PD ISO/TS 17915:2013

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Optics and photonics — Measurement method of semiconductor lasers for sensing

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ISBN 978 0 580 81129 6

ICS 31.260

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 July 2013.

Amendments issued since publication

Date	Text affected

PD ISO/TS 17915:2013

TECHNICAL SPECIFICATION

ISO/TS 17915

First edition
2013-07-15

Optics and photonics — Measurement method of semiconductor lasers for sensing

Optique et photonique — Méthode de mesure des lasers semi-conducteurs pour la sensibilité

Reference number
ISO/TS 17915:2013(E)

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Foreword

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Optics and photonics — Measurement method of semiconductor lasers for sensing

1 Scope

This Technical Specification describes methods of measuring temperature, injected current dependence and lasing spectral line width in relation to semiconductor lasers for sensing applications. This Technical Specification is applicable to all kinds of semiconductor lasers, such as edge-emitting type and vertical cavity surface emitting type lasers, bulk-type and (strained) quantum well lasers, and quantum cascade lasers, used for optical sensing in e.g. industrial, medical and agricultural fields. This Technical Specification is an application of ISO 13695, in which the physical bases are explained.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13695, *Optics and photonics — Lasers and laser-related equipment — Test methods for the spectral characteristics of lasers*

3 Optical sensing using semiconductor lasers

3.1 General

The methods described in this Technical Specification are to be followed in accordance with ISO 13695.

Optical sensing using tunable semiconductor laser spectroscopy has been widely used in various engineering fields. For example, optical sensing is being used for bio-sensing and environmental monitoring. Semiconductor lasers are key devices for those applications and are indispensable for building sensing equipment. Semiconductor lasers and sensing techniques are described in 3.2 to 3.6.

3.2 Semiconductor laser

3.2.1 General

A semiconductor laser is an optical semiconductor device that emits coherent optical radiation in a certain direction through stimulated emission resulting from electron transition when excited by an electric current that exceeds the threshold current of the semiconductor laser. Here, the mechanism of coherent optical radiation is divided into two categories, (1) electron-hole recombination due to interband electron transition between conduction and valence band (bulk type) or between two quantized states (quantum well type, see 3.2.5) and (2) intraband electron transition between two quantized states (quantum cascade type, see 3.2.5).

Edge-emitting types with single lasing modes, such as distributed feedback (DFB) lasers, have been conventionally used in sensing equipment because of their high power and single lasing modes. Surface-emitting types are also widely used in sensing systems because they are easy to handle. Some names are given to those lasers from various aspects. Those lasers are briefly categorized in 3.2.2 to 3.2.5.

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3.2.2 Basic structure

a) Edge emitting type semiconductor laser: a semiconductor laser that emits coherent optical radiation in the direction parallel to junction plane.

b) Surface emitting type semiconductor laser: a semiconductor laser that emits coherent optical radiation in the direction normal to junction plane. Vertical cavity surface emitting type semiconductor laser (VCSEL) is the typical one.

3.2.3 Transverse mode stabilizing structure

a) Gain guiding: a semiconductor laser in which emitted light propagates along the gain region generated by carrier injection and is amplified by stimulate emission along the gain region. Planar type lasers are typical ones in gain guiding.

b) Refractive index guiding: a semiconductor laser in which a stripe-shape active layer (light emitting layer) or junction is formed to introduce effective refractive index difference between the stripe and the outer region. Buried heterostructure (BH) is typical in refractive index guiding.

3.2.4 Mode (wavelength) selection structure

a) Distributed feedback (DFB) semiconductor laser: a semiconductor in which stimulated emission is selected by a grating (equivalent to distributed mirror). This laser operates in single longitudinal mode.

b) Distributed Bragg reflector (DBR) semiconductor laser: a semiconductor laser in which stimulated emission is selected by a Bragg grating (equivalent to distributed mirror) jointed at a side or the both sides of light emitting layer. This laser operates in single longitudinal mode.

c) Fabry-Perot (FP) semiconductor laser: a semiconductor laser in which stimulated emission is generated between two mirror facets. This laser normally operates in multiple longitudinal modes.

d) External cavity controlled semiconductor laser: a semiconductor laser in which the optical cavity is composed of one mirror and an external mirror (ex. grating) set on the opposite side of the mirror. Stimulated emission is generated at the semiconductor part in the optical cavity. This laser normally operates in single longitudinal mode.

3.2.5 Active layer structure

a) Double heterostructure semiconductor laser: a semiconductor laser in which the active layer (light emitting layer) is sandwiched with two heterojunctions (pn- and iso-junction).

b) Quantum well semiconductor laser: a semiconductor laser that emits coherent optical radiation through stimulated emission resulting from the recombination of electrons and holes between two quantized states. Here, the light emitting layer is composed of a single quantum well layer or multiple quantum well layers. Quantum wire and quantum dot (box) semiconductor laser are included in this category but the light emitting area of quantum wire and dot is two-dimensional and three-dimensional structure, respectively.

c) Strained quantum well semiconductor laser: a semiconductor laser that emits coherent optical radiation through stimulated emission resulting from the recombination of free electrons and holes between two quantized states. Here, the light emitting layer is composed of strained single quantum well layer or multiple quantum well layers.

d) Quantum cascade semiconductor laser: a semiconductor laser that emits coherent optical radiation through stimulated emission resulting from electron transition between two quantized states without any electron-hole recombination. The light emitting layer is composed of quantum cascade layers.

