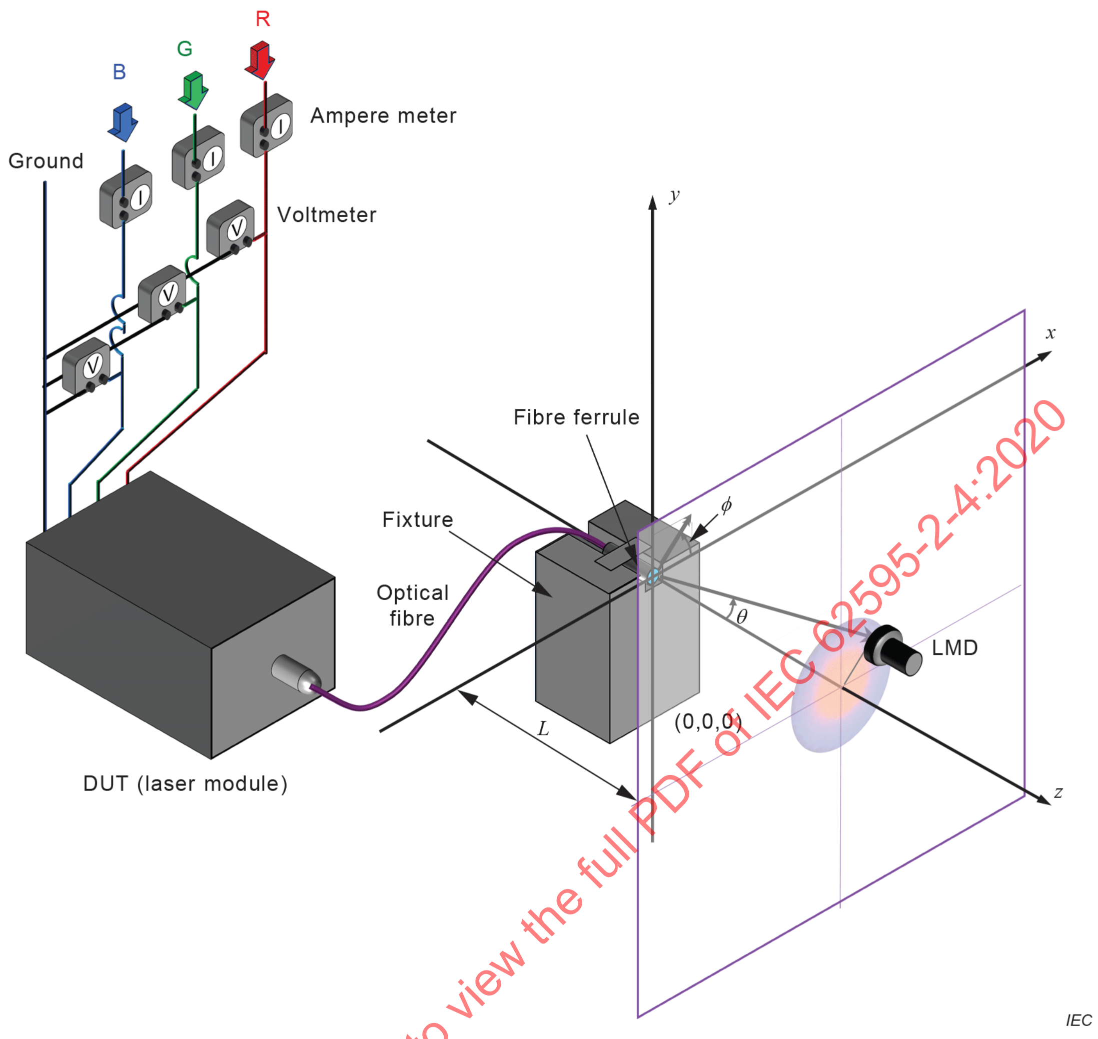


Figure 2 – Measurement setup and coordinate system (Cartesian)

The coordinate system shown in Figure 3 shall be used for speckle-related measurements using a diffusive screen (see IEC 62906-5-2, and IEC 62906-5-4). The measuring methods of speckles are shown in 5.5. The speckle is observed on the FFP. If speckle can be removed from the FFP, the visualized FFP can be measured two-dimensionally without mechanical scanning of the LMD as in Figure 1 and Figure 2. The value of speckle contrast and colour speckle distribution can also be obtained easily by removing the FFP. That is, the speckle-free FFP and the speckle/colour speckle of the output laser beam can be measured simultaneously by this setup using the screen.

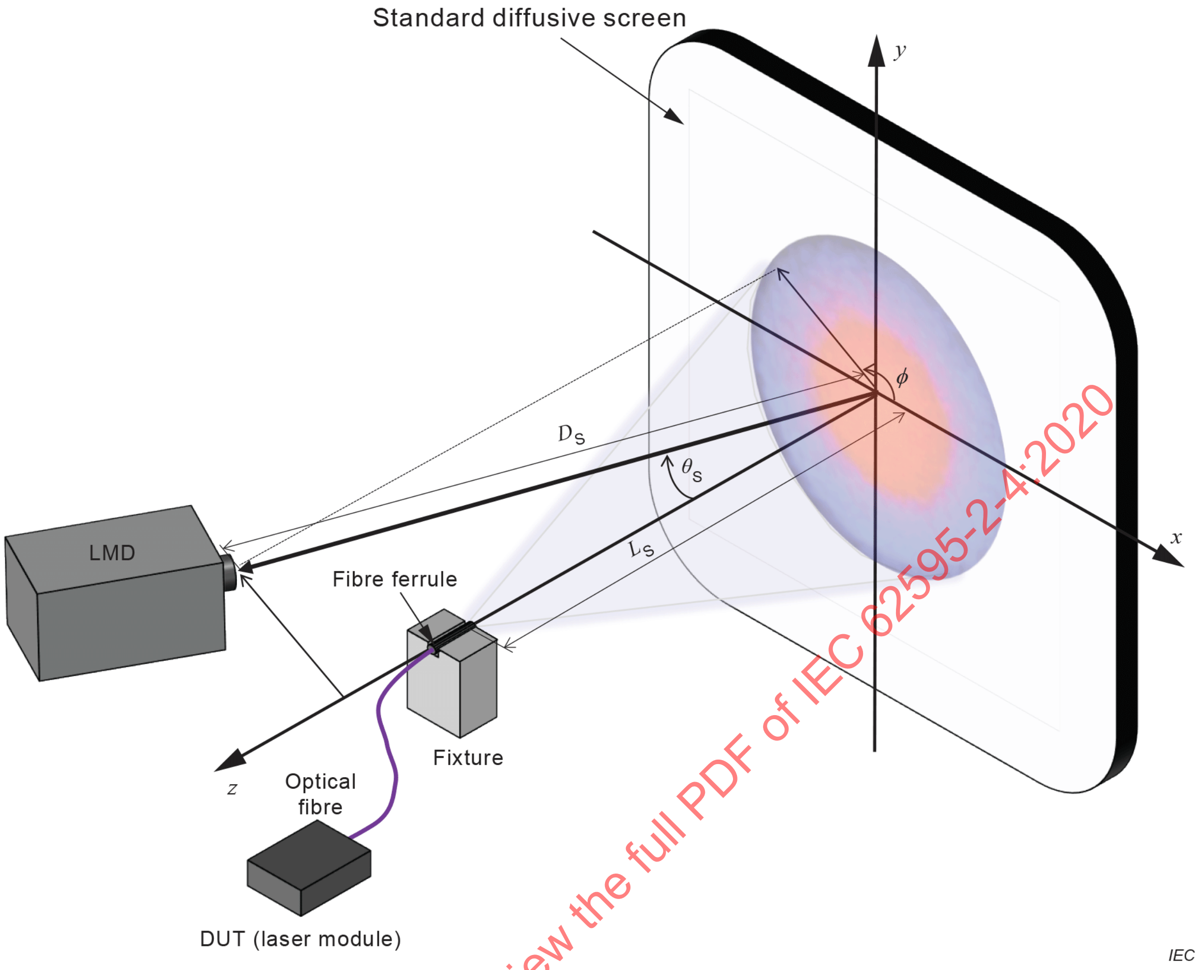


Figure 3 – Measurement setup and coordinates for speckle-related optical performance

5 Measuring methods

5.1 General

Clause 5 describes fundamental measurement items and their measuring methods. There are various types of laser displays such as a raster-scanning retina direct projection (very small-form-factor with very low-power RGB laser module), raster-scan mobile projectors, middle-class projectors using high-power blue lasers for pumping phosphors, digital cinema projectors (using ultra-high-power RGB laser modules), and so on. The laser-driving method is different depending on the display types. Therefore, some of the measurement items are not necessary for certain applications. For example, speckle measurements are not necessary for the retina direct projection displays because speckle does not occur without external screen scattering. Speckle contrast is a metric of speckle strength. It is important for many of the laser displays to design a speckle reducer. It is necessary for accurately measuring speckle contrast to use a uniformly projected window area with statistically enough data points. However, the output beam from the laser module cannot be projected onto the screen uniformly due to the FFP. The speckle patterns and the FFP shall be separated.

5.2 Current-light output characteristics

5.2.1 General

The laser modules applied for a light source of the display light engine with a spatial light modulator (SLM) are usually operated in automatic current control (ACC). In this case, the light output power P_{o} at the operating current is of primary interest. However, it is necessary to measure the current-light output (I-P_{o}) characteristics for each colour channel, for feedback control of automatic power control (APC), white chromaticity control of the multi-colour laser modules, and direct modulation of scanning laser displays.

5.2.2 I-P_{o} and I- P_{o} / P_{i} characteristics

The I-P_{o} characteristics shall be obtained by measuring the output optical power, P_{o}, using an optical power meter, a laser power meter or a laser multi-meter, changing the operating current I. For multi-colour laser modules, the I-P_{o} characteristics shall be measured independently for each colour input channel because the colour output of the module is controlled by the power balance (power ratio) of the colours.

Measurement of the I-P_{o} characteristics shall be carried out using the coordinate systems in Figure 1 or Figure 2. The LMD shall be placed in the proximity of the output plane on the z-axis (0, 0, $L \approx 0$). The positioning of the LMD is common in both Figure 1 and Figure 2. The receiving area of the power meter shall be larger than the laser beam size. Since the beam divergence is very narrow, it is easy to receive all the output power. A calibrated optical attenuator should be used if the power meter cannot cover the maximum ratings.

Wall-plug efficiency (WPE) is the power conversion efficiency defined as the light output power (P_{o}) by the electrical input power ($P_{\mathrm{i}} = IV$).

$$\mathrm{WPE} \equiv P_{\mathrm{o}} / P_{\mathrm{i}} = P_{\mathrm{o}} / IV \tag{1}$$

WPE shall be calculated by the above formula using the data of the I-P_{o} characteristics.

It should be noted that WPE is negligible below the threshold current. Even just above the threshold, WPE is still at small levels. As the current increases, WPE increases as well, compensating the electric power loss below the threshold. The WPE for laser modules with multiple-driver channels shall be measured channel by channel.

An example of the I-P_{o} and I- P_{o} / P_{i} characteristics is shown in Figure 4. Slope efficiency, η_{s}, is defined as ΔP_{o} / ΔI.

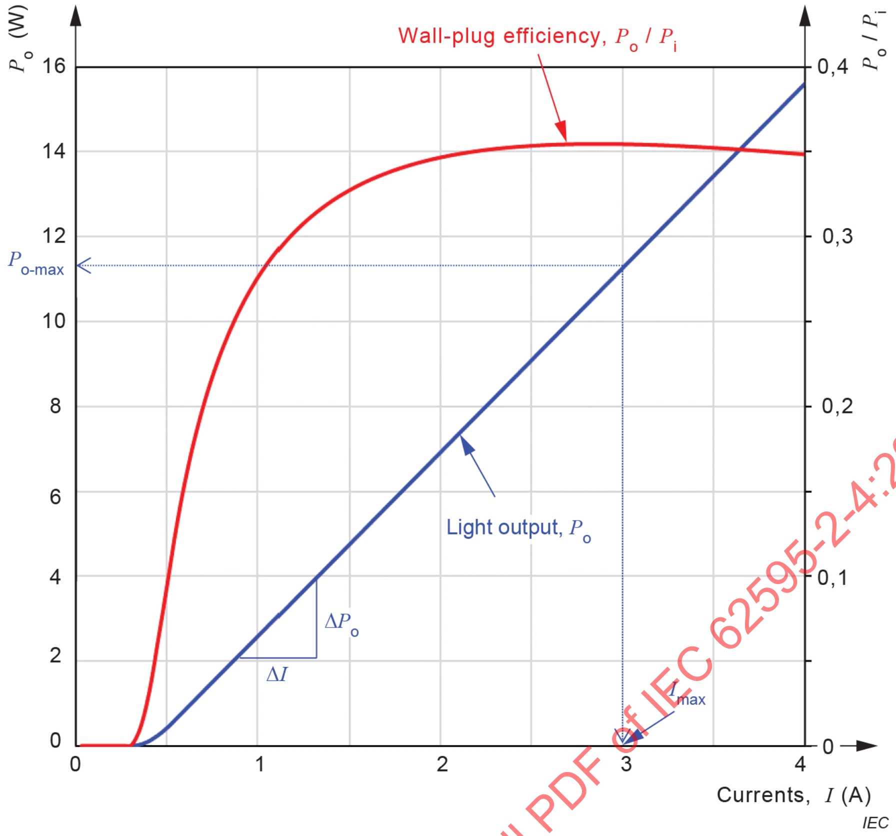


Figure 4 – Example of I-P_o and I- P_o / P_i characteristics

5.2.3 CW and PWM operations

The LDs in the laser modules for display applications are usually CW or PWM-operated as described in 4.4. The current pulse repetition waveforms at 2,4 kHz of PWM with respect to the duty cycle are also shown in Figure 5. The pulse peak level is usually set at the maximum rating of currents, I_{max} corresponding to the maximum rating of the CW output power, $P_{o\text{-}max}$, in Figure 4. Therefore, the PWM peak optical power never exceeds the CW maximum optical power. The PWM waveform at duty cycle of 1,0 completely agrees with the flat CW level at $P_o = P_{o\text{-}max}$. The width of the pulse is adjusted to increase the average optical output power. The WPE can be kept constant for PWM operation because the pulse peak is set at the highest WPE level, which is a great advantage of PWM operation. The modulation at a few kilohertz is not fast enough to generate an overshooting pulse rise of relaxation oscillation. Therefore, an almost rectangular pulse shape is realized if the pulse driver or the pulse pattern generator is appropriately designed without any surge or overshooting currents. The pulse shape should be checked just in case if necessary.

The RMS voltmeter, and the time-averaged power meter shall be used for laser modules operated in PWM. To keep the accuracy of the measurements, the measurement time shall be sufficiently longer than the period of PWM. For example, the error of the average power of 240 pulses for a power measurement time (integrating time) of 0,1 s is less than 0,5 % even if the integrating time is not an integer multiple of the period. In other word, the integrating time shall be an integer multiple of the period if the integrating time is much shorter.