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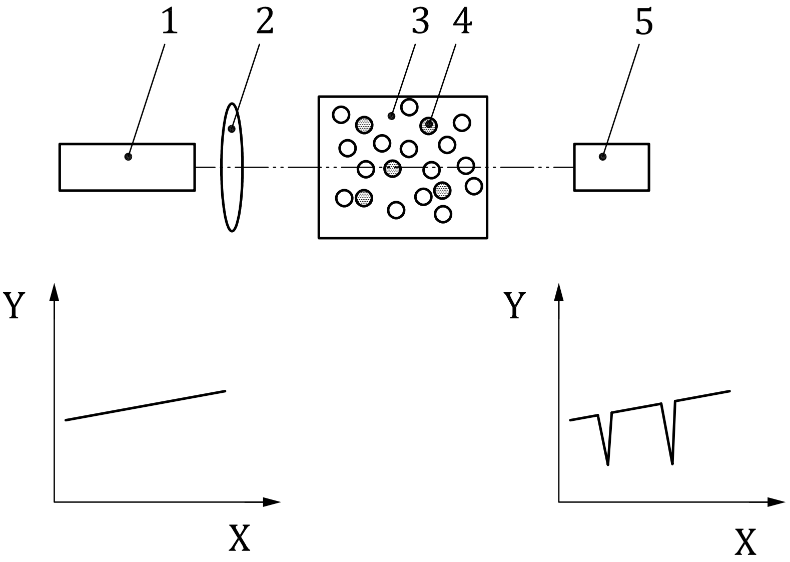
3.3 Common sensing technique and equipment using semiconductor laser

3.3.1 General

Semiconductor lasers including quantum cascade semiconductor lasers have various advantages: compact size, light weight, low power consumption, easy controlling of wavelength by pulsed or continuous wave operation, etc. Sensing techniques and equipment using such semiconductor lasers have been researched and developed in academic and industrial fields. The main sensing techniques are described in 3.3.2 to 3.3.4.

3.3.2 Tunable laser absorption spectroscopy (TLAS)

Absorption spectrum is monitored by scanning repeatedly the wavelength of light emitted from semiconductor laser as shown in Figure 1. The composition of material and mixture to be examined are qualitatively and quantitatively analysed based on the monitored spectrum (shape, peak wavelength and intensity). The lasing wavelength of semiconductor laser is scanned by controlling the ambient temperature or injected current in this technique.



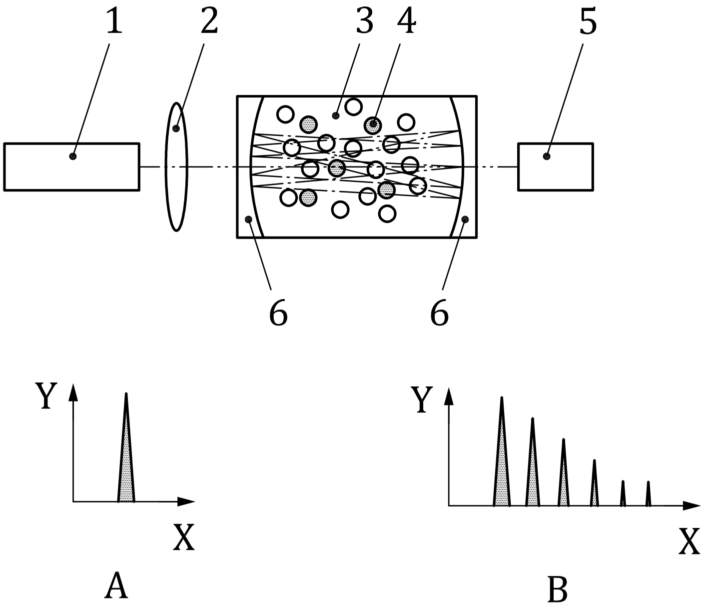
Key

X	wavelength
Y	optical intensity
1	tunable laser diode
2	lens
3	cell
4	element to be detected
5	optical detector

Figure 1 — Basic concept of tunable laser absorption spectroscopy (two absorption peaks are observed)

3.3.3 Cavity ring down spectroscopy (CRDS)

This technique is usually used for detecting trace element and originated from tunable semiconductor laser spectroscopy. Material to be analysed is introduced into the cavity built up with two mirrors as shown in Figure 2. Light pulse (with a certain wavelength) introduced to the cavity is repeatedly reflected between the mirror and passes through the material. A part of reflecting light escapes through the mirror, and a pulse train with a time interval determined with the cavity length is monitored. The trace element is qualitatively and quantitatively analysed with the decay time of the pulse train and the wavelength of the light.



Key

X	wavelength
Y	optical intensity
A	optical pulse
B	optical pulse train
1	tunable laser diode
2	lens
3	cell
4	element to be detected
5	optical detector
6	mirror

Figure 2 — Basic concept of cavity ring down spectroscopy

3.3.4 Photoacoustic spectroscopy (PAS)

When material to be analysed is illuminated with laser light, the light is absorbed at the material. The light power absorbed induces lattice vibration, and the vibration results in the emission of a supersonic wave as shown in Figure 3. The supersonic wave is detectable with a microphone, and the element contained in the material is quantitatively analysed by monitoring the frequency and intensity.

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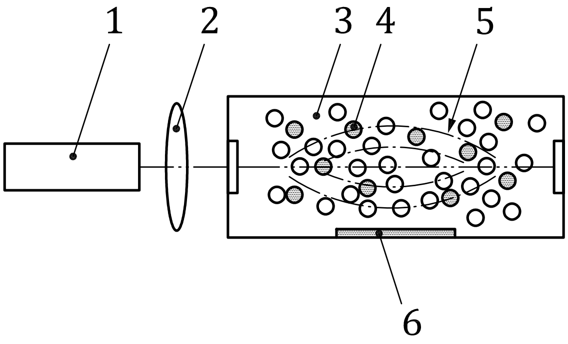

Key

1	tunable laser diode
2	lens
3	cell
4	element to be detected
5	supersonic wave
6	microphone

Figure 3 — Basic concept of photoacoustic spectroscopy

3.4 Temperature and current dependence of wavelength

The lasing wavelength of semiconductor lasers is changed by various methods. In external cavity control semiconductor lasers, the lasing wavelength can be selected by controlling the angle of grating if a grating is set as an external mirror. The lasing wavelength is widely scanned by controlling the grating angle.

In normal semiconductor lasers, their lasing wavelength is ordinarily controlled by varying the ambient temperature and injected current in tunable semiconductor laser spectroscopy. These variables corresponding to band-gap change due to ambient temperature and the band-filling effect induced by carrier injected into the active layer of semiconductor lasers. In addition, refractive index change of the active layer, which is induced by temperature and injected carrier density, takes the important role of changing the lasing wavelength. The changing rate of these physical properties determines the conventionally used temperature and current dependence of lasing wavelength. The physical mechanisms of temperature and current control of the lasing wavelength are explained in this subclause.

Several factors govern the change in lasing wavelength of semiconductor lasers as shown in Figure 4. A decrease (an increase) in the refractive index of the active region originates from an increase (a decrease) in threshold carrier density and shortens (lengthens) the lasing wavelength of each Fabry-Pelot (FP)-mode in FP-lasers. This phenomenon is induced by the plasma effect related to carrier density in semiconductors. In DFB lasers, the lasing mode is shortened (lengthened) with a decrease (an increase) in effective grating pitch introduced by the decrease (increase) in the refractive index. The increase (decrease) in the refractive index is introduced by rising (lowering) temperature. In addition, the rising (lowering) temperature shifts the envelope of FP-modes (gain envelope) to the longer (shorter) range. This is due to a reduction (an increase) of the band-gap energy.

Before lasing, the peak wavelength of FP-modes shortens due to the band-filling effect, and that of DFB-mode also shortens as the injected carrier density increases through the refractive index reduction. After lasing, the main factor is the thermal effect because threshold carrier density is fixed at the threshold value after lasing. Joule heating is generated and light output power changes in response to injected current under the constant carrier density.

These are basic mechanisms for changing lasing wavelength in semiconductor lasers. Among them, the change in lasing wavelength by controlling ambient temperature under a constant current is mainly generated by band-gap change in FP-lasers and refractive index change in DFB lasers. Controlling the

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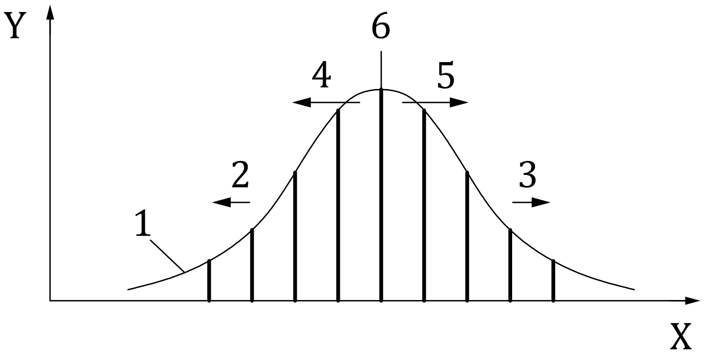
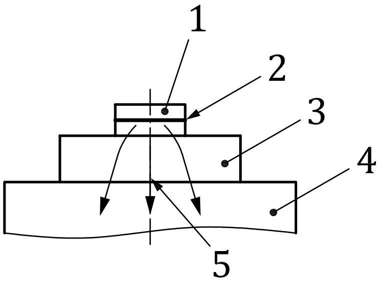
lasing wavelength with the magnitude of injected current also occurs by the band-gap change due to Joule heating at the active layer (or pn-junction) because the injected carrier density is nearly constant after lasing. The temperature and current dependence of lasing wavelength is analysed in DFB lasers from the viewpoint of thermal conductivity in the following parts.



Key

X	wavelength
Y	intensity
1	gain envelope
2	energy level change due to band filling
3	band gap change due to temperature increase
4	refractive index change due to carrier (plasma) effect
5	refractive index change due to heating
6	each lasing mode

Figure 4 — Main factor of lasing-wavelength change



Key

1	semiconductor laser
2	active layer
3	heat sink
4	package stem
5	heat flow

Figure 5 (a) — Sample configuration

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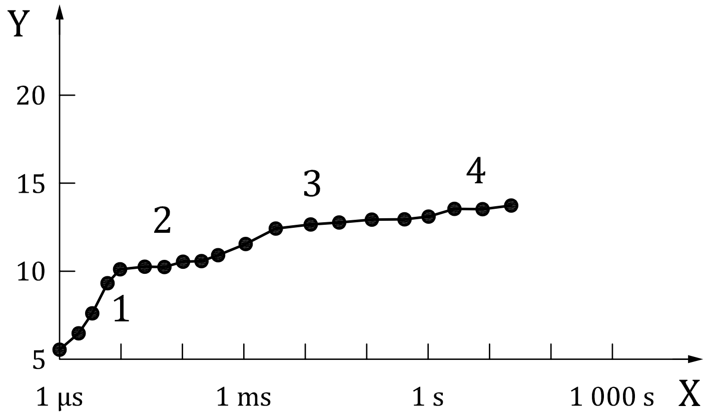


Key

X	current pulse width
Y	active layer temperature, in ° C
1	LD chip
2	heat sink
3	package stem
4	package

NOTE 1 Pulse height: 100 mA.

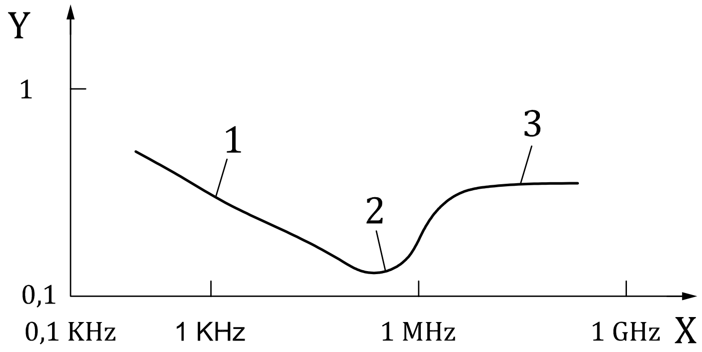
NOTE 2 The sample is a 1 300 nm-band FP semiconductor laser. The labels indicated by 1, 2, 3 and 4 indicate the responsible parts of heat conduction for the heat generated at the active layer.