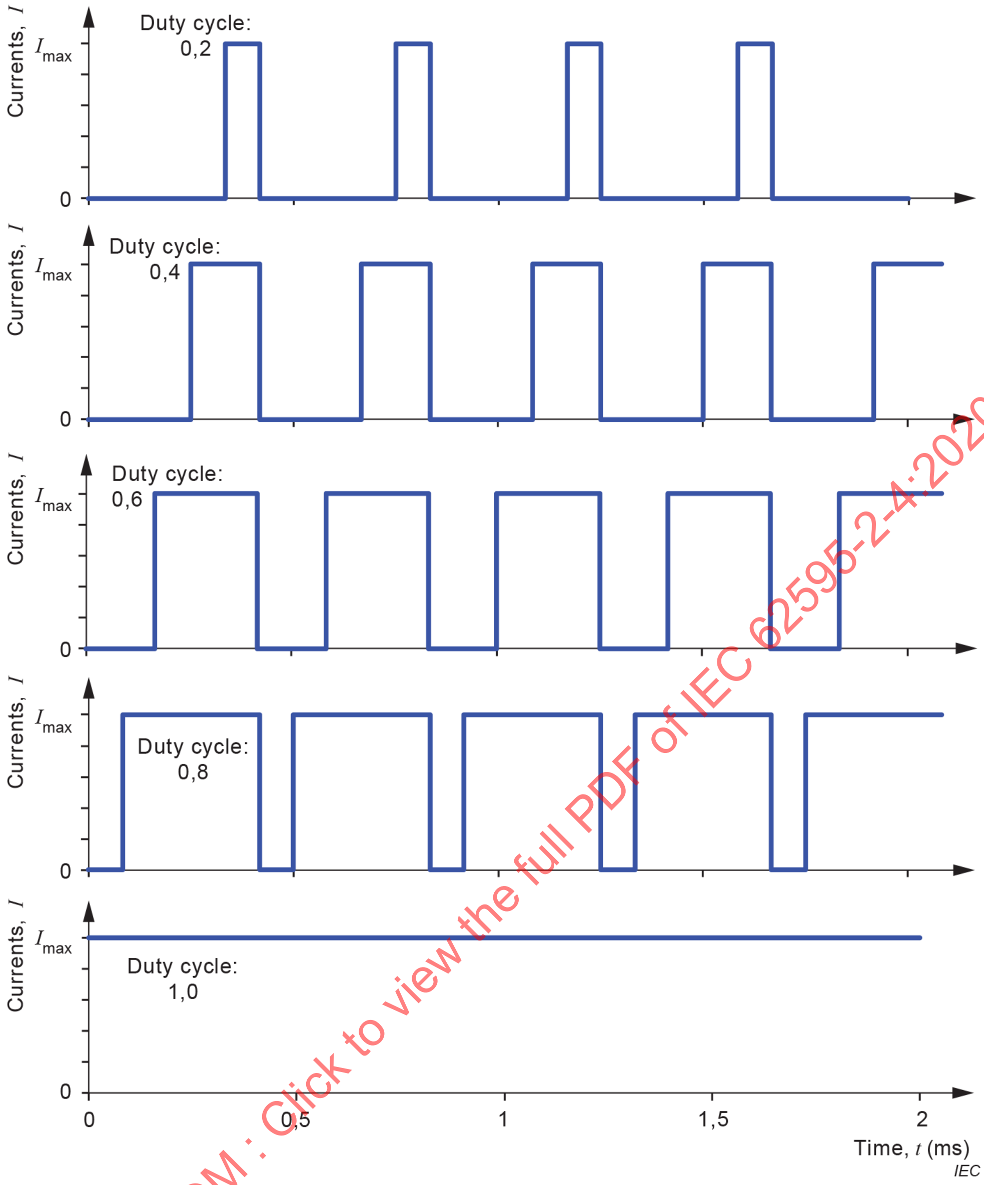


Figure 5 – Pulse repetition waveforms of PWM drive with respect to duty cycle

5.2.4 Threshold currents (I_{th})

The laser module normally uses more than two LDs with different threshold currents. As total currents increase, the LD with the lowest threshold current starts the oscillation. Then the LDs with higher threshold currents start the oscillation until the highest threshold current finally starts the oscillation. The transient current levels between the current when the lowest threshold LD starts the oscillation and the current when all the LDs finally oscillate is unstable. Unlike a single LD, it is not easy to exactly determine the threshold current from the I-P_o characteristics due to this unstable transient region. That is, the lasing of the last LD is buried with the laser outputs of the rest which have started lasing already. An example of a high-power blue LD module with nine blue LDs connected in a 3 × 3 parallel-serial configuration (Figure B.1) is shown in Figure 6.

The threshold current of the laser module with single-channel driving should be defined approximately as the intersection point of the I axis with the extended line plotted through two points at the relatively linear and stable region of the I-P_o characteristics (see Figure 6).

The threshold current of a laser module with multiple-driver channels shall be measured channel by channel. For example, the RGB or multi-colour laser module is designed to drive each colour channel independently. To control output colour, the threshold of each colour channel is important.

If a single LD is used for each channel, the conventional measuring method for LD packages shall be applied.

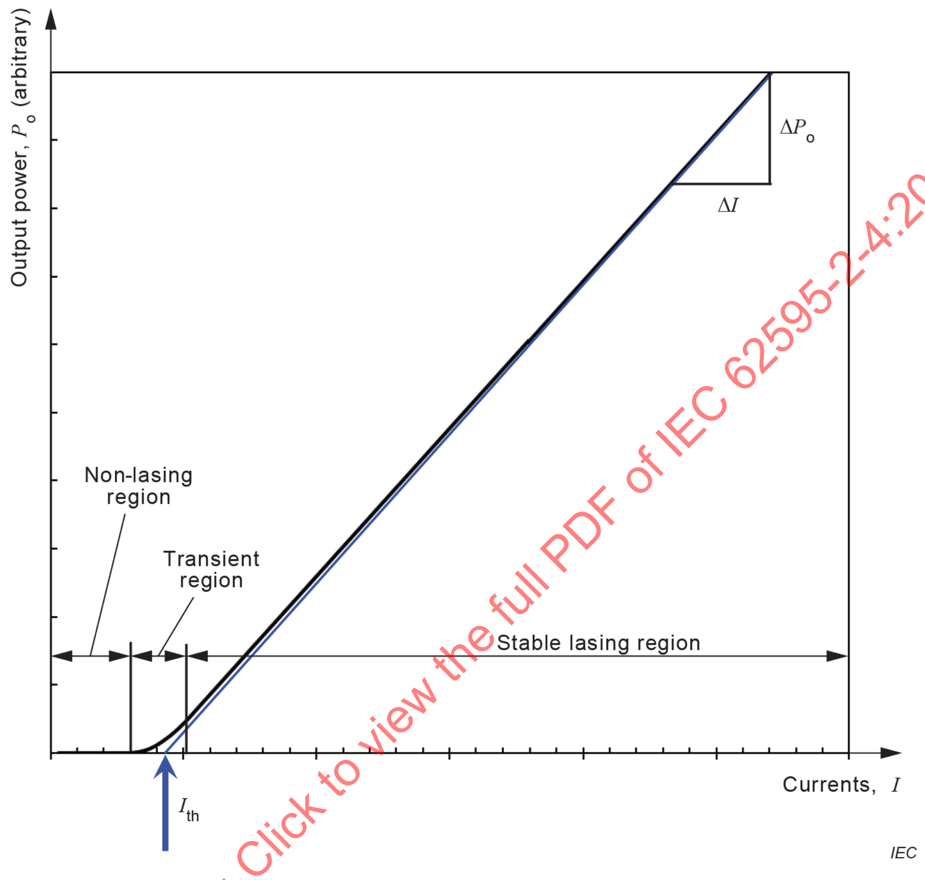


Figure 6 – I_{th} and I-P_o characteristics

5.2.5 Measurement procedures

The measurement procedures of current-light output characteristics shall be as follows:

a) Confirm whether or not the DUT includes the temperature control unit.
b) Measure the environmental temperature.
c) Measure the case temperature (if necessary).
d) Confirm whether or not the DUT has the current control functions.
e) Confirm whether the DUT is current-driven in CW or PWM.
f) Prepare an appropriate current variable source (CW or PWM) if the DUT does not have the current control functions.
g) Prepare the LMDs for the optical power, current, and voltage (if necessary) appropriate for CW or PWM.
h) Set the LMD for optical output power in the proximity of the output plane on (0, 0, $L \approx 0$) as shown in the setup in Figure 1 or Figure 2.
i) Confirm all the optical output power is detected by the LMD.
j) Select the colour channel of the DUT (if it is a multi-colour laser module).

k) Select the input current level of the DUT.

l) Wait until the DUT and the LMDs gain stability.

m) Measure the optical output power.

n) Calculate WPE (P_o / P_i) using Formula (1) (if necessary).

o) Repeat the procedures k) to n), changing the input current level until the necessary data are obtained.

p) Repeat the procedures k) to n), changing the colour channel (if it is a multi-colour laser module).

q) Plot the I-P_o characteristics.

r) Plot the I- P_o / P_i characteristics (if necessary).

s) Report the LMD specifications, the DUT specifications/conditions, the measurement setup/conditions and the measured results.

NOTE See 4.5 and 5.2.3 for the PWM measurements.

5.3 Spectra (wavelength) and chromaticity measurements

5.3.1 General

The spectral structure emitted from a single output of the laser modules including multiple LDs usually consists of combined spectra. For example, the spectra of multiple LDs are superposed in the range of a couple of nanometres for a high-power monochromatic laser module (Figure B.1). The spectra of R, G, B LDs are superposed for high-power RGB laser modules (Figure B.2). The typical RGB laser modules for lower power applications use only one LD for each colour (Figure B.3). Chromaticity measurements/calculations using such narrow and complicated spectra shall be carried out carefully to keep the accuracy of the obtained chromaticity coordinates.

Examples of the measurement accuracy of chromaticity for such narrow spectra are shown in Annex C and Annex D.

5.3.2 Measurement procedures

The measurement procedures of spectra and chromaticity shall be as follows.

a) Confirm whether or not the DUT includes the temperature control unit.

b) Measure the environmental temperature.

c) Measure the case temperature (if necessary).

d) Confirm whether or not the DUT has current control functions for each colour channel.

e) Confirm whether the DUT is current-driven in CW or PWM.

f) Prepare appropriate current variable sources (CW or PWM) if the DUT does not have the current control functions.

g) Prepare the LMDs for the current and optical power (if necessary) appropriate for CW or PWM.

h) Prepare the LMDs for spectrometric, wavelength or colorimetric measurement.

i) Set the LMD for spectrometric, wavelength or colorimetric measurement equipment in the proximity of the output plane on (0, 0, $L \approx 0$) as shown in the setup in Figure 1 or Figure 2.

j) Select the input current levels of the DUT (for each colour).

k) Wait until the DUT and the LMDs gain stability.

l) Measure the spectra, wavelength, or colorimetric values.

m) Measure the optical output power for each colour if the spectral power cannot be measured accurately by the LMD.

n) Calculate the chromaticity using the measured optical power for each colour if the spectral power cannot be measured accurately by the LMD.

o) Repeat the procedures j) to n), changing the input current level (if necessary).

p) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measured results.

NOTE See 4.5 and 5.2.3 for the PWM measurements.

5.4 FFP

5.4.1 General

The FFP of the fibre, light guide, or other optical output is important for designing the optics of laser displays or laser display lighting units. Particularly for scanning type laser displays, the FFP data provide us with the beam quality.

The FFP shall be measured at a distance along the z-direction significantly greater than W^2 / λ, where λ is the wavelength and W is the largest dimension in the output aperture. The above conditions guarantee that the FFP is measured in the Fraunhofer diffraction region.

The direct measurement of the FFP without using projected screens is not affected by speckle. However, the spherical surface move (scan) of the LMD is time-consuming. The distance L should be much longer, or the aperture of the LMD should be smaller to obtain higher spatial resolutions.

For laser modules operated in PWM, the RMS voltmeter and the time-averaged power meter shall be used. To keep the accuracy of the measurements, the measurement time (integrating time) shall be sufficiently longer than the period of PWM as explained in 5.2.3. For automated scan systems, the scan speed shall be slow enough to keep the integrating time to keep accuracy.

5.4.2 Monochromatic FFP

The monochromatic FFP of laser diodes has usually been radiometrically measured using a power meter at the point on the sphere surface centred at the output point.

The fundamental measurement setup with the spherical coordinate system in Figure 1 shall be used. The transverse/longitudinal mode behaviours of LDs vary depending on their output levels. Therefore, the FFP would also vary with the mode variations. The FFP measurements at other output levels should be carried out if necessary.

The fundamental measurement procedures of a monochromatic FFP shall be as follows:

a) Confirm whether or not the DUT includes the temperature control unit.

b) Measure the environmental temperature.

c) Measure the case temperature (if necessary).

d) Confirm whether or not the DUT has the current control functions.

e) Confirm whether the DUT is current-driven in CW or PWM.

f) Prepare appropriate current variable sources (CW or PWM) if the DUT does not have the current control functions.

g) Prepare the LMDs for the optical power, current, and voltage (if necessary) appropriate for CW or PWM.

h) Set the LMD for optical output power measurement on the initial point of the spherical surface (ϕ, θ, L) as shown in the setup in Figure 1.

i) Select the colour channel of the DUT (if it is a multi-colour laser module).

j) Select the input current level of the DUT.

k) Wait until the DUT and the LMDs gain stability.

l) Obtain the monochromatic FFP data by moving the LMD at the same speed on the spherical surface (ϕ, θ, L) in Figure 1.

m) Repeat the procedures j) to l), changing the input current level (if necessary).

n) Repeat the procedures i) to m), changing the colour channel (if it is a multi-colour laser module).

o) Plot the monochromatic FFP data.

p) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measured 2D data.

In another version of the setup, the LMD is fixed and the output head (the laser diode) rotates horizontally and vertically, as the relative move gives the same results.

The Cartesian coordinate system shown in Figure 2 shall be also used if the divergence between the output laser beam and the laser modules is narrow enough, as explained in 4.6. The virtual flat screen at (x, y, L) in the Cartesian coordinate system is easier to realise. The LMD can automatically move (scan) on the virtual flat screen. The conversion from the spherical system to the Cartesian coordinate system is shown in Annex F.

An alternative measurement method with the Cartesian coordinate system is shown in 5.5.2, as a part of the speckle measurement methods. The speckle-free FFP shall be obtained by eliminating the effects of speckle. For example, post-processing (local averaging) of the measured speckled 2D FFP data, or the iris-opening of the speckle measurement equipment are very useful for measuring both the speckle and FFP simultaneously.

When these alternative versions of setup or methods are used, they shall be specified in detail in the report.

5.4.3 Colorimetric FFP

The colorimetric FFP is a new metric specific to display/lighting applications, which shall be measured using a colorimeter/illuminance meter including a laser multi-meter at the point on the sphere surface centred at the output point. The fundamental measurement setup and spherical coordinate system in Figure 1 shall be used unless otherwise specified.

The transverse/longitudinal mode behaviours of LDs vary depending on their output levels. Therefore, the FFP would vary with the mode variations. The FFP measurements at other output levels should be carried out if necessary. Particularly for colorimetric FFP, the I-P_{o} characteristics, threshold current I_{th}, and the transverse/longitudinal mode behaviours are different colour by colour. The photometric/colorimetric behaviours of the colorimetric FFP are greatly affected by the driving current levels of the LDs emitting each colour.

As shown in Annex E, the core-clad refractive index difference becomes slightly larger for shorter-wavelength colour for silica fibre. Hence, NA for B is the largest, and NA for R is the smallest. Therefore, the periphery of FFP becomes more bluish than the centre.

The fundamental measurement procedures of the colorimetric FFP shall be as follows.

a) Confirm whether or not the DUT includes the temperature control unit.

b) Measure the environmental temperature.

c) Measure the case temperature (if necessary).

d) Confirm whether or not the DUT has the current control functions.

e) Confirm whether the DUT is current-driven in CW or PWM.

f) Prepare the appropriate current variable sources (CW or PWM) if the DUT does not have the current control functions.

g) Prepare the LMDs for colorimetric measurements, and the LMDs for current and voltage (if necessary) measurements appropriate for CW or PWM.

h) Set the LMD for colorimetric measurements on the initial point of the spherical surface (0, 0, L) as the setup in Figure 1.

i) Determine the target chromaticity.

j) Select the DUT input current levels for each colour to obtain the target chromaticity.

k) Wait until the DUT and the LMDs gain stability.

l) Confirm the target chromaticity and repeat j) to k) until the target chromaticity is obtained.

m) Obtain the colorimetric FFP data by moving the LMD at the same speed on the spherical surface (ϕ, θ, L) in Figure 1.

n) Plot the colorimetric FFP data.

o) Repeat the procedures i) to n) (if necessary).

p) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measured 2D data.

In another version of the setup, the LMD is fixed and the output head rotates horizontally and vertically, as the relative move gives the same results.

The measurement setup with the Cartesian coordinate system is shown in Figure 2. The virtual flat screen at (x, y, L) in the Cartesian coordinate system is easier to realise. The LMD can automatically move (scan) on the virtual flat screen. The conversion from the spherical system to the Cartesian coordinate system is shown in Annex F.

The alternative measurement method with the Cartesian coordinate system is shown in 5.5.2 and 5.5.3, as part of the speckle measurement methods. The speckle-free FFP shall be obtained by eliminating the effects of speckle. For example, post-processing (local averaging) of the measured speckled 2D FFP data or the iris-opening of the speckle measurement equipment are very useful for measuring both the speckle and FFP simultaneously.

When these alternative versions of setup or methods are used, they shall be specified in detail in the report.

An example of measured results of colorimetric FFP is shown in Figure 7. The MMF output of a laser module with RGB LDs is projected on a standard diffusive screen (Cartesian coordinates in Figure 2). The NA of the MMF is 0,22 (see Annex E). The value of θ_{max} of the MMF is estimated to be 12,7° by finding the angle at which the illuminance data become zero along the diagonal direction in the 2D data in Figure 7. This value agrees with that calculated from the NA value of 0,22.

A viewgraph of 2D colorimetric FFP data is shown on top, which is the same as the W-data in Figure H.4. The colour expression of the 2D data (512 × 512 = 262 144) is just for reference. The 2D-FFP data is measured by the alternative method for obtaining speckle-free FFP using the iris-opening technique shown in 5.5.2 and 5.5.3.

The illuminance normalised by the maximum value, CIE 1931 chromaticity, x and y are plotted along the central horizontal line, converted into spherical coordinates in Figure 1. The formulae in Annex F are used for the conversion. They are also shown below the viewgraph of the coloured 2D data in Figure 7.