Figure 5 (b) — Estimated temperature rise in active layer as a function of pulse width

3.5 Effect of current injection on lasing wavelength

The rate of temperature change in the active layer depends on a transient phenomenon determined by heat conduction. The Joule heating generated at the active layer gradually diffuses from the active layer to the surrounding region, and thus the change rate in lasing wavelength strongly depends on the mounting configuration and packaging structure. Figure 5 shows an example of active layer temperature increase as a function of the current pulse width for a 1 300 nm-band FP semiconductor laser. The active layer temperature is estimated from the junction voltage because the junction voltage linearly decreases with temperature. The junction voltage at 1 mA is monitored just after turning off the 100 mA-pulsed current. The pulsed current and the monitoring current of the junction voltage is set at 100 and 1 mA, respectively. Here, the value of the monitoring current is determined so that the Joule heating due to the current is negligible. The temperature dependence of the junction voltage is about 1 mV/°C in the 1 300 nm-band semiconductor lasers. The Joule heating due to current injection diffused within the laser chip and then towards the outside of the active layer, heat sink, package stem, package, and equipment, as the pulse width was widened. This heat conduction transient phenomenon governs the temperature of the active layer and is influenced by the laser-chip mounting configuration (configuration of the heat-conducting path).

These behaviours are closely related to the rate and range of wavelength change under current modulation. In Figure 6, the horizontal axis indicates modulation frequency and the vertical axis corresponds to the frequency deviation, which corresponds to the wavelength variation. As modulation frequency increases from 100 Hz, the frequency deviation decreases because the response to heat conduction is gradually small. This behaviour is also recognized in Figure 5, in which the current pulse width corresponds to the modulation frequency of the semiconductor laser from the viewpoint of heat conduction. A dip appears after 100 kHz in Figure 6. After the dip, the plasma effect is dominant and the lasing wavelength tends to be shortened (blue shift). This frequency deviation is called FM-response or chirping in the optical fibre communication field.[4] The frequency range used for tunable semiconductor laser spectroscopy is below the dip frequency and the frequency at which the influence of heat is dominant (red shift).



Key

X modulation frequency

Y frequency deviation, in GHz/mA

1 Joule heating (lengthening)

2 dip

3 plasma effect (shortening)

NOTE The modulation current was a 0,5 mA peak-to-peak sinusoidal wave and the DC bias was set at 60 mA.

Figure 6 — Lasing frequency (wavelength) deviation for a 1 300 nm-band DFB semiconductor laser as a function of frequency

When the injected current is quickly changed, the increase in the temperature is not sufficient and the increase is not saturated. The temperature difference between the active layer and the package temperature becomes large or small in response to the magnitude of injected current when the package temperature is set at a constant temperature. The current dependence is, therefore, not constant and varies with the rate of current increase. Their dependences are, however, kept at fixed values if the time interval of monitoring are fixed at the constant values and strongly influenced by the materials used and the chip-mount configuration.

3.6 Effect of ambient temperature on lasing wavelength

Heat is inversely transmitted from the ambient to the active layer of the semiconductor laser through the package when the ambient temperature or package temperature is changed. The heat conductance of the package, package stem, and heat sink is the same for the case of the diffusion of Joule heating at the active layer, and a certain time interval is needed until the temperature of the active layer is equal to the ambient temperature as shown in Figure 5.

The temperature dependence of wavelength and absorption peak wavelength vary depending on the time interval of monitoring after changing the ambient temperature. If the change rate of package temperature is set at values of more than 1 s, the temperature dependence is the same because the change in package temperature can diffuse to the active layer (see Figure 5). Figure 7 shows a set of the change in absorption peak in the spectrum monitored at different scanning rate of the package temperature for one of CO_2-gas absorption peaks. (The CO_2-gas pressure is set at an atmospheric pressure, and the spectral width is broadened because of Doppler shift.) These scanning rates correspond to the package-temperature change rate of less than 1 s. As the rate is high, the peak position shifts to the direction of the temperature scan and the magnitude of the absorption peak tends to be small. These phenomena are caused by the time constant of heat diffusion between the package and active layer, and should be paid attention under measurement.

These dependences are governed by the change of each factor discussed in 3.4. When ambient temperature is changed, for example, threshold current density and band-gap energy vary simultaneously and lasing wavelength changes complicatedly. The dependences result from the overall change in the factors. Consequently, the dependences will vary with the material used, the mounting configuration, the monitoring time interval, etc. It can be said that the change rate of the injected current and ambient

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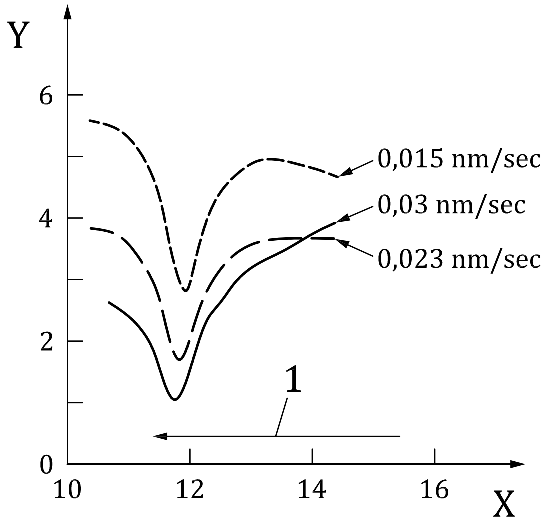
(package) temperature has to be constant during tumble semiconductor laser spectroscopy to eliminate wavelength error, although the dependence differs with the change rate.



Key

X package case temperature, in °C

Y light power, in a.u

1 temperature scan

NOTE A 2 000 nm-band semiconductor laser was used in this experiment.

Figure 7 — Shape change in absorption spectrum monitored at different scanning rates of the package temperature for one of CO_2-gas absorption peaks

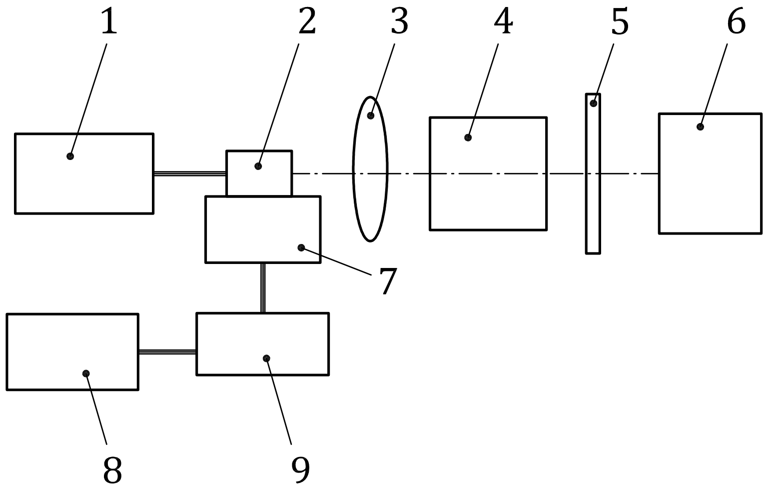
4 Measurement method for temperature dependence of wavelength

4.1 General

As described in Clause 3, the lasing wavelength of semiconductor lasers is scanned or fixed by temperature control when they are used for sensing application. The temperature dependence corresponds to the magnitude of lasing wavelength shift and is a measure of the lasing wavelength change with temperature. This characteristic is therefore important for semiconductor lasers for sensing. A semiconductor laser used for sensing is normally a single longitudinal mode laser (see 3.2 and Figure 4), and the shift value of wavelength is, for instance, monitored with the amount of the change in peak-emission wavelength under temperature or current variation. The measurement method of the temperature dependence is described in 4.2 to 4.4.

4.2 Description of measurement setup and requirements

The measurement setup is depicted in Figure 8.



Key

1	LD driver
2	device (semiconductor laser) being measured
3	lens
4	spectrometer
5	attenuator
6	optical detector
7	thermoelectric cooler
8	controller of power supply
9	power supply of thermoelectric cooler

Figure 8 — Basic measurement setup of temperature dependence of lasing wavelength

The LD driver is supplying current to the semiconductor laser, and if the laser is not capable of operating in continuous wave throughout measurement, is supplying pulsed current to the lasers, such as quantum cascade ones.

The spectrometer (spectrophotometer or spectroscope) is resolving the spectral components of input light in corresponding to the wavelength by wavelength-tunable optical filter and outputting light of the individual spectral components within a certain wavelength range. A diffraction grating or Fabry-Perot interferometer is used as the tunable optical filter.

The optical spectrum analyser is applicable to monitor, instead of the spectrometer and optical detector, if the spectrum analyser is corrected. Besides the diffraction-grating-based and Fabry-Perot interferometer-based optical spectrum analysers, Michelson interferometer-based spectrum analyser, which outputs the autocorrelation function of the input light signal is also applicable.

4.3 Precautions to be observed

The linearity of optical detector response should be maintained within the input and output range during measurement.

The spectral response of the optical detector shall be calibrated.

The wavelength resolution and the bandwidth of the spectrometer shall be such that the measurement is carried out with adequate accuracy.

For measurement, light reflected into the laser shall be minimized to ensure that the spectral response is not significantly affected.

The temperature monitoring point should be set at the device being measured as close as possible.

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The rate of temperature change has to be set at a constant value throughout measurement, unless the monitoring data are deviated and scattered. The constant rate should be determined under taking the time constant of heat conductance between the active layer and package of device being measured.

4.4 Measurement procedures

The specified current, cw or pulse, is applied to the device being measured.

The wavelength of the spectrometer is adjusted within the required range until the maximum reading on the optical detector has been achieved. The wavelength corresponding to this peak value is recorded. This is the peak-emission wavelength.

The temperature of the device being measured is changed with a constant rate. The peak-emission wavelength is continuously monitored with a constant temperature interval.

The change in the peak-emission wavelength is linearly proportional to the temperature of the device being measured.

The slope of the change in the peak-emission wavelength to the temperature is calculated and the temperature dependence of the peak-emission wavelength is obtained. If the relationship is not linear, the calculation has to be performed within the linear range.

The wavelength temperature tuning range is determined and limited by the kink point or the point at which the linear relationship is deviated at the low and high temperature range.

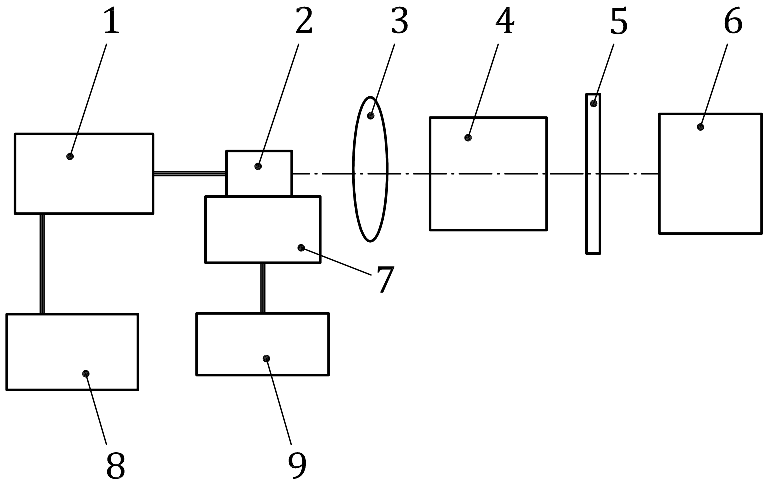
5 Measurement method for current dependence of wavelength

5.1 General

The lasing wavelength of semiconductor lasers is scanned with injected current when they are used for sensing application. The current dependence corresponds to the magnitude of lasing wavelength shift under current control and is a measure of the lasing wavelength change with current. This characteristic is therefore important for semiconductor lasers for sensing. The measurement method of the current dependence is described in 5.2 to 5.4.