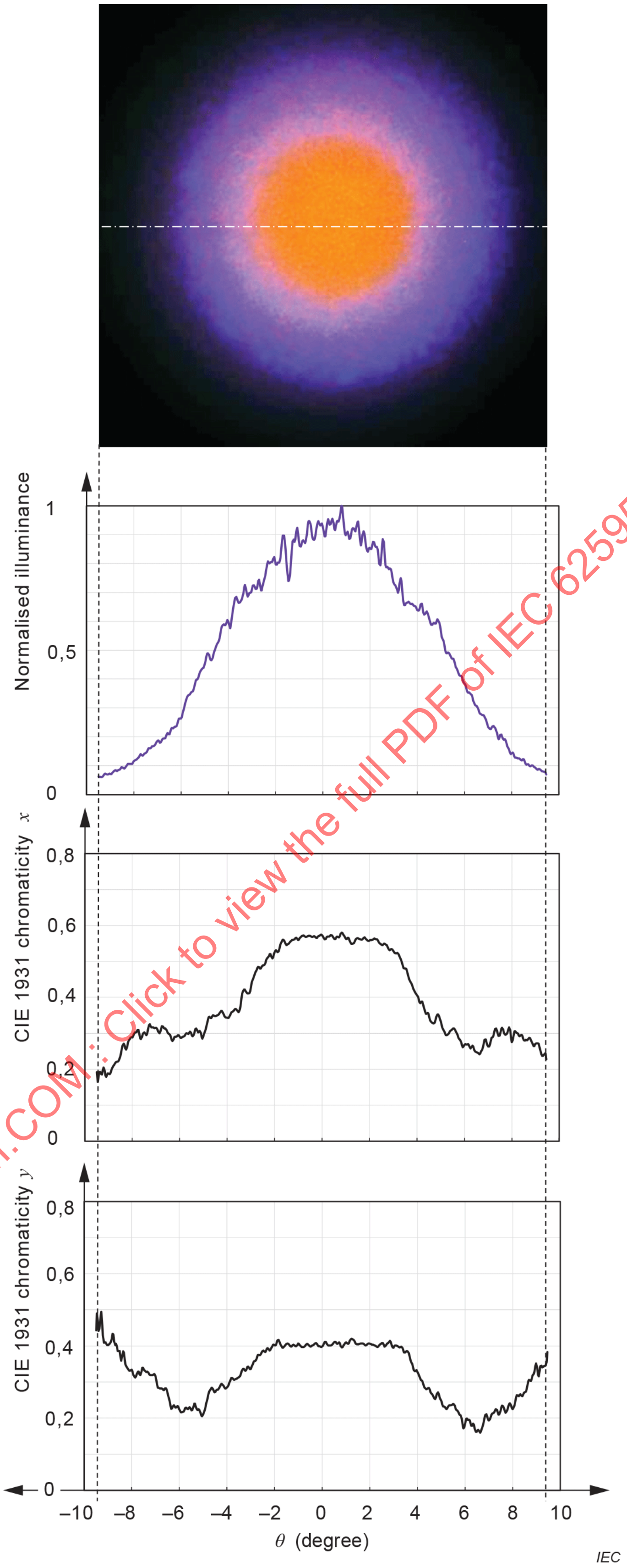


Figure 7 – Example of measured colorimetric FFP

5.5 Monochromatic speckle and colour speckle

5.5.1 General

Speckle and colour speckle greatly affect the visual quality of laser displays. Many laser displays are equipped with various kinds of speckle reducers, depending on the strength of the speckle (measured as speckle contrast) of the laser light sources. Therefore, it is important when designing a speckle reducer to measure the speckle contrast and colour speckle of the laser module.

NOTE Some laser displays are equipped with very effective speckle reducing technologies. For example, the phosphor wheel is capable of effectively reducing the speckle of low-luminosity blue laser lights.

Speckle and colour speckle measurements shall be carried out based on IEC 62906-5-2 and IEC 62906-5-4, respectively. Measurement setup for speckle-related optical performance is shown in Figure 3. However, for the speckle measuring methods of the laser beams, it is necessary to add some procedures to eliminate the field effects as described later.

The standard diffuse reflectance surface screen shall be used as a screen. The screen shall have Lambertian diffusive reflectance values of more than 95 % at the RGB wavelengths. Otherwise, the screen specifications related to screen gain such as the viewing angle characteristics, peak gain, half-gain angle, and so on, shall be reported. The screen should be held rigidly as the measurement results might be affected by long exposure time, or by unintentional moves.

For monochromatic speckle measurements, speckle contrast C_s shall be measured as the metric. For colour speckle measurements, the photometric speckle contrast C_{ps}, the variance and covariance of the colour speckle distribution in the chromaticity diagram shall be measured as the metrics. Speckle is created on the retina as an interference pattern of lights scattered on the screen. A standard diffusive reflectance screen shall be used for projecting the output of the DUT unless otherwise specified.

For laser modules operated in PWM, the RMS voltmeter and the time-averaged power meter shall be used. To keep the accuracy of the measurements, the measurement time (integrating time) shall be sufficiently longer than the period of PWM as explained in 5.2.3.

5.5.2 Monochromatic speckle measurement affected by FFP

Speckle contrast in monochromatic speckle measurement shall be carried out within a uniformly projected region. Speckle contrast is defined to be statistically calculated as the standard deviation divided by the average of the data. However, speckle of the projected laser beam from the laser modules is inevitably observed on the non-uniform FFP. Speckle contrast cannot be accurately calculated for such data on a non-uniform pattern. Therefore, it is necessary for accurate measurement of speckle contrast to eliminate the effect of the FFP. The measured 2D speckle data shall be normalized by dividing pixel by pixel through the corresponding speckle-free FFP data in order to remove the FFP effect. The speckle-free FFP data shall be obtained by the measuring method shown in 5.4.2. The FFP data should be also approximately obtained using speckle measurement equipment. One of the approximated methods is the post-process of the measured speckle data. The 2D speckle data in a small local area are averaged. Then this local-area averaging process is repeated pixel by pixel to obtain a smoothed profile of the speckle-free FFP [5]. The local-area size shall be optimized depending on the shape of the FFP. Abrupt variation in the FFP and higher speckle contrast will increase the errors.

The other approximated method is related to a measurement technique. The optics of speckle measurement equipment are designed to reproduce the speckle grain size on the human retina. By properly detuning the optics, the speckle effects can be minimized and averaged. As a result, the FFP profile becomes observable [6].

An example of conversion of the measured speckle data on the FFP into data on a uniform pattern is shown in Figure 8. The speckle data (512 × 512 = 262 144) of the red-colour output (636,9 nm) from a low-power RGB laser module with SLM were obtained. The graphs in Figure 8 are the data plots along the vertical centre line in the inserted 2D data.

The FFP data were approximately obtained by opening the iris of the speckle measurement equipment. The value of the speckle contrast was finally obtained as $C_{s\text{-}R}$ = 0,229.

The method for obtaining the approximated FFP data using the speckle measurement equipment shall be noted in detail in the report.

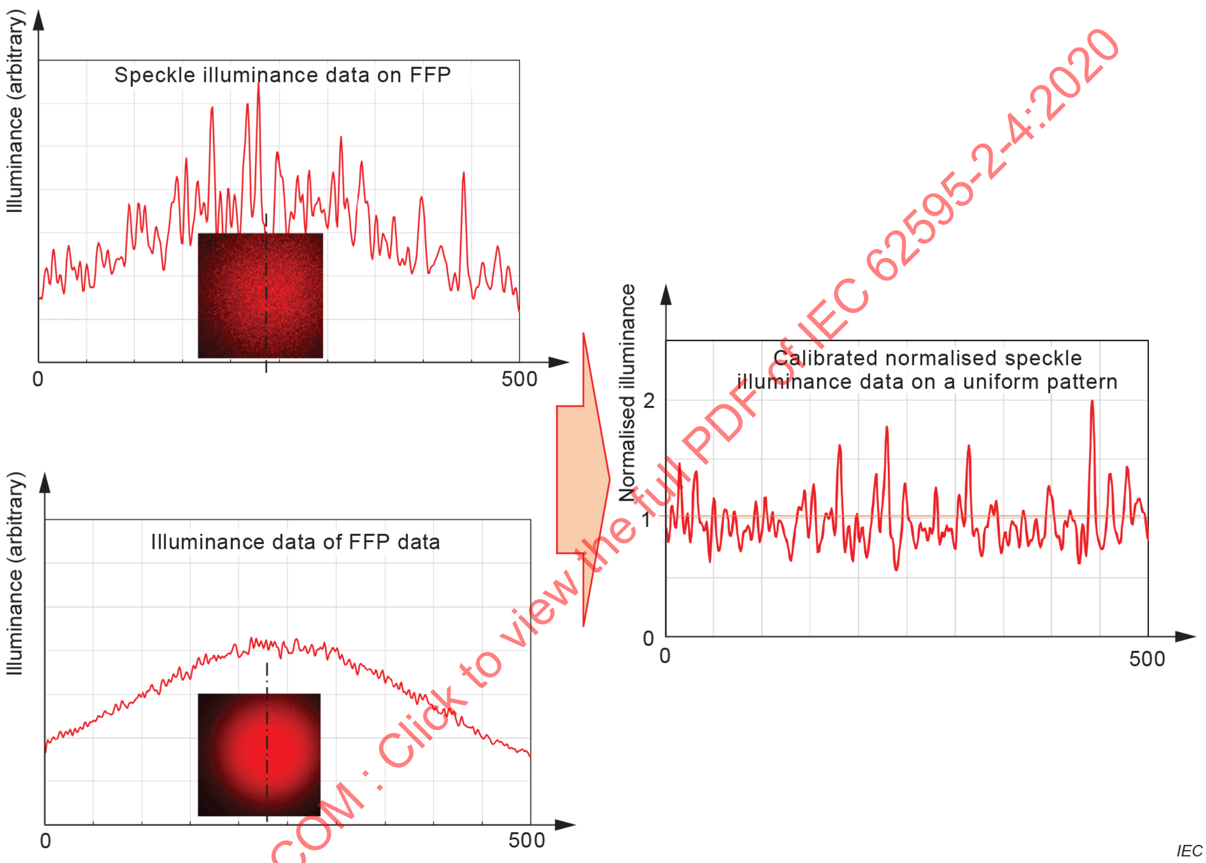


Figure 8 – Example of conversion of the measured speckle data on the FFP into data on a uniform pattern

The fundamental measurement procedures of monochromatic speckle contrast shall be as follows:

a) Confirm whether or not the DUT includes the temperature control unit.
b) Measure the environmental temperature.
c) Measure the case temperature (if necessary).
d) Confirm whether or not the DUT has the current control functions.
e) Confirm whether the DUT is current-driven in CW or PWM.
f) Prepare the appropriate current variable sources (CW or PWM) if the DUT does not have the current control functions.
g) Prepare the LMDs for the optical power, current, voltage (if necessary) appropriate for CW or PWM.
h) Set the LMD for speckle measurement as shown in the setup in Figure 3.
i) Select the colour channel of the DUT (if it is a multi-colour laser module).

j) Choose the appropriate colour filter of the LMD to measure the laser output of the selected colour.

k) Select the input current level of the DUT.

l) Wait until the DUT and the LMDs gain stability.

m) Obtain the monochromatic speckle data.

n) Repeat the procedure m) until statistically enough data are obtained (if data size is too small).

o) Repeat the procedures k) to n), changing the input current level (if necessary).

p) Repeat the procedures j) to o), changing the colour channel (if it is a multi-colour laser module).

q) Measure the monochromatic FFP (see 5.4.2). If the FFP is obtained by the approximated method using the speckle measurement equipment, note the method in detail in the report.

r) Convert the monochromatic speckle data on the FFP measured in m) into those on the uniform pattern, using the FFP data measured in q).

s) Calculate speckle contrast for each colour (e.g. $C_{\text{s-R}}$, $C_{\text{s-G}}$, $C_{\text{s-B}}$) using the converted speckle data in r).

t) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measurement results.

5.5.3 Colour speckle measurement affected by FFP

Colour speckle shall be calculated by colour addition of the monochromatic speckle data of each colour. The monochromatic speckle data of each colour shall be converted into data on a uniform pattern, eliminating the FFP effects. The ratio of the laser output powers of each colour shall be measured for the colour speckle calculation.

An example of conversion of the measured colour speckle data (normalized illuminance) on the FFP into data on a uniform pattern is shown in Figure 9. The colour speckle data (512 × 512 = 262 144) for the target white colour (u' = 0,211 2, v' = 0,475 2) by addition of the red-colour (636,9 nm), green-colour (520,3 nm) and blue-colour output (456,7 nm) from a low-power RGB laser module with SMF output were obtained. The graphs in Figure 9 are the normalized illuminance data plots along the vertical centre line in the inserted 2D data.

The speckle-free FFP data were approximately obtained by opening the iris of the speckle measurement equipment. The value of the speckle contrast was finally obtained as C_{ps} = 0,173.

An example of conversion of the measured colour speckle data (chromaticity distribution) on the FFP into data on a uniform pattern is shown in Figure 10. Half data (512 × 256 = 131 072: left half of the FFP) were plotted in Figure 10 because the full-data (512 × 512 = 262 144) are too heavy for the graph plot. The effect of the FFP on the chromaticity distribution is limited to the colour variation due to the R, G, B colour variation in beam spreading, or the transverse mode behaviour. The colour variation in the beam spreading is dominant in this example of the low-power RGB laser module with SMF output. Therefore, the periphery of FFP becomes more bluish and reddish in the centre.

The measured results for the example above are summarised in Table 2.

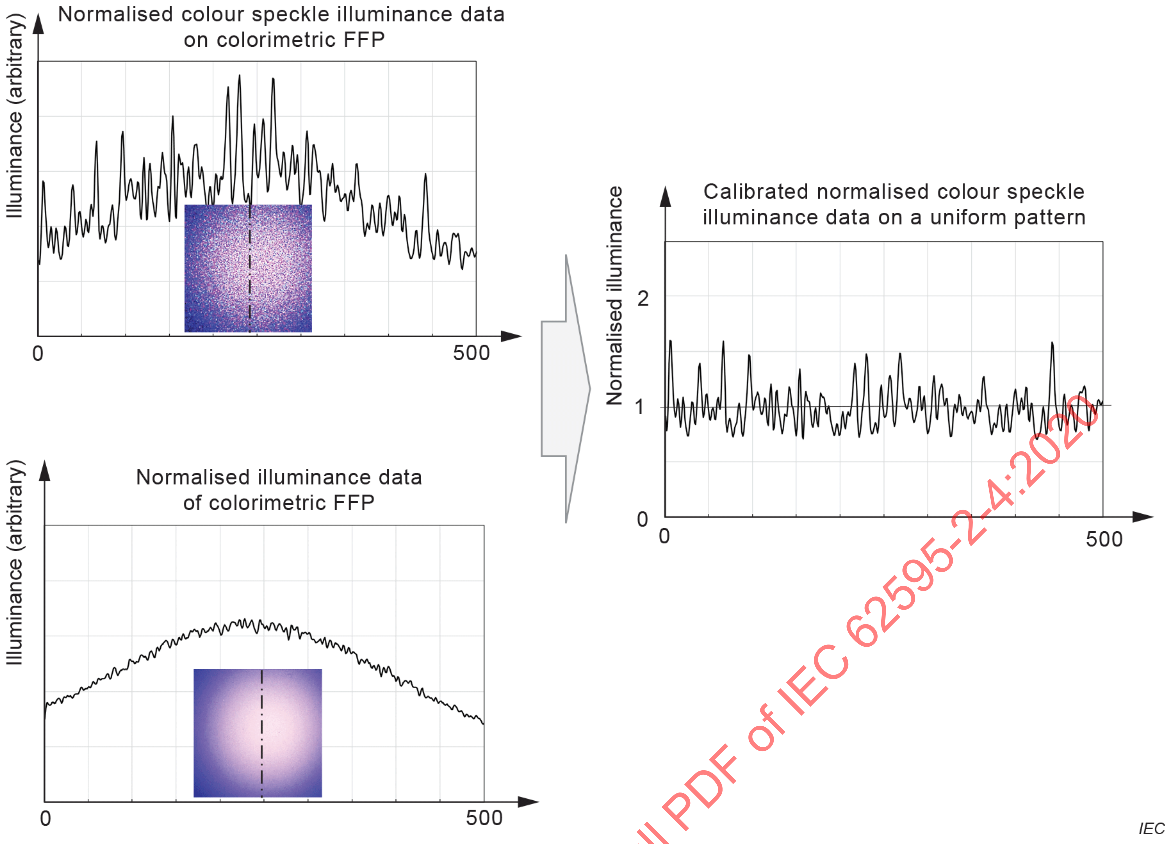


Figure 9 – Example of conversion of measured normalised illuminance data of colour speckle on the FFP into data on a uniform pattern

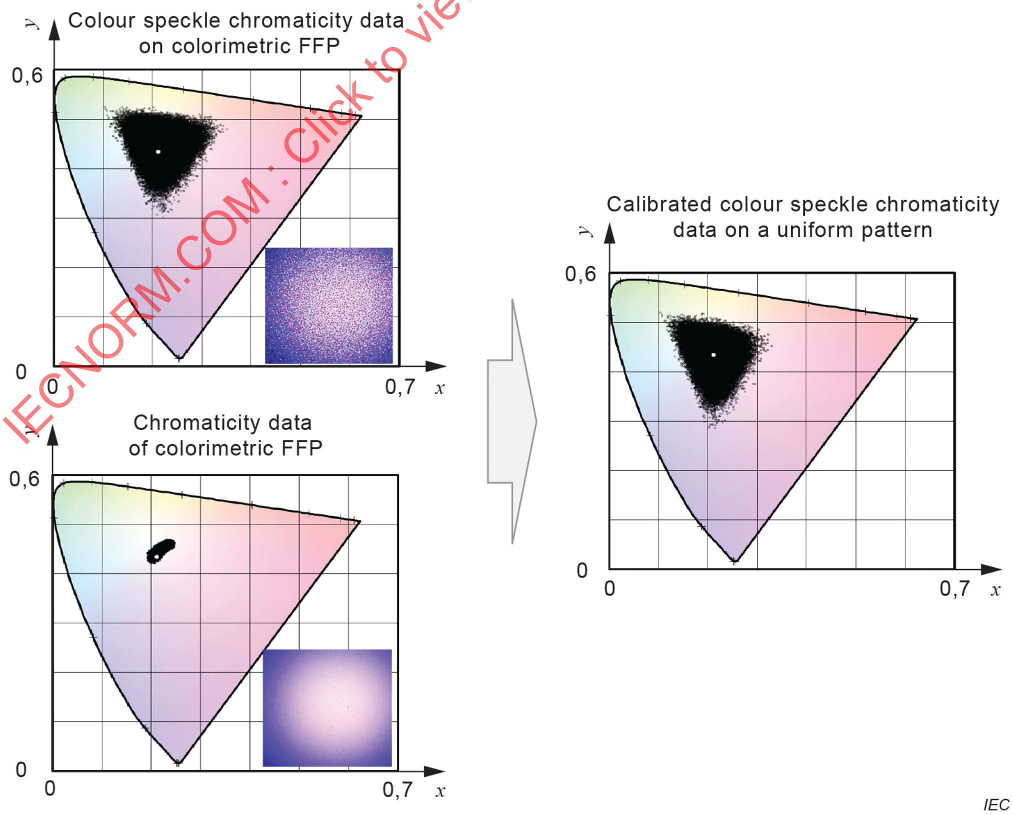


Figure 10 – Example of conversion of measured colour speckle chromaticity data on the FFP into data on a uniform pattern

Table 2 – Summarised results of the colour speckle measurements (example)

	W	R	G	B
Wavelength (nm)	-	636,9	520,3	455,7
W-chromaticity	u' = 0,211 2 v' = 0,475 2	-	-	-
RGB power ratio	-	0,462	0,278	0,260
C_{ps}, C_s	0,173	0,229	0,224	0,247
Variance	$\sigma_{u'}$ = 6,85 × 10^{-4} $\sigma_{v'}$ = 7,96 × 10^{-4}	-	-	-
Covariance	$\mu_{u'v'}$ = −1,42 × 10^{-4}	-	-	-

The speckled FFP measured using the speckle measurement equipment and the FFP using the same equipment with the opening iris are shown in Figure H.1 and Figure H.2, respectively. The filtered-out R, G, B projected patterns and the white pattern are included in these figures. The DUT (the low-power RGB laser module with SMF) and the measurement conditions are the same as in the above example.