5.2 Description of measurement setup and requirements

The measurement setup is depicted in Figure 9.



Key

1	LD driver
2	device (semiconductor laser) being measured
3	lens
4	spectrometer
5	attenuator
6	optical detector
7	thermoelectric cooler
8	controller of LD driver
9	power supply of thermoelectric cooler

Figure 9 — Diagram of measurement setup for current dependence of lasing wavelength

The LD driver is supplying current to the semiconductor laser, and if the laser is not capable of operating in continuous wave throughout measurement, is supplying pulsed current to the lasers, such as quantum cascade ones.

The spectrometer (spectrophotometer or spectroscope) is resolving the spectral components of input light in corresponding to the wavelength by wavelength-tunable optical filter and outputting light of the individual spectral components within a certain wavelength range. The diffraction grating or Fabry-Perot interferometer is used as the tunable optical filter.

The optical spectrum analyser is applicable to monitor, instead of the spectrometer and optical detector, if the spectrum analyser is corrected. Besides the diffraction-grating-based and Fabry-Perot interferometer-based optical spectrum analysers, Michelson interferometer-based spectrum analyser, which outputs the autocorrelation function of the input light signal is also applicable.

5.3 Precautions to be observed

The linearity of optical detector response should be maintained within the input and output range during measurement.

The spectral response of the optical detector shall be calibrated.

The wavelength resolution and the bandwidth of the spectrometer shall be such that the measurement is carried out with adequate accuracy.

For measurement, light reflected into the semiconductor laser shall be minimized to ensure that the spectral response is not significantly affected.

The temperature monitoring point should be set at the device being measured as close as possible.

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The rate of current change has to be set at a constant value throughout measurement, unless the monitoring data are deviated and scattered. The constant rate should be determined under taking the time constant of heat conductance between the active layer and package of device being measured.

5.4 Measurement procedures

5.4.1 Static current dependence

The specified injected current, cw or pulse, is applied to the device being measured.

The specified temperature is set to the device being measured.

The wavelength of the spectrometer is adjusted within the required range until the maximum reading on the optical detector has been achieved. The wavelength corresponding to this peak value is recorded. This is the peak-emission wavelength.

The injected current of the device being measured is changed with a constant rate. The peak-emission wavelength is monitored continuously or with a constant current interval.

The change in the peak-emission wavelength is linearly proportional to the magnitude of the injected current of the device being measured.

The slope of the change in the peak-emission wavelength to the magnitude of the injected current is calculated and the current dependence of the peak-emission wavelength is obtained. If the relationship is not linear, the calculation has to be performed within the linear region.

The wavelength current tuning range is determined and limited by the kink point or the point at which the linear relationship is deviated at the small and large magnitude of injected current.

If the laser is not capable of operating in continuous wave near room temperature, the specified pulsed current is set to the device being measured. The current pulse height is changed with a constant pulse width and duty ratio. The other procedures are the same as described above.

5.4.2 Dynamic current coefficient

The specified injected current, cw, is applied to the device being measured.

The specified temperature is set to the device being measured.

An etalon plate or a Fabry-Perot etalon, replaced with the spectrometer in Figure 9, is adjusted within the required finesse [free spectral range (FSR)/FWHM of resonance peak]. The optical detector can monitor cavity modes with the finess.

A small signal current, sinusoidal wave, is biased to the laser under tested in addition to the specified current.

The width of the peak deviation is divided with the peak height of injected current, and the dynamic current dependence is calculated in unit of Hz/mA.

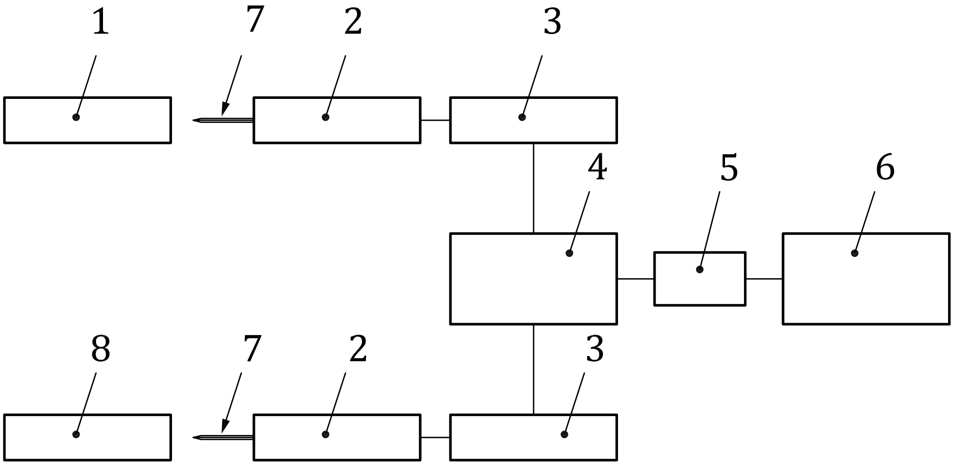
6 Measurement method of spectral line width

6.1 General

Lasing spectral line width is a device characteristic of semiconductor lasers with single mode, and therefore the measurement method is described for only semiconductor lasers operating under continuous wave. The lasing spectral line width is uncritical in most cases of sensing but is important when narrow absorbing lines at low pressure are monitored. If the spectral line width is wider than that of absorption line shapes, the line shape measured is broadened and vague. This characteristic is therefore important for semiconductor lasers for some sensing application. The measurement method of lasing spectral line width is described in 6.2 to 6.4.