The speckled FFP and the FFP of a middle-power RGB laser module with MMF output are also shown in Figure H.3 and Figure H.4, respectively. For the MMF output, concentric ring-shape FFPs (transverse modes) are observed for the B and G colours. Due to this complexity, various colours in the FFP of the MMF output can be seen.

The fundamental measurement procedures of colour speckle shall be as follows:

a) Confirm whether or not the DUT includes the temperature control unit.

b) Measure the environmental temperature.

c) Measure the case temperature (if necessary).

d) Confirm whether or not the DUT has the current control functions.

e) Confirm whether the DUT is current-driven in CW or PWM.

f) Prepare the appropriate current variable sources (CW or PWM) if the DUT does not have the current control functions.

g) Prepare the LMDs for speckle measurement equipment, wavelength, optical power, current, and voltage (if necessary) appropriate for CW or PWM.

h) Determine the target chromaticity.

i) Select the DUT input current levels for each colour to obtain the target chromaticity.

j) Wait until the DUT and the LMDs gain stability.

k) Confirm the target chromaticity and repeat i) and j) until the target chromaticity is obtained.

l) Set the LMD for wavelength and output power for each colour (spectrum) in front of the DUT output.

m) Measure the wavelength (spectrum) and illuminance (output power for each colour).

n) Set the LMD for speckle measurement as shown in the setup in Figure 3.

o) Obtain the monochromatic speckle data for each colour, changing the colour filter of the LMD as in 5.5.2.

p) Measure the monochromatic FFP (see 5.4.2). If the FFP is obtained by the approximated method using the speckle measurement equipment, note the method in detail in the report.

q) Convert the monochromatic speckle data on the FFP measured in m) into those on a uniform pattern, using the FFP data measured.

r) Calculate speckle contrast for each colour (e.g. $C_{s\text{-}R}$, $C_{s\text{-}G}$, $C_{s\text{-}B}$) using the converted speckle data.

s) Calculate the colour speckle metrics (C_{ps}, chromaticity distribution).

t) Repeat the procedures h) to s) (if necessary).

u) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measurement results.

5.6 Temperature dependence

5.6.1 General

For each LD product, the manufacturers usually provide typical temperature dependence data. Therefore, the module manufacturers can estimate the temperature performance of the module based on the provided data. Some of the modules are equipped with an automatic power control (APC) system using monitoring PDs for each colour. However, the junction temperature T_j of each LD depends on the thermal design of the assembly of multiple LDs. The temperature dependence of a single LD is explained in Annex I, as a fundamental behaviour.

Particularly for RGB laser modules which utilise LDs based on the different material systems, the thermal behaviour of the R LD based on the AlInGaP/GaAs material system is much poorer than that of the B LD based on InGaN/GaN material system. The thermal interference among the RGB LDs also makes the thermal behaviour of the module more complicated. Therefore, the chromaticity of the RGB laser module is sensitive to temperature variation.

It is necessary for designing the control system to measure the temperature dependence of the module.

The methods here can also be applicable to temperature-accelerating reliability tests.

5.6.2 High-power LD module

A typical measurement setup of the temperature dependence of a high-power LD module is schematically shown in Figure 11.

For large-size high-power LD modules with high thermal capacity, a thermostatic chamber shall be used to control their temperature. However, the electro-optical measurements specified in this document can be measured easily using the optical fibre output by setting LMDs outside the chamber. It is much easier than the LED assembly which needs to set the LMD inside the chamber. It is necessary to wait for an appropriate time after changing the temperature until the system reaches the steady state. The waiting time depends on the thermal resistance and the thermal capacity of the module. The chamber can control the atmospheric temperature T_a. The case temperature T_c shall be measured using a thermocouple or other methods at the case position (not shown in Figure 11), if necessary. The junction temperature T_j of the LDs can be calculated using thermal resistance from the case to the junction, or from the atmosphere to the junction.

The details of the measurement such as the controlled temperature (T_a or T_c), the T_c position (if T_c is used), and the waiting time shall be reported.

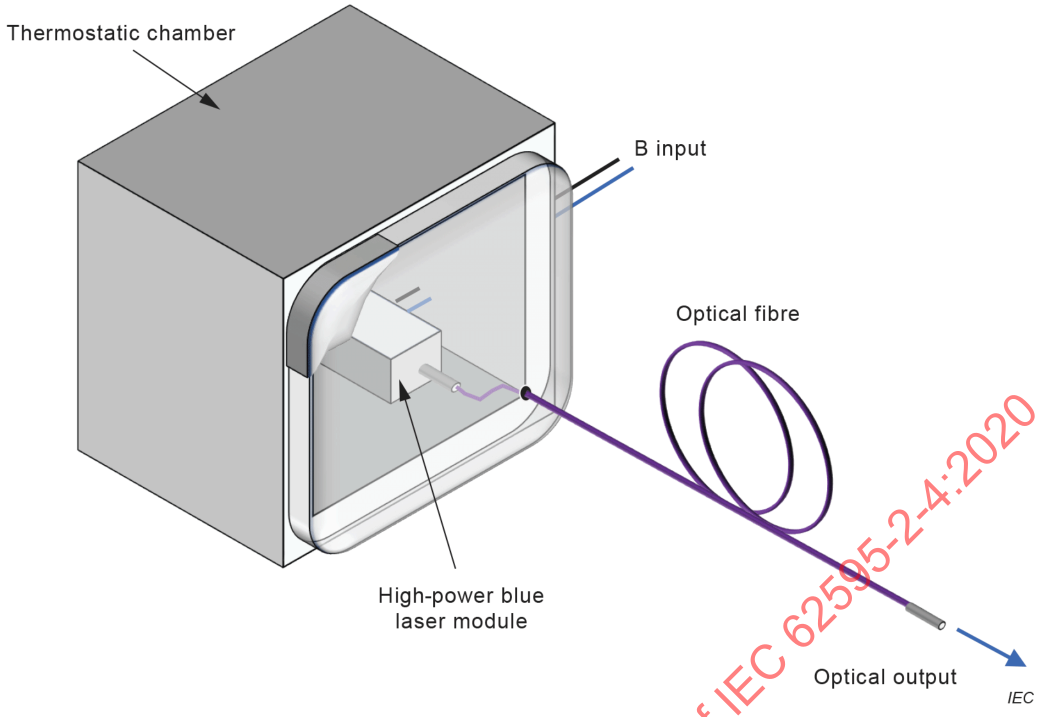


Figure 11 – Temperature dependence measurement setup for high-power laser modules

5.6.3 Low-power RGB LD module

For small-form-factor, low-power RGB LD modules, a thermostatic chamber, a TEC (thermo-electric cooler, Peltier cooler), or a heating/cooling plate shall be used to control their temperature.

For simple and low-cost measurements, a setup using a TEC or heating/cooling plate is convenient. The case temperature T_c can be monitored using a thermometer at the case position. A typical measurement setup of the temperature dependence of low-power LD modules is schematically shown in Figure 12. However, it should be noted that the junction temperature T_j of the LDs is higher than the case temperature T_c due to thermal resistance from the case to the LD chips (junctions).

The thermostatic chamber for the high-power LD module is also useful to measure many low-power LD modules simultaneously.

The details of the measurement such as the controlled temperature (T_a or T_c), the T_c position (if T_c is used), and waiting time shall be reported.

The theoretical model of I-P_o characteristics and their temperature dependence of a single LD are shown for information in Annex I. The measured results of the temperature dependence of R, G, B output powers, R, G, B wavelengths, and the 2D white speckled FFP data for an RGB laser module are also shown in Annex I.

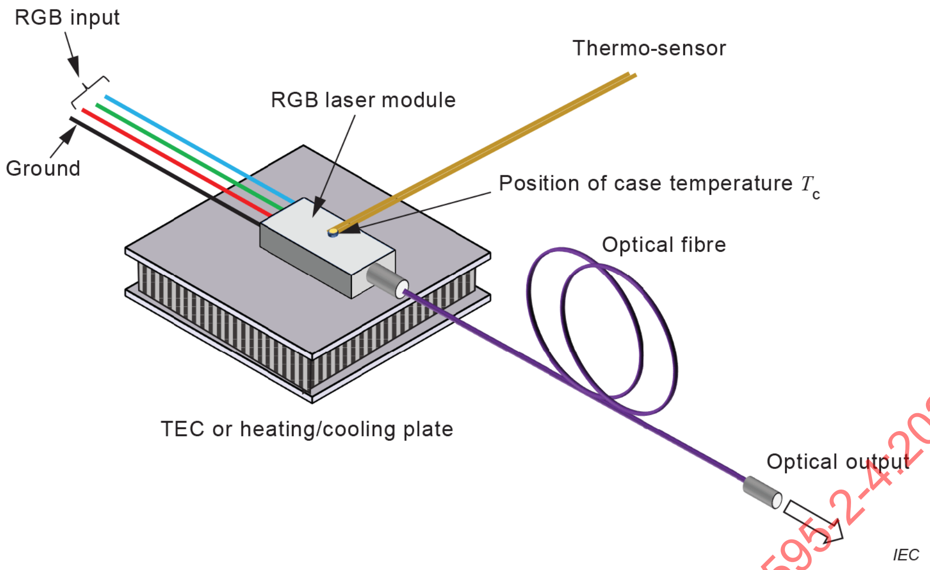


Figure 12 – Temperature dependence measurement setup for low-power laser modules

5.7 High-speed pulse modulation properties

5.7.1 General

High-speed pulse modulation properties are necessary when applied for scanning laser displays. The images are created as virtual pixels high-speed modulation of the R, G, and B LDs. The rise/fall time and delay time of the R, G, and B LDs are not synchronised, the transient colours and illuminance of the image signals being unstable [7]. To design high-speed RGB driver circuits, the optical output pulse waveform and rise/fall times, t_r, t_f should be measured. For example, the modulation frequency of LDs is calculated to be 94 MHz for XGA (1 024 × 768) at a frame rate of 60 Hz with a blanking rate of 0,5.

5.7.2 Optical output pulse waveform measurement

An example of the measurement setup for the output waveform is shown in Figure 13 for an RGB laser module. In general, the small-form-factor RGB laser modules applied for raster-scan RGB mobile projectors do not have a temperature control unit inside. In such a case, an external temperature control unit, for example a TEC, shall be used for stabilizing the temperature of the DUTs.

For high-speed measurements up to 100 MHz or more, special care for microwave frequencies shall be taken, such as usage of bias tee (bias T), coaxial cables, etc. An optical signal detection system covering the high frequencies shall be used.

An example of an electrical input pulse pattern and optical output pulse pattern is shown in Figure 14. High and low reference levels for defining the rise/fall times, t_r, t_f, shall be 90 % and 10 %, respectively.

The delay time of the LD, t_d, shall be defined as a time for building up laser oscillation by reaching the threshold current, I_{th}.

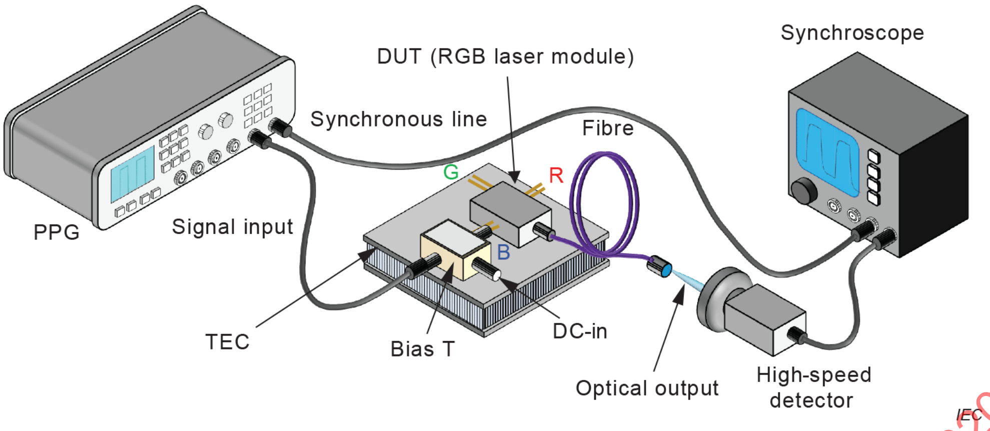


Figure 13 – Measurement setup for output pulse waveform

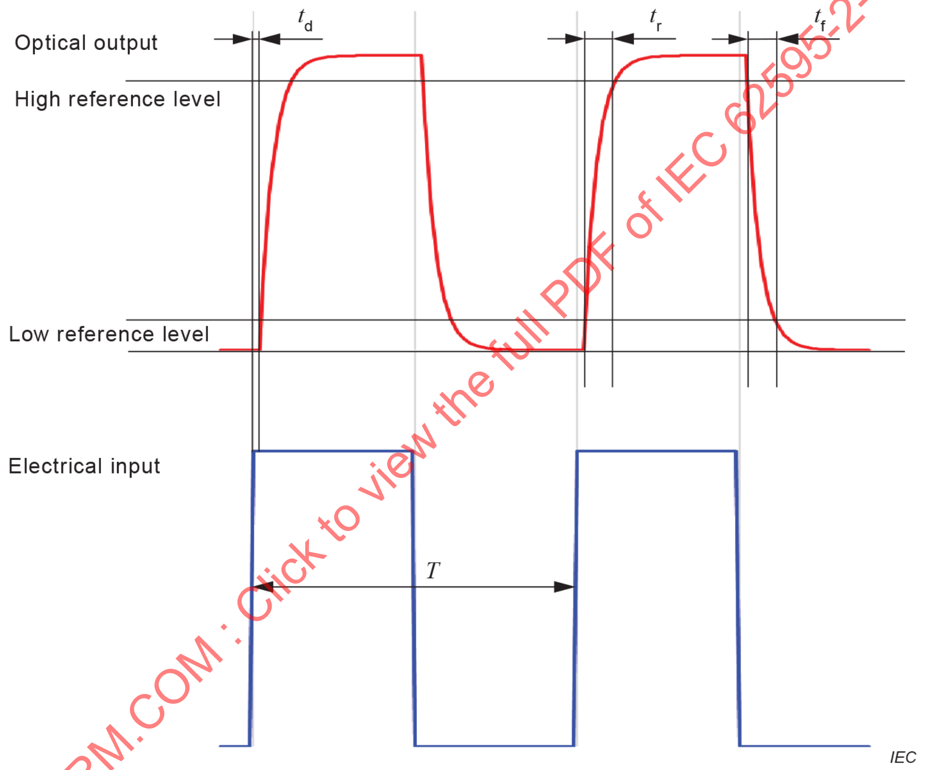


Figure 14 – Example of input/output pulse waveforms

The measurement shall be carried out as follows:

a) Confirm whether or not the DUT includes the temperature control unit.
b) Use an external temperature control unit for stabilizing the DUT temperature.
c) Measure the environmental temperature.
d) Measure the case temperature (if necessary).
e) Apply a pulse repetition signal to the RGB laser module colour by colour.
f) Measure the output pulse waveform and the input signal.
g) Determine the rise/fall times t_r, t_f and t_d of the output waveform.
h) Report the LMD details, the DUT specifications/conditions, the measurement setup/conditions and the measured results t_r, t_f and t_d.

The measurements related to the eye diagram should be optionally added for evaluating high-speed pulse modulation properties in more detail. Examples of the measured eye diagrams are shown in Annex J.

Annex A
(informative)

Laser devices

A.1 Edge-emitting laser diode

Most widely-used semiconductor lasers (for example, laser diodes (LDs) or diode lasers) are categorized as edge-emitting types. Lasing (stimulated emission) occurs in a stripe region of the active layer between the front and rear edges (cleaved mirror facets). This structure is called "optical cavity" for optical feedback. The current effectively flows into the stripe region only, blocked by the insulating dielectric layer. That is, the optical cavity is formed along the horizontal direction. When applying currents to the active layer stripe, spontaneous emission occurs. If optical gain exceeds unity at the threshold current (I_{th}), lasing starts and the laser beams with narrow divergence angles are emitted out of the stripe edges. The rear facet is usually high-reflectivity (HR) coated to pick up most of the optical output power efficiently from the front edge.

Figure A.1 is a schematic structure of a narrow stripe edge-emitting LD. The stripe structure is a so-called ridge-waveguide. The stripe width is approximately 1 µm, and the active layer thickness is approximately 0,1 µm, dimensions of the same order as the wavelength. Due to this waveguide structure which is much wider horizontally, the edge-emitting LDs usually operate in transverse electric (TE) polarized modes, suppressing the transverse magnetic (TM) polarized modes.

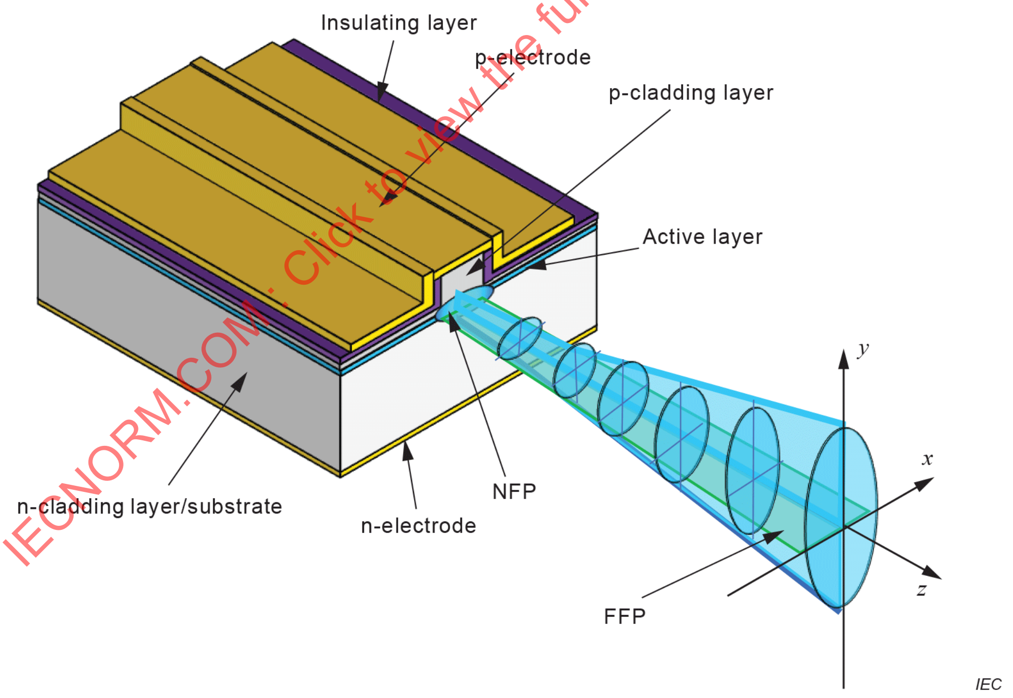


Figure A.1 – Schematic structure of narrow-stripe edge-emitting laser diode

Figure A.2 is a schematic structure of a wide stripe edge-emitting LD. The stripe width is approximately a few tens of micrometres, much wider than the above-mentioned narrow-stripe laser diode. The wide-stripe laser diode is used for watt-class high power applications.

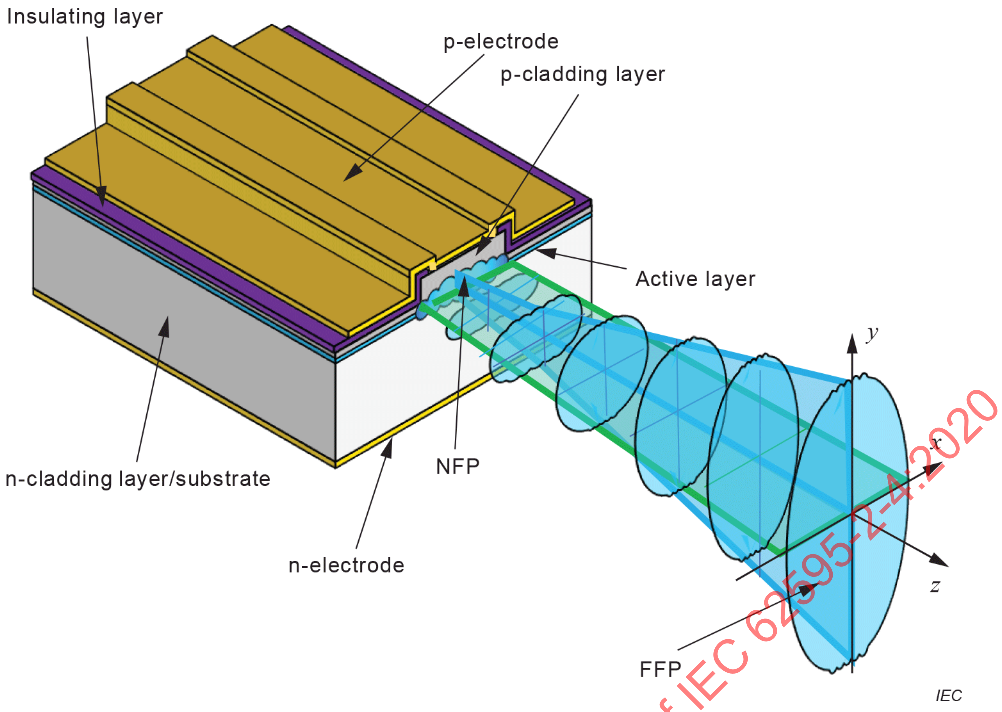


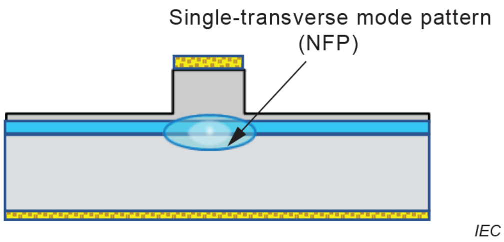
Figure A.2 – Schematic structure of wide-stripe edge-emitting laser diode

A.2 Single- and multi-transverse modes

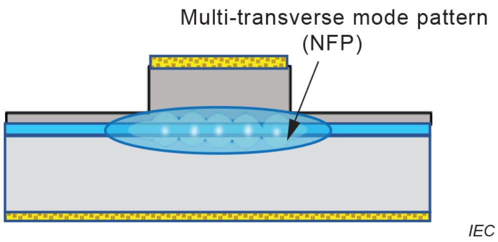
The transverse mode of the laser waveguide is expressed as a spatial optical power distribution on the plane perpendicular to the guided direction. A single-transverse mode pattern realised by the narrow stripe width of the same order as the wavelength, and a multi-transverse mode pattern of a much wider stripe are shown, respectively, in the left and the right drawings in Figure A.3. The transverse mode pattern at the output (front) edge facet is known as NFP. The single-transverse mode pattern is single peaked, whereas the multi-transverse mode pattern is multiple peaked along the stripe-width direction.

The FFP is expressed as the Fourier transform of the NFP at a distance far enough in the region where Fraunhofer diffraction approximation holds. However, it should be noted that the shape of the FFP is different from the original NFP. For example, as in the FFP in Figure A.1 and Figure A.2, the beam divergence in the vertical direction is much wider than that in the horizontal direction, which is affected by diffraction of the smaller NFP in the vertical direction. This is because the active layer thickness is around 0,1 µm, much smaller than the waveguide stripe width. Therefore, the FFP in the vertical direction is usually more than 40° (FWHM).

The horizontal array of obvious bright spots in the NFP for the multi-transverse mode lasers becomes unclear in the FFP, as in Figure A.2. However, it is more difficult for the multi-transverse mode to focus the beam via optics. The NFP of single-transverse mode LDs is around 1 µm in the horizontal direction, whereas that of multi-transverse mode LDs is usually 10 µm to 30 µm. The FFP is narrower than 20° (FWHM) in the horizontal direction.



a) Single-transverse mode



b) Multi-transverse mode

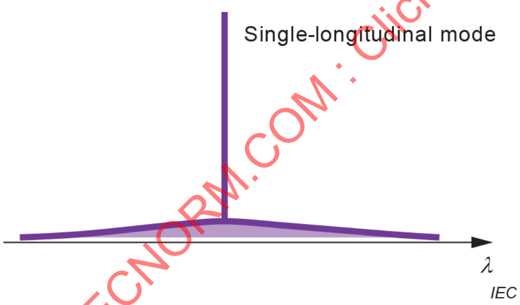
Figure A.3 – Single- and multi-transverse mode patterns

A.3 Single- and multi-longitudinal modes

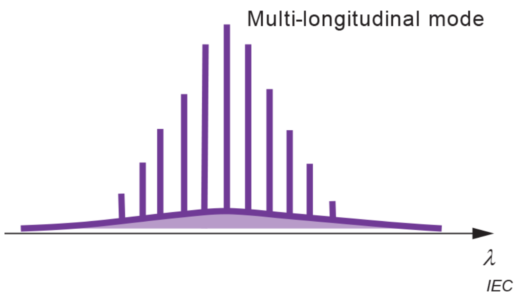
The longitudinal mode (for example, cavity mode) is observed as lasing spectral behaviour. It is closely related to the phase and gain condition of running and counter-running optical waves along the cavity. A schematic view of the spectrum for a single longitudinal mode operation is shown in the left of Figure A.4. A very sharp single line spectrum is obtained. Temporal coherence is higher than the multi-longitudinal mode operation (speckle contrast is also larger).

A spectral view of the multi-longitudinal mode is shown in the right of Figure A.4. Many line spectra are allowed to oscillate. The envelope of the spectra is strongly affected by the gain spectrum. Therefore, temporal coherence becomes worse, but speckle contrast is relatively small. In case of a Fabry-Perot etalon (optical cavity between the two mirrors), the mode interval, $\delta\lambda$, depends on the cavity length L, wavelength λ, and refractive index n. Ignoring the wavelength dependence of the refractive index, $\delta\lambda$ is approximately given by

$$\delta\lambda = \lambda^2 / 2nL \qquad \text{(A.1)}$$



a) Single-longitudinal mode



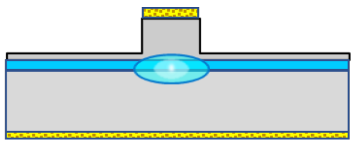
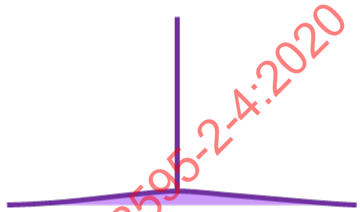
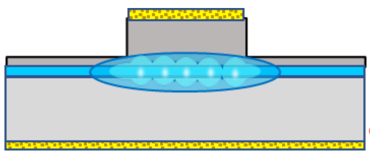
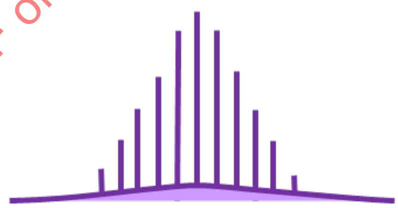
b) Multi- longitudinal mode

Figure A.4 – Single- and multi-longitudinal mode patterns

Just above the threshold current, it is easier to realise the single longitudinal mode operation because optical feedback concentrates on only the one longitudinal mode closest to the gain spectral peak. However, it becomes a little difficult to keep the single mode operation stable as currents increase. This is because of mode-competition with the adjacent modes. A sudden mode jump, or mode hopping, is likely to occur and jeopardizes the dynamic stability of the single-mode LD with a narrow stripe. It is necessary to avoid inhomogeneity of the current injection or to eliminate the deficiency of the active layer. However, for the LDs with a much wider stripe, unavoidable interactive mode-competition of so many longitudinal modes paradoxically realises statistically the dynamic stability of the multi-longitudinal mode operation. The mode-competition between a few modes makes a big impact on the LD characteristics, whereas multiple-mode interactions average the total competing effects and minimize the obvious effects.

The features of single- and multi-mode LDs are summarized in Table A.1.

Table A.1 – Features of single- and multi-mode LDs

Single/Multiple	Transverse mode	Longitudinal mode
Single	Low-power LD Single-peaked NFP 	Single, narrow line spectrum High temporal coherence (Larger speckle contrast) 
Multiple	High-power LD Multiple-peaked NFP (along horizontal direction) 	Multiple, narrow line spectra Low temporal coherence (Smaller speckle contrast) 

A.4 Vertical cavity surface-emitting laser diode (VCSEL)

Vertical cavity surface-emitting laser diodes (VCSELs) are another unique type of laser diode. The cavity direction is 90°, different from the widely used edge-emitting LDs. An example of a schematic structure of VCSELs is illustrated in Figure A.5. The optical cavity is realised between the lower and upper distributed Bragg reflectors (DBRs), instead of the cleaved edge-facet mirrors in the edge emitting type. The DBR is a layer stack fabricated in the epitaxial crystal growth process as well as the active layer and other indispensable crystal layers. As a result, the cavity is very small with extremely short length. It is easier to operate with low threshold currents. However, it is difficult for such a small volume cavity to achieve high-power operation. On the other hand, it is much easier to monolithically integrate many VCSELs. It is not necessary for VICSELs to use the cleavage process for obtaining the edge mirror facet which is indispensable for the edge-emitters when separating into discrete chips.

High-power operation can be achieved by such a monolithically integrated VCSEL array as shown in Figure A.6. However, it is difficult to achieve optical density as high as the edge-emitters.

The TE/TM suppression ratio is small for the VCSEL because the circular-transversal shape of the vertical cavity of VCSELs is isotropic.