6.2 Description of measurement setup and requirements

The measurement setup is depicted in Figure 10 a), Figure 10 b) and Figure 10 c).



Key

1	device being measured
2	optical isolator
3	polarization controller
4	fibre coupler
5	optical detector
6	rf spectrum analyser
7	optical fibre
8	local oscillator

Figure 10 (a) — Lasing spectrum line width measurement system: Optical heterodyne fibre system

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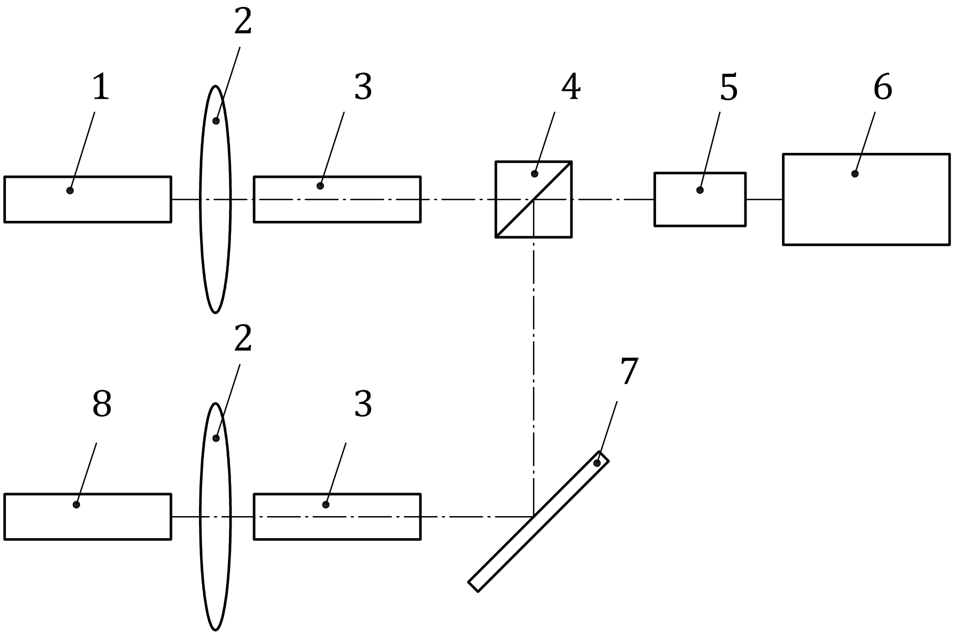
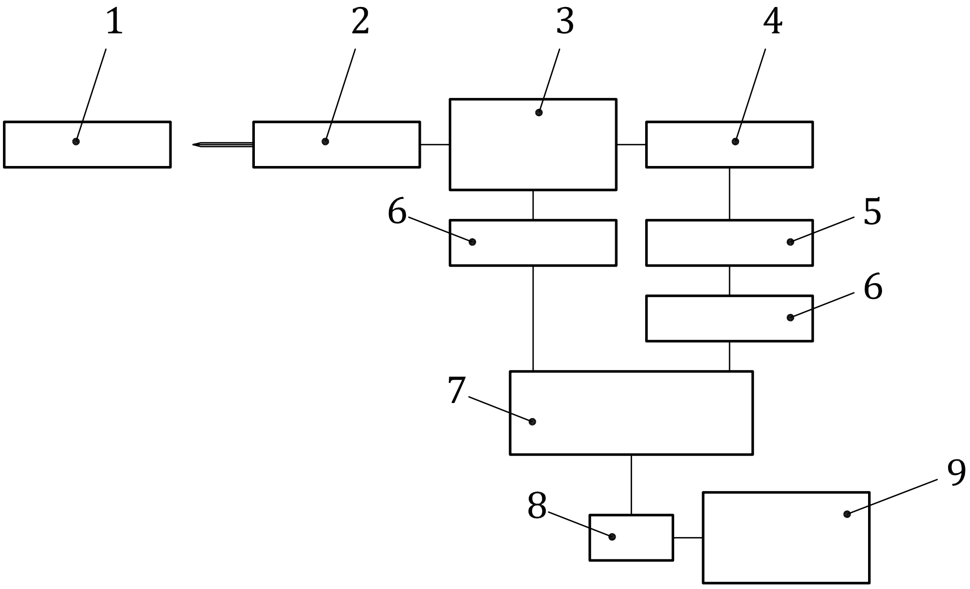


Key

1	device being measured
2	lens
3	optical isolator
4	optical beam combiner
5	optical detector
6	rf spectrum analyser
7	mirror
8	local oscillator

Figure 10 (b) — Lasing spectrum line width measurement system: Optical heterodyne system



Key

1	device being measured
2	optical isolator
3	fibre coupler
4	optical fibre for phase delay
5	optical frequency modulator
6	polarization controller
7	fibre coupler
8	optical detector
9	rf spectrum analyser

Figure 10 (c) — Lasing spectrum line width measurement system: Self-delayed optical heterodyne fibre system

In Figure 10, three heterodyne systems are depicted: (a) two-laser fibre system, (b) two laser system without fibre, and (c) self-delayed system. The systems shown in (a) and (c) are composed of optical fibre, and optical output power form semiconductor laser is coupled to the fibre with lens, etc. The equipment is connected to each other with the optical fibre. The fibre used here is single mode fibres.

The system depicted in (b) is a beam optic system without fibre. The laser beam emitted from the semiconductor laser is converted to parallel beam with lens and then pass through the optical components and equipment. In lasers emitting light in the wavelength range of more than 2 μm, the beam optic system is usually used.

The polarization controller is controlling the polarization direction of light transmitted through the fibre and adjusting the two light from the device being measured and local oscillator.

The optical fibre of phase delay is delaying the phase of transmitted light. The length of the fibre influences monitoring resolution.