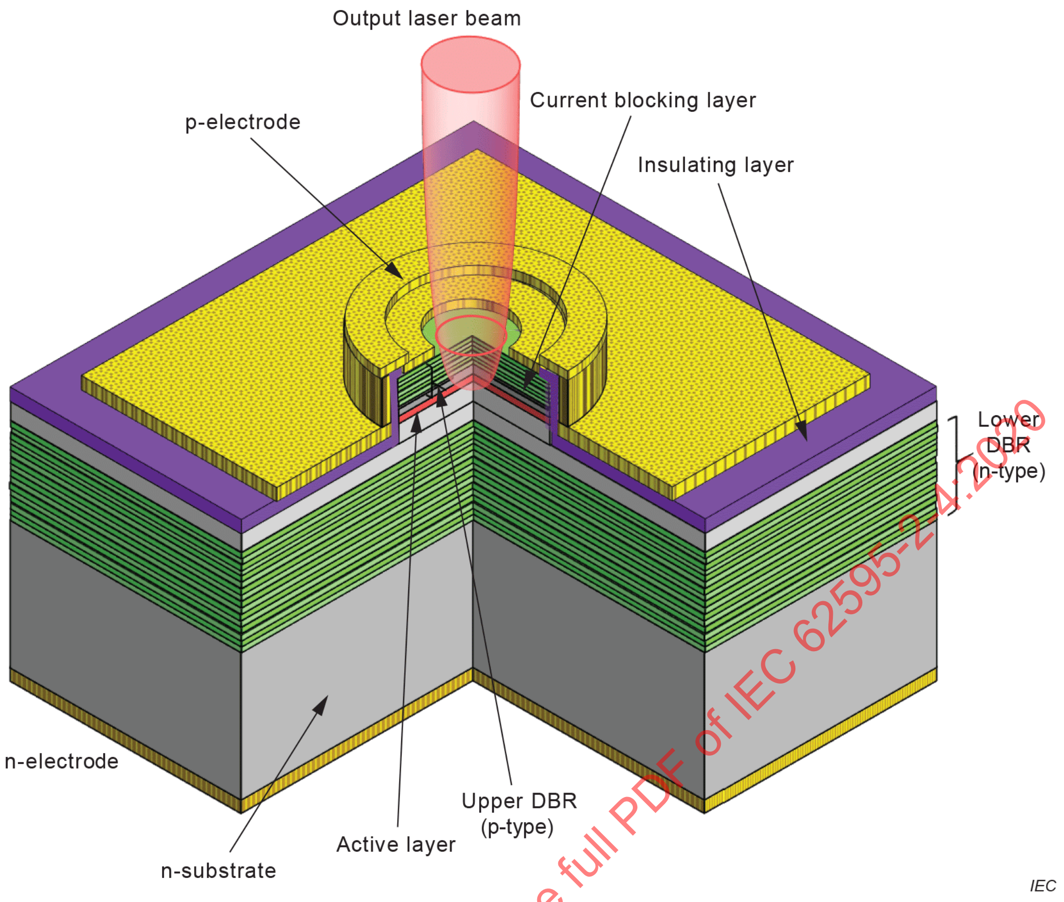


Figure A.5 – Schematic structure of VCSEL

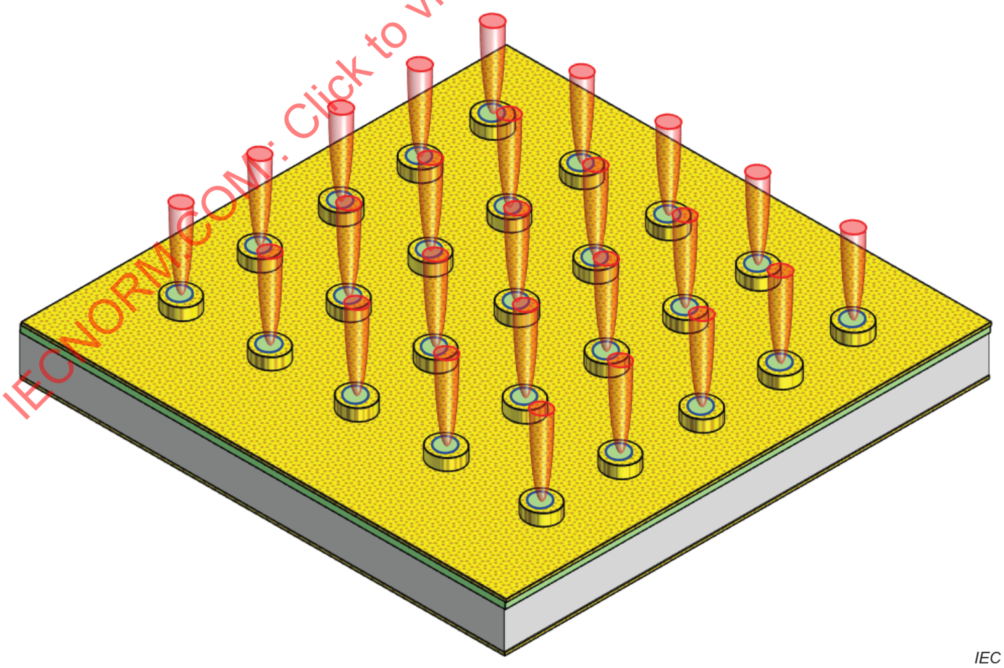


Figure A.6 – VCSEL array

A.5 Photon up-conversion laser device

Photon up-conversion is a technology converting lower energy photons to higher energy photons using non-linear optical materials. Two inputs of photons with energies of $h\nu_1$ and $h\nu_2$ create a single output photon with an energy of the sum of those two input photons, i.e., $h\nu_3 = h\nu_1 + h\nu_2$. The symbols ν_1, ν_2, and ν_3 are the photon frequencies, and h is the Planck constant. In the degenerate case of $\nu_1 = \nu_2 = \nu$, the output photon energy is expressed as $2h\nu$, which is called second harmonic generation (SHG). Third harmonic generation (THG) is also available. In terms of wavelength, photon up-conversion can be rephrased as wavelength conversion from longer wavelength to shorter wavelength. The conceptual image is shown in Figure A.7.

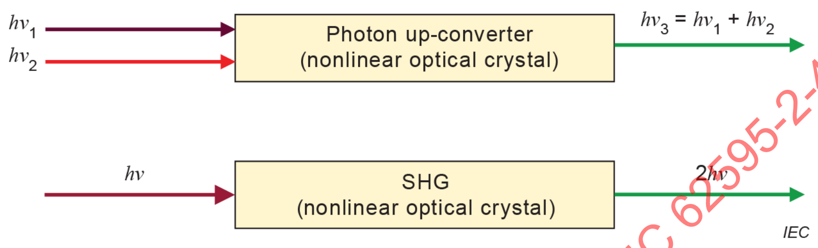


Figure A.7 – Conceptual image of photon up-conversion

The availability of practical deep green LDs emitting at wavelengths longer than 530 nm has not been good enough. The InGaN/GaN material system is used for LDs emitting at blue/green wavelengths. For longer wavelengths, it becomes more difficult to keep the quality of the InGaN active layer due to larger strain caused by increasing lattice-mismatch to the GaN substrate. Therefore, the green SHG laser devices have been employed instead of the green InGaN/GaN LDs. Figure A.8 illustrates an example of the SHG laser devices for an output at a wavelength of 532 nm. The input (pump) LD is a high-power, high-efficient IR LD emitting at 1 064 nm. For efficient conversion, the up-converter often has a waveguide with a periodic polarization inverse structure designed to optimise the quasi-phase-matching (QPM) condition.

The crystal growth technique for an InGaN/GaN LD is improving and overcoming the mismatch problem. Therefore, the SHG devices are replaced by the improved InGaN/GaN green LDs.

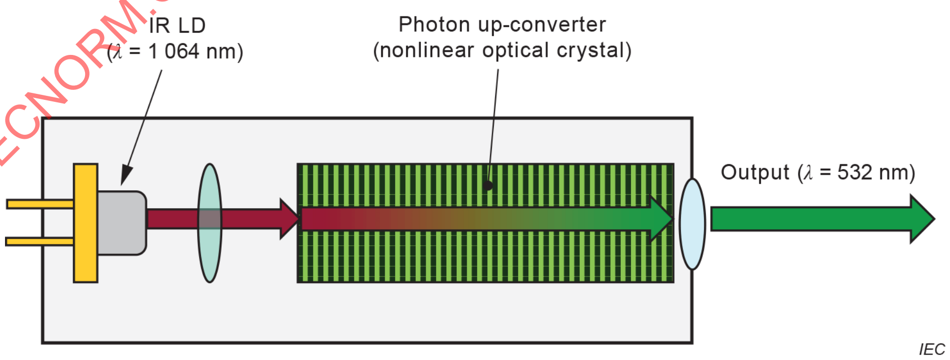


Figure A.8 – Example of SHG laser device emitting at 532 nm

Annex B
(informative)

Structure of laser module

B.1 Monochromatic laser module

A monochromatic laser module for high-power applications basically comprises multiple laser diodes (LDs) emitting within a wavelength range of a couple of nanometres, an electrical input and an optical output of combined powers of the multiple LDs. The optical output component is usually provided as a pigtail fibre, a fibre with a connector, a light guide, or other specific optics for convenience for display applications.

Figure B.1 is a schematic structure of a typical monochromatic laser module. It includes nine watt-class B (450 nm)-emitting InGaN/GaN LDs (CAN package). Three PCB branches have three LDs connected in series that are connected in parallel. The electrical B-signal is applied as a single channel input. The nine B laser beams are coupled into a multi-mode fibre (MMF) with angles within the fibre numerical aperture (NA) via the combining optics. The combined B laser power is emitted as a single output beam from the other fibre end.

The watt-class LDs usually operate in multi-transverse modes and in multi-longitudinal modes. The transverse modes of the LD are converted into the fibre transverse modes as traveling along the fibre.

The high-power monochromatic B laser module can be applied for phosphor-conversion type laser displays or it can be applied for RGB laser displays together with high-power R and G monochromatic laser modules. The blue LDs can be replaced by the watt-class violet (405 nm)-emitting InGaN/GaN LDs for application of pumping phosphors.

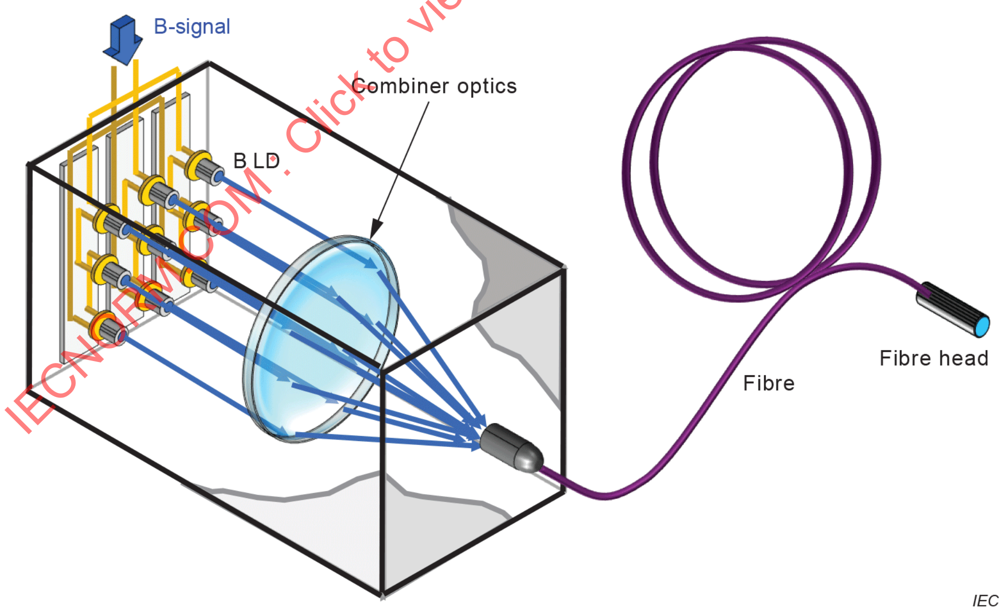


Figure B.1 – High-power monochromatic laser module

B.2 RGB laser module

An RGB laser module for high-power applications comprises multiple R, G, B LDs, electrical input channels for each R, G, B signal and an optical output of combined RGB optical powers. The optical output component is usually provided as a pigtail fibre, a fibre with a connector, a light guide, or other specific optics for convenience for display applications.

Figure B.2 is a schematic structure of a typical RGB laser module. It includes watt-class B-emitting InGaN/GaN LDs, watt-class G-emitting InGaN/GaN LDs, and watt-class R-emitting AlInGaP/GaAs LDs which are connected in series on each B, G, R branch of the PCB. The electrical R, G, B signals are applied to each branch independently as multi-channel input for output colour control. The R, G, B laser beams are coupled into an MMF with angles within the fibre NA via the combining optics. The combined R, G, B laser power is emitted as a single output beam from the other fibre end.

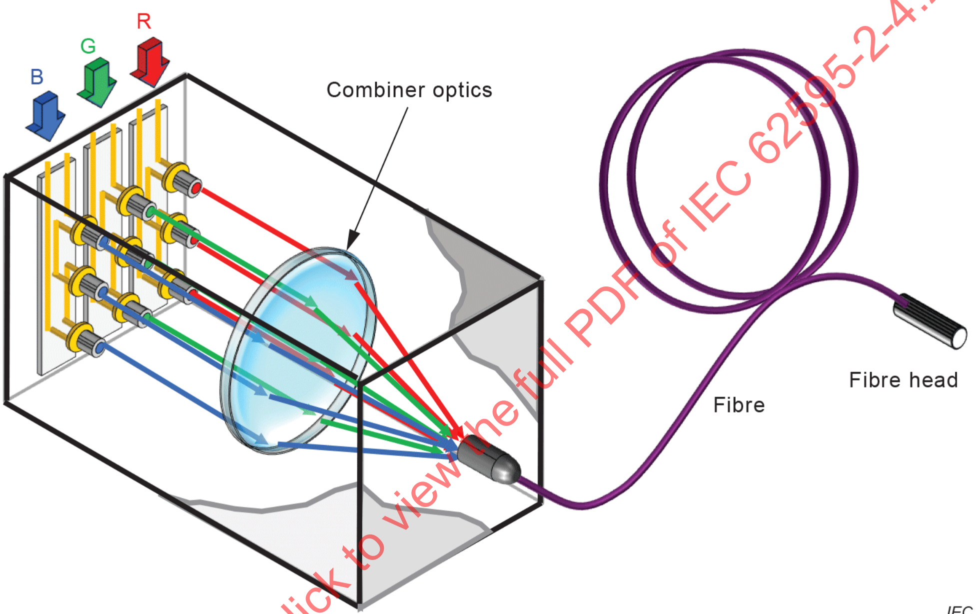


Figure B.2 – High-power RGB laser module

An RGB laser module for low-power applications comprises a single monochromatic LD for each R, G, B colour, electrical input channels for each R, G, B signal and an optical output emitting the combined RGB optical powers. The optical output component is usually provided as a pigtail fibre, or a fibre with a connector for convenience for display applications.

Figure B.3 is a schematic structure of a typical low-power RGB laser module. It includes a low-power B-emitting InGaN/GaN LD, a low-power G-emitting InGaN/GaN LD, and a low-power R-emitting AlInGaP/GaAs LD. The electrical R, G, B signals are applied to each R, G, B LD independently as multi-channel input for output colour control. The R, G, B laser beams are coupled into a single-mode fibre (SMF) via the combining optics. The combined R, G, B laser power is emitted as a single output beam from the other fibre end. The RGB LDs are compactly assembled or integrated to downsize the module.

The low-power LDs usually operate in a single-transverse mode and a single-longitudinal mode. The transverse mode of the LD is converted into the fibre transverse mode when the fibre-coupled light beam is traveling through the fibre.

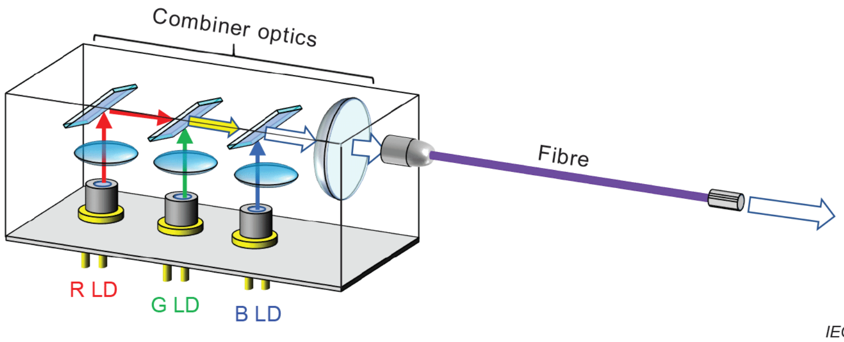


Figure B.3 – Low-power RGB laser module

B.3 Other output optics

The output optics other than fibres are shown in Figure B.4. A rigid light guide stick much thicker in size, a simple lens, or a simple aperture is an alternative to fibres.

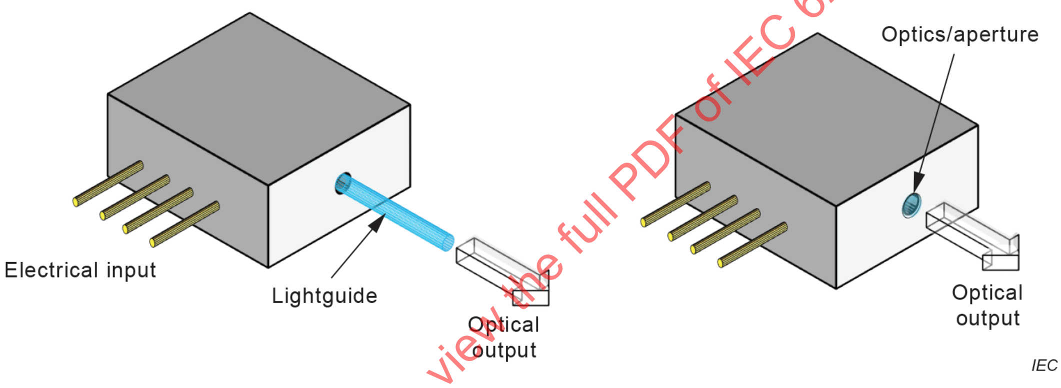


Figure B.4 – Other types of optical output

Annex C
(informative)

Narrow-linewidth emission spectra of laser modules

C.1 Spectra of monochromatic high-power LD modules

High-power LDs usually operate in a multi-longitudinal mode. Each LD has a different line-spectral structure if it is measured exactly with less than a sub-nanometre wavelength resolution. The spectrum of an LD operating in a multi-longitudinal mode has a fine comb structure of longitudinal modes with an equal spacing, as shown in Clause A.3. Therefore, the envelope of longitudinal modes can be considered as a spectral power distribution.

However, the superposed spectrum of such mode structures does not have an equal spacing. The interval of the longitudinal mode is a function of the laser cavity length, the effective refractive index of the waveguide structure, and the wavelength (see Formula (A.1)). Hence, high-power density regions and low-power density regions appear in the superposed spectrum. Therefore, the spectral envelope does not express an exact spectral power distribution.

Figure C.1 shows an example of the multi-mode comb structure with a resolution of 0,01 nm, which comprises the spectra of the light emitted from three LDs, #1, #2, and #3. It is necessary for observing such a fine longitudinal mode behaviour of multiple LDs to use a high-resolution spectrum analyser or a spectroradiometer.

The above high-resolution spectrometric measurements are the reference of the narrow-linewidth spectral analysis. However, the spectrum of CW-operated high-power LDs shows such fine multi-longitudinal mode structures only at lower current levels. Each modal line is broadened due to carrier density fluctuations at higher current levels (mode-competition). The large and rapid carrier density variation in PWM-operation broadens the modal lines to a bigger extent and the fine spectral structure vanishes. This phenomenon is called "wavelength chirp" [3]. Considering such broadening of the line spectra of the LDs, the spectrometric resolution of 0,01 nm should be over the specification from a practical viewpoint. The CIE 1931 chromaticity coordinates (x, y) calculated from the precise spectral structure in Figure C.1 and the colour matching functions with the 0,01 nm resolution are (0,161 62, 0,013 34).

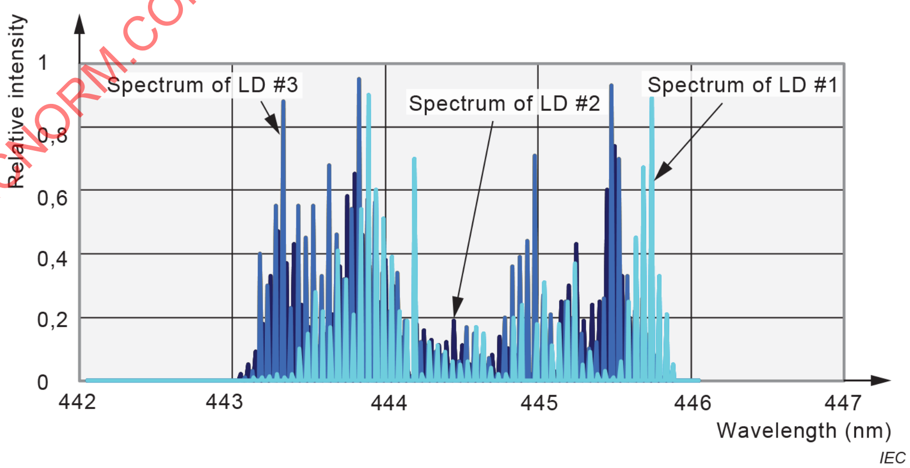


Figure C.1 – Superposition of multi-mode structures of three LDs

Spectral measurement with the lower resolution of 0,1 nm should be accurate. Figure C.2 shows the spectral power density $S(\lambda)$ with the resolution of 0,1 nm. The CIE 1931 chromaticity coordinates (x, y) are calculated as (0,161 66, 0,013 30) which are very close to those calculated from Figure C.1.

From a practical viewpoint, chromaticity coordinates are also calculated using the spectrum with a resolution of 1 nm in Figure C.3. The CIE 1931 chromaticity coordinates (x, y) are calculated as (0,161 54, 0,013 41), giving a good approximation.

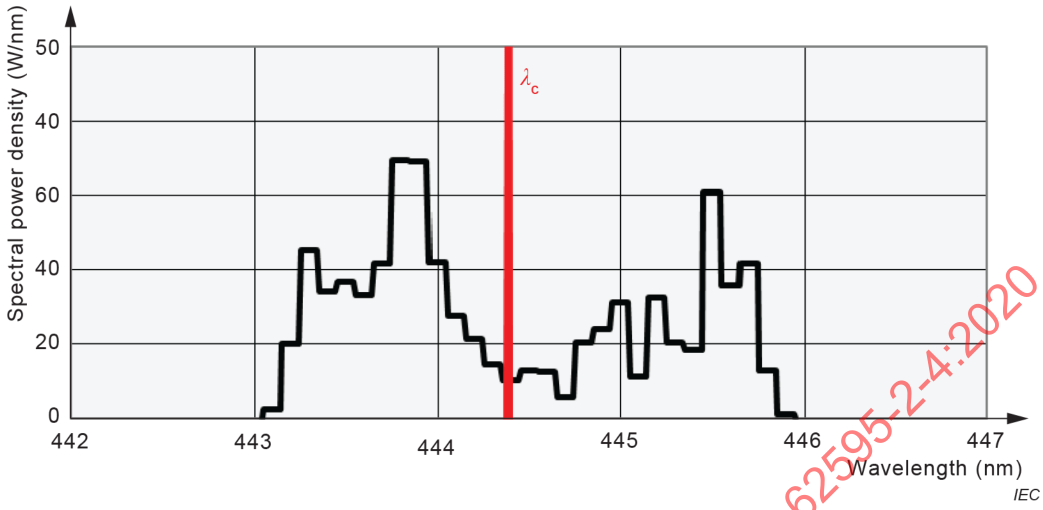


Figure C.2 – Spectral power density $S(\lambda)$ with a resolution of 0,1 nm

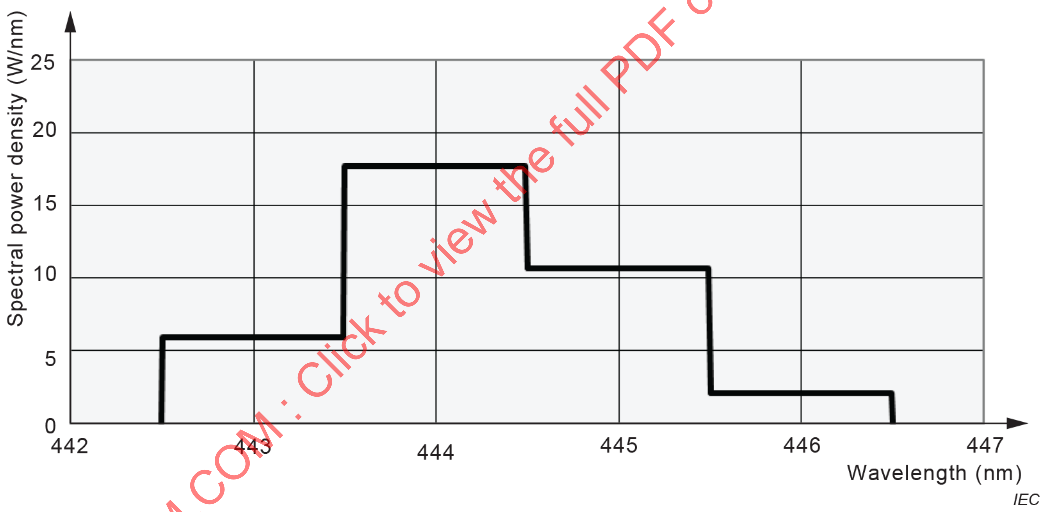


Figure C.3 – Spectral power density $S(\lambda)$ with a resolution of 1 nm

The centroid wavelength is convenient for representing such a narrow but irregular spectral power distribution at a single wavelength value. The centroid wavelength λ_c which implies the weighted mean of the wavelength is given in IEC 61280-1-3 [9]. The approximated chromaticity coordinates calculated using λ_c, are much more accurate than those using peak wavelength [1]. The results from [1] are summarized in Annex G.

The centroid wavelength of the spectrum in Figure C.3 is 444,4 nm. The CIE 1931 chromaticity coordinates (x, y) are calculated as (0,161 55, 0,013 40) using the single wavelength value of 444,4 nm. This value almost agrees with the result calculated from Figure C.3.

The CIE 1931 chromaticity coordinates calculated for resolutions of 0,01 nm (Figure C.1), 0,1 nm (Figure C.2), and 1 nm (Figure C.3), and for the centroid wavelength, are summarised in Table C.1. The chromaticity difference (Δx, Δy) among them are within 1,2 × 10^{-4}.

Table C.1 – CIE 1931 chromaticity calculated from the higher to the lower resolution spectra

	CIE 1931 chromaticity coordinates	
	x	*y*
Spectrum with a resolution of 0,01 nm	0,161 62	0,013 34
Spectrum with a resolution of 0,1 nm	0,161 66	0,013 30
Centroid wavelength of the above spectrum	0,161 55	0,013 40
Spectrum with a resolution of 1 nm	0,161 54	0,013 41

C.2 Spectra of multi-colour, single-longitudinal mode LD modules

Scanning laser displays use a laser module with single-transverse/longitudinal-mode R, G, B LDs. The output spectrum of each LD has a very narrow linewidth of less than 1 nm. An example of the R, G, B spectral set is shown in Figure C.4. The spectra should be measured using a spectroradiometer, a spectrum analyzer, a laser multi-meter, or a wavelength meter. The wavelength accuracy of the LMDs to keep the chromaticity accuracy depends on the wavelength itself, as described in Annex D.

The RGB peak intensity ratio does not always agree with an accurate power ratio because the spectral linewidth of each colour LD is different. The power of R, G, B spectra should be measured accurately colour by colour using the optical power measuring method in 5.2 because the RGB power ratio is important for chromaticity calculation and/or calibration.

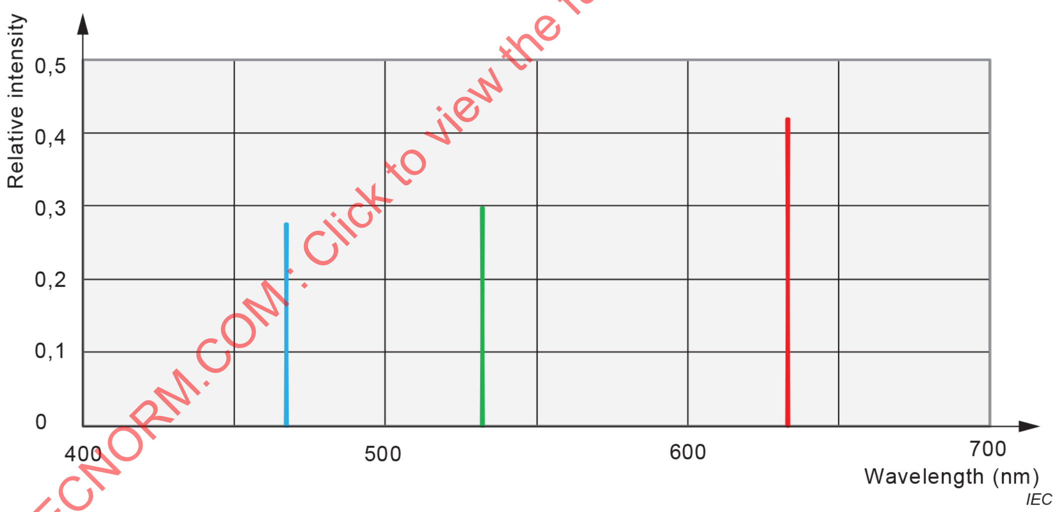


Figure C.4 – Example of RGB single-longitudinal mode spectra

C.3 Spectra of multi-colour, multi-longitudinal mode LD modules

High-power multi-colour laser modules including high-power multi-colour LDs which combine their outputs into an output fibre, or an output light guide, have a spectrum as in Figure C.1 for each colour wavelength. Therefore, the contents in Clause C.1 should be applied.

C.4 Chromaticity measurements using a colorimeter

The output optical power of the superposed spectrum in Figure C.1 is limited to the wavelength range of 443 nm to 446 nm. The fibre-coupled LD spectra are truncated without spectral tailing because the spontaneous emission below the threshold with much wider divergence angles hardly couples into the fibre.

It is difficult for such a narrow spectrum to obtain accurate values of chromaticity when measured using a colorimeter with XYZ filters. The available XYZ filters are not exactly the same as the ideal colour matching functions, as defined in 3.1.13. Most of the colorimeters are calibrated for much broader spectra such as LEDs [1], [4]. To obtain accurate chromaticity values, it is necessary to calibrate the colorimeter with a reference spectrometer using narrow spectra [4].

Annex D
(informative)

Chromaticity accuracy when measuring narrow spectral linewidth

D.1 General

Most of the spectrometric LMDs for the conventional displays are, in general, optimised for measuring spectra with a relatively wide wavelength range. However, the spectra of the laser modules, laser backlight units, and laser displays have very narrow linewidths. Therefore, it is important to use spectrometric LMDs capable of measuring such narrow line spectra with colorimetric accuracy.

Spectral measurement accuracy required for LMDs depends on the target colorimetric accuracy and the wavelength of the laser devices. The target colorimetric accuracies are assumed to be less than 0,001 or of chromaticity accuracy < 0,005 both for CIE 1931 and CIE 1976 chromaticity diagrams. The colour matching functions with an interval of 0,01 nm are preliminarily calculated by interpolation for this purpose.

D.2 Wavelength accuracy to keep chromaticity accuracy < 0,001 or < 0,005

The wavelength accuracy to keep the chromaticity accuracy < 0,001 or < 0,005 is calculated to evaluate the validity of the wavelength accuracy of ±0,3 nm for the spectrometric LMDs listed in 4.5. The wavelength accuracy $\pm\delta$ is defined as the wavelength difference from the reference wavelength λ_r. The wavelength differences, $\delta \equiv |\lambda - \lambda_r|$ with an interval of 0,5 nm are tabulated in the range of 450m $\leqq \lambda_r \leqq$ 650nm with an interval of 0,5 nm. The CIE 1931 coordinates, x, y, are calculated and also tabulated corresponding to δ.

In Figure D.1, the two lines of δ-values satisfying the chromaticity accuracies of $|\Delta x|$, $|\Delta y|$ = 0,001 are plotted with respect to the reference wavelength λ_r. The regions below the two criteria lines meet $|\Delta x|$, $|\Delta y|$ < 0,001. The peaks around 506 nm and 522 nm correspond to the non-sensitive locus positions where the locus curves are tangential for x and y, respectively. For the blue colour around 460 nm, a wavelength accuracy of ±0,65 nm is allowed. An accuracy of ±1,1 nm is allowed for the red colour around 640 nm. However, a very tight accuracy of ±0,2 nm is required for the green colour around 530 nm.

The two lines of $|\Delta x|$, $|\Delta y|$ = 0,005 are also plotted in Figure D.2. The wavelength accuracy becomes much more relaxed than the case of $|\Delta x|$, $|\Delta y|$ < 0,001. For the blue colour around 460 nm and the red colour around 640 nm, a wavelength accuracy of more than ±2 nm is allowed. An accuracy of ±1,1 nm (for the y-coordinate) is allowed even for the green colour around 530 nm. Only around 500 nm, ±0,2 nm is required (particularly for the y-coordinate).

As in the above, the wavelength accuracy of the LMD should be considered depending on the colour (wavelength) and the target criteria of the chromaticity accuracy.

Similar wavelength accuracy plots are carried out for the CIE 1976 chromaticity diagram. The two lines of $|\Delta u'|$, $|\Delta v'|$ = 0,001 are plotted in Figure D.3, and those of $|\Delta u'|$, $|\Delta v'|$ = 0,005 are plotted in Figure D.4, respectively. In Figure D.3, the wavelength accuracy of ±0,25 nm is required for the blue colour around 460 nm. An accuracy of ±0,35 nm for $|\Delta u'|$ < 0, 001 is required for the green colour around 530 nm, and ±0,55 nm for $|\Delta u'|$ < 0,001 is required for the red colour around 640 nm. In Figure D.4, a wavelength accuracy of ±1,2 nm is allowed for the blue colour around 460 nm. An accuracy of ±1,8 nm for $|\Delta u'|$ < 0,005 is allowed for the green colour around 530 nm, and more than ±2,0 nm is allowed for the red colour around 640 nm. However, in both cases, the accuracy with respect to the coordinate v' is much more relaxed in the wavelength range longer than 515 nm because of the wider wavelength locus region which is less sensitive to v.

It should be noted that the wavelength accuracy depends on what kind of chromaticity diagram is used, involving the curvature of their wavelength locus.

A wavelength accuracy of ±0,3 nm for spectrometric LMDs listed in 4.5 is reasonable mostly for the wide range of visible wavelengths if the chromaticity accuracy < 0,005 is assumed. A wavelength accuracy of ±0,1 nm is required if the chromaticity accuracy < 0,001 is assumed depending on the wavelength and the kind of chromaticity diagram.

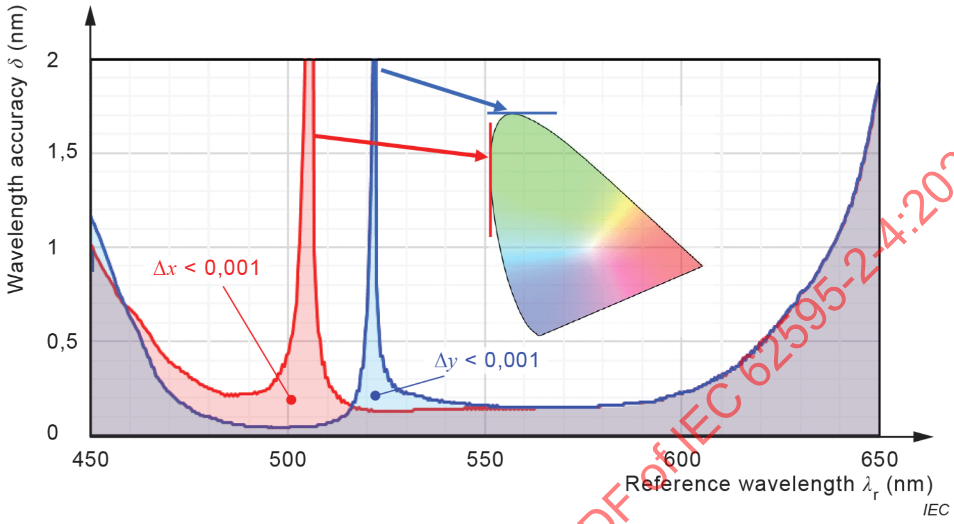


Figure D.1 – Calculated wavelength accuracy to keep |Δx|, |Δy| < 0,001

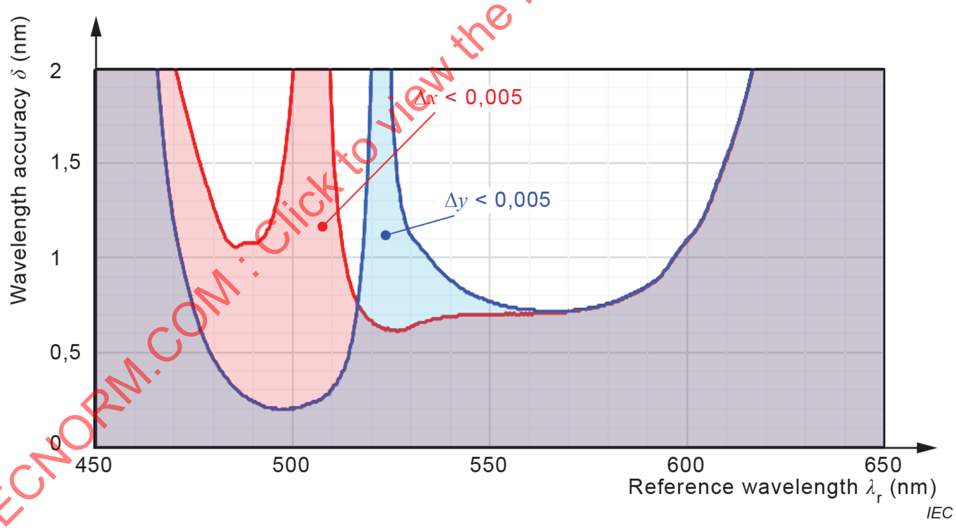


Figure D.2 – Calculated wavelength accuracy to keep |Δx|, |Δy| < 0,005

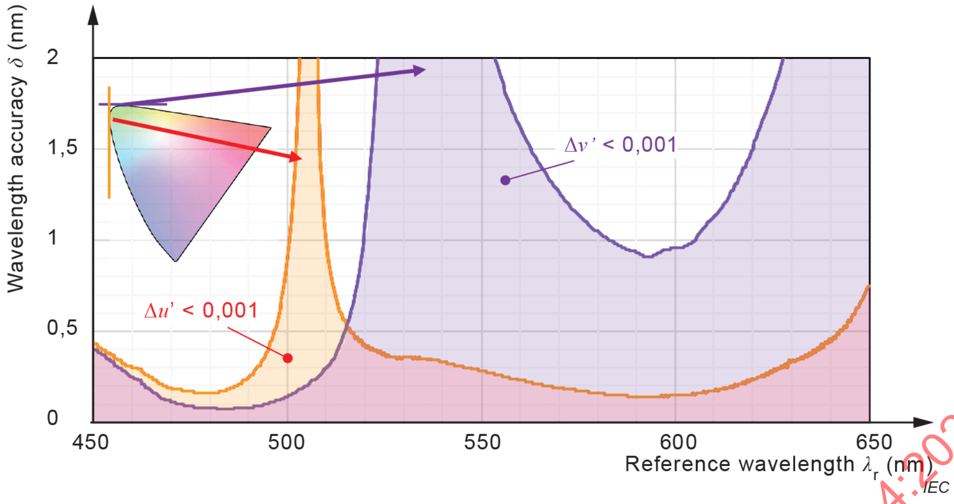


Figure D.3 – Calculated wavelength accuracy to keep |Δu'|, |Δv'| < 0,001

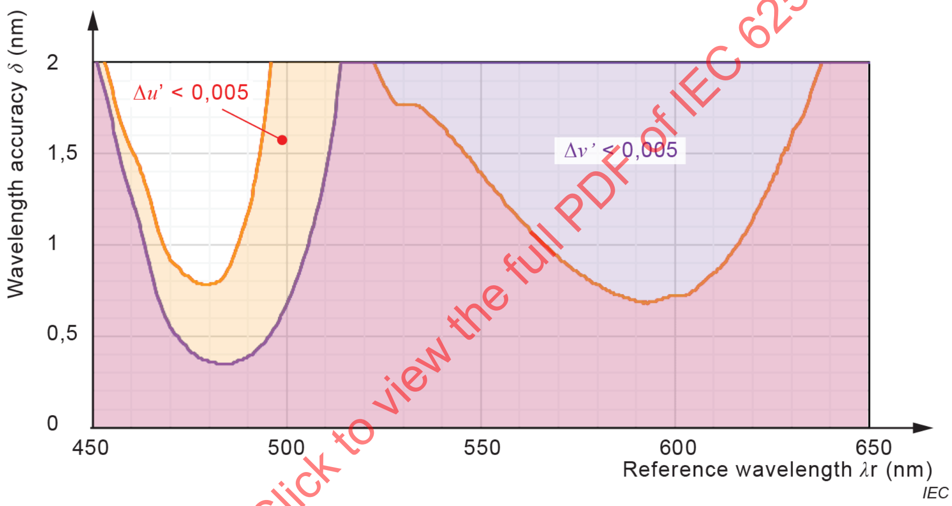


Figure D.4 – Calculated wavelength accuracy to keep |Δu'|, |Δv'| < 0,005

D.3 Spectral bandwidth to keep chromaticity accuracy < 0,001

The spectral bandwidth (BW) to keep the chromaticity accuracy < 0,001 is calculated for to evaluate the validity of the spectral bandwidth of 5 nm of the LMD listed in 4.5. (The spectrum analyzer for measuring a much finer spectral bandwidth of less than 1 nm is excluded). The spectral bandwidth of the isosceles triangular slit function of a spectrometer is assumed. The CIE 1931 and CIE 1976 chromaticity coordinates are calculated by increasing the bandwidth of the isosceles triangular slit function as in Figure D.5. The bandwidth required for the LMD is defined as the chromaticity difference from that of the ideal line spectrum at the reference wavelength λ_r. The target chromaticity accuracy of ±0,001 is assumed as the above chromaticity difference of 0,001. This procedure is repeated from the reference wavelengths of 450 nm to 650 nm with an interval of 2 nm. The results are shown in Figure D.6 for CIE 1931 chromaticity diagram, and Figure D.7 for CIE 1976 chromaticity diagram, respectively.

For CIE 1931 chromaticity diagram in Figure D.6, the bandwidth tolerance is larger than 5 nm at the blue and red wavelengths. The spectral bandwidth tolerance is tightest as 3 nm at the green wavelength range of 510 nm to 520 nm. The green wavelength at 532 nm for B.T.2020 satisfies the bandwidth tolerance larger than 5 nm. The bandwidth tolerance is larger than 5 nm in the whole wavelength range of 450 nm to 650 nm for the CIE 1976 chromaticity diagram in Figure D.7. The spectral bandwidth requirement of 5 nm for spectrometric LMDs listed in 4.5 is reasonable mostly for the wide range of visible wavelengths even if the chromaticity accuracy < 0,001 is assumed.

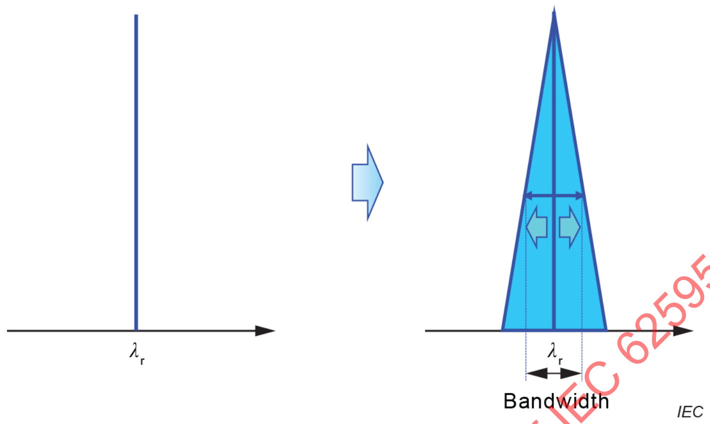


Figure D.5 – Assumption for calculating the spectral bandwidth accuracy

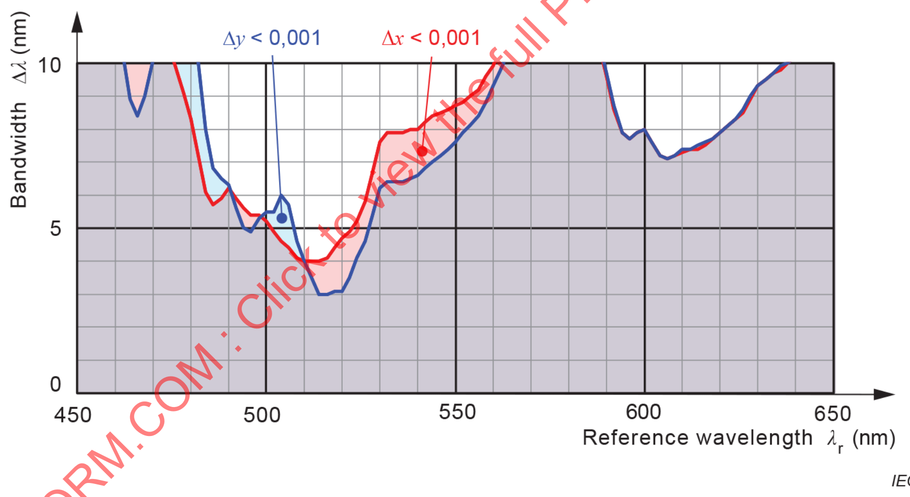


Figure D.6 – Calculated spectral bandwidth accuracy to keep |Δx|, |Δy| < 0,001

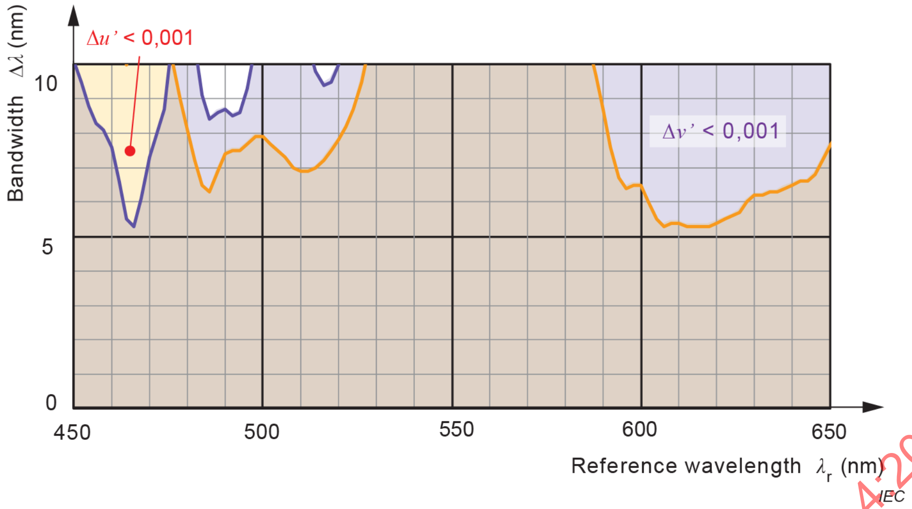


Figure D.7 – Calculated spectral bandwidth accuracy to keep |Δu'|, |Δv'| < 0,001

Annex E
(informative)

Numerical aperture (NA) of fibre

E.1 Fibre NA and maximum divergence angle

Numerical aperture (NA) of the fibre is the sine of the maximum angle, θ_{max}, of an incident/outgoing ray with respect to the fibre axis. Only incident light within θ_{max} can be guided along the fibre. The fibre cross-section of the step-index MMF is schematically shown in Figure E.1. (A representation with simple ray optics is used for conceptual understanding. Normally, wave optics are used.)

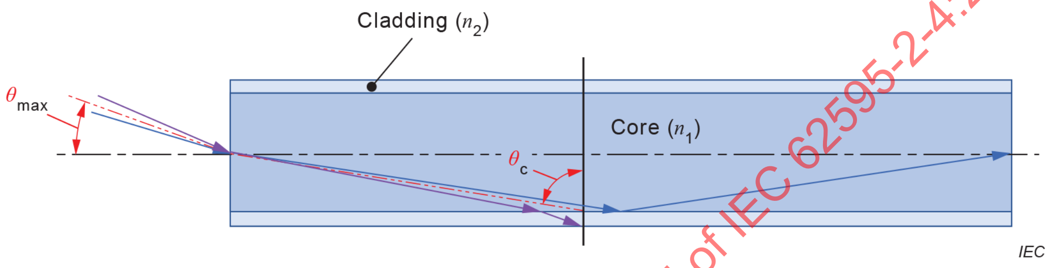


Figure E.1 – Fibre cross-section of MMF (step-index)

NA is determined by the refractive index difference between core (n_1) and cladding (n_2).

$$\mathrm{NA} \equiv \sin\theta_{max} = \sqrt{n_1^2 - n_2^2} \quad \text{(E.1)}$$

For silica fibre, θ_{max} is usually less than 12°.

E.2 Colour-dependence of fibre NA

For silica fibre, the core-clad refractive index difference becomes slightly larger for shorter-wavelength colours. Therefore, the NA values are: NA for B > NA for G > NA for R.

Annex F
(informative)

Conversion of the spherical and Cartesian coordinate systems

Cartesian coordinates (x, y, z) on the spherical surface in Figure 1 are expressed as:

$$x = L\cos\varphi\sin\theta,\quad y = L\sin\varphi\sin\theta,\quad z = L\cos\theta \tag{F.1}$$

whereas the Cartesian coordinates (x, y, z) on the x-y plane in Figure 2 are expressed as:

$$x = L\cos\varphi\sin\theta / \cos\theta,\quad y = L\sin\varphi\sin\theta / \cos\theta,\quad z = L \tag{F.2}$$

The conversion factor is just $\cos\theta$.

The above formulation is consistent with equatorial gnomonic projection. The origin is set at the centre of the sphere in Figure 1 whereas it is set at the equatorial tangential point in the equatorial gnomonic projection.

Annex G
(informative)

Centroid wavelength

Figure G.1 shows an example of a multi-longitudinal mode spectrum of high-power LDs. The peak wavelength λ_p is the maximum peak of the spectrum and the centroid wavelength λ_c is convenient for representing such a narrow and irregular spectral distribution with a single wavelength value.

The centroid wavelength implying the weighted mean of the wavelength is given by the following formula as in IEC 61280-1-3 [9].

$$\lambda_c = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda} \qquad \text{(G.1)}$$

where

$S(\lambda)$ is the spectral power density.

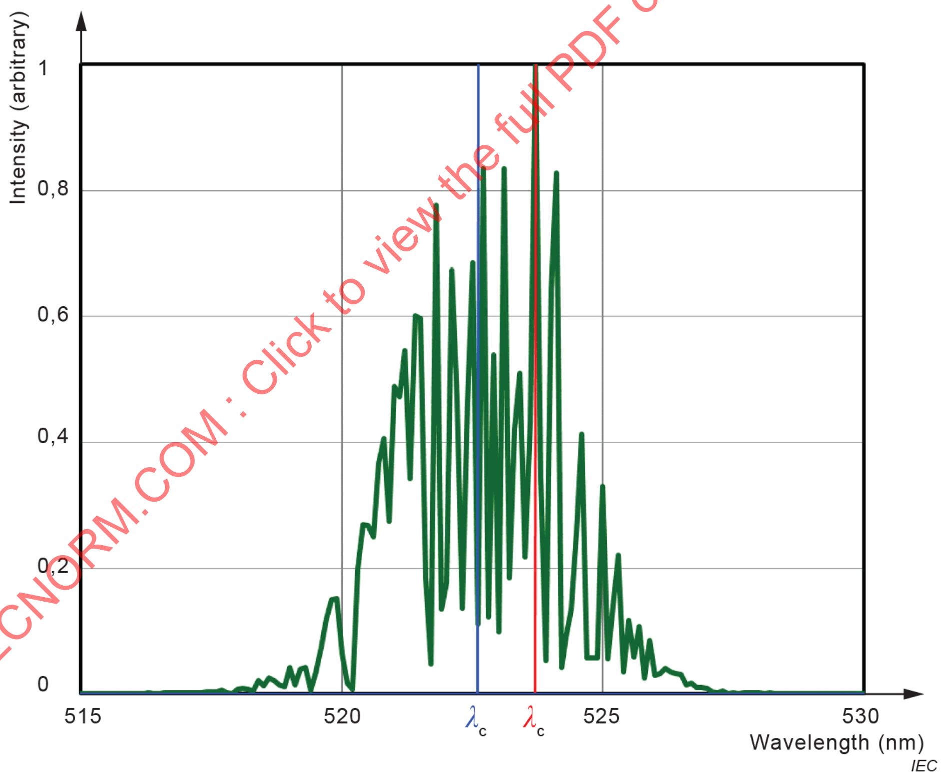


Figure G.1 – Example of laser spectrum (peak and centroid wavelengths)

The true value of chromaticity can be calculated precisely by integrating with 0,1 nm intervals and then multiplied by the interpolated colour matching functions (see Figure 8). Calculating the chromaticity values of various examples of LDs operating in multi-longitudinal modes using the peak wavelength of each spectrum, the CIE 1931 chromaticity errors from the true value are plotted in Figure G.2. The errors spread widely in the range of Δx, Δy = ±0,015. The errors in the case of using the centroid wavelength spread within a much smaller range of Δx, Δy = ±0,002. Therefore, the centroid wavelength is verified to represent the wavelength of the multi-longitudinal LD spectra [1].