The optical frequency modulator is modulating the frequency of light separated with the fibre coupler and differing the frequency from the light transmitted through the other fibre path for heterodyne detection. An acousto-optical modulator is usually used as the modulator.

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6.3 Precautions to be observed

For measurement, light reflected into the semiconductor laser has to be eliminated or suppressed to less than −50 dB at least by using optical isolator because spectral line width is strongly affected from the back-reflected light. In addition, anti-reflecting film had better being coated on all optical parts indicated in Figure 7 to reduce the back-reflection.

If the setup is built with single mode optical fibre, the back-reflection at the connection point between fibres has to be suppressed to of less than −50 dB by using suitable fibres.

The electrical source driving the semiconductor lasers has to be low noise to eliminate its influence on the spectral line width. For instance, battery cell is favourable.

The optical isolation of the isolator has to be set at the value of less than −50 dB.

The spectral response of the optical detector should be calibrated.

The rf spectral analyser should be corrected.

The beat frequency of the both semiconductor lasers or the frequency of optical modulator should be relatively high frequency to eliminate the influence of 1/f noise.

6.4 Measurement procedures

6.4.1 System employing two semiconductor lasers [shown in Figures 10 (a) and (b)]

The specified injected current is applied to the device being measured.

The specified temperature is set to the device being measured.

The specified wavelength is set to the device being measured, and the wavelength of the local oscillator is set at a required value which determines the beat frequency.

The frequency range of the rf spectrum analyser is adjusted within the required range for monitoring the beat frequency.

The polarization is controlled by the polarization controller so that the peak value of beat signal on rf spectrum analyser is the maximum in the case of fibre system [Figure 10 (a)].

If the beam system is used [Figure 10 (b)], the polarization of the both semiconductor lasers have to be adjusted.

The spectral line width is read on the rf spectrum analyser at 3 dB-down point or other values such as 20 dB-down point and calculated. Here, the spectral line width monitored on the rf spectrum analyser is the sum of the line width of the both semiconductor lasers under consumption of Lorentzian line shapes.

Here, when the lasing wavelength of the both semiconductor lasers is coincided each other, this technique is called homodyne detection technique. The monitoring procedure is, however, the manner similar to those of heterodyne technique, although the beat spectrum is observed at 0 Hz and the spectral line width is directly obtained.

6.4.2 Self-delayed heterodyne [shown in Figure 10 (c)]

The specified injected current is applied to the device being measured.

The specified temperature is set to the device being measured.

The specified wavelength is set to the device being measured.

The frequency range of the rf spectrum analyser is adjusted within the required range for monitoring the beat frequency.

The light frequency modulation is performed with the optical frequency modulator.

The beat spectrum on the rf spectrum analyser is confirmed to appear at the modulation frequency.

The polarization is controlled by the polarization controller so that the peak value of beat signal on rf spectrum analyser is the maximum.

If the beam system without optical fibre is used, the polarization of the semiconductor laser has to be adjusted.

The spectral line width is read on the rf spectrum analyser at 3 dB-down point or other values such as 20 dB-down point and calculated. Here, the spectral line width monitored on the rf spectrum analyser is twice of the true value under consumption of a Lorentzian line shape.

Here, when the lasing wavelength of the both semiconductor lasers is coincided each other, this technique is called self-delayed homodyne detection technique, although the influence of 1/f noise is large. If the fibre system is employed, the optical modulator is omitted. The monitoring procedure is, however, the manner similar to those of heterodyne technique, although the beat spectrum is observed at 0 Hz and the spectral line width is obtained.

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Annex A
(informative)

Essential ratings and characteristics

A.1 General

Device characteristics of semiconductor lasers are complicated, and many kinds of electrical and optical characteristics are explained in this Technical Specification. Some examples of absolute maximum ratings, essential ratings and characteristics are, therefore, given for semiconductor lasers installed in TO-can packages and fibre-pigtail modules in Annex A.

A.2 Symbols (and abbreviated terms)

Table A.1 — Symbols (and abbreviated terms)

Symbol	Unit	Term
ϕ_e	W	radiant power
η_e, h	W/A	radiant power efficiency
η_ed, η_d	W/A	differential radiant power efficiency
η_s	W/A	slope efficiency
$I_\mathrm{(th)}$	A	threshold current
$L\phi_\mathrm{e}$	%	linearity (in current – radiant power relation)
λ_air	m	wavelength in air
$P_\lambda(\lambda)$	W/m	spectral radiant power distribution
ΔP_t	W	Radiant power variation across wavelength (frequency) tuning range [a]
λ_p	m	peak-emission wavelength
$\bar{\lambda}$	m	central wavelength
$\Delta\lambda$	m	rms spectral radiation bandwidth
$\Delta\lambda_\mathrm{rms}$	m	rms spectral bandwidth
$\Delta\lambda_\mathrm{L}$	m (or Hz)	spectral line width FWHM
S_msp	m	mode spacing
N_m		number of longitudinal modes
SMS	dB	side mode suppression ratio
$\Delta\lambda_\mathrm{c}$	m	spectral shift
$\delta\lambda_\mathrm{T}$	m/°C	temperature dependence of wavelength
$\delta\lambda_\mathrm{c}$	m/A	current dependence of wavelength

[a] radiant power change over the defined temperature or current tuning range.

$\Delta P_\mathrm{t} = P_\mathrm{e1} - P_\mathrm{e2}$,

here P_e1 and P_e2 is the end and the opposite end of the tuning range, respectively.

[b] maximum range of wavelength in which the ratio of wavelength to current or temperature is kept constant.

[c] required time at which the shift of lasing wavelength becomes constant or within a defined value just after changing in current or temperature.

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Table A.1 *(continued)*

Symbol	Unit	Term
$\Delta\lambda_{tr}$	m	wavelength tuning range [b]
$\Delta\lambda_{tt}$	s	wavelength tuning time [c]
$R(f)$ or RIN	dB	relative intensity noise (RIN)
C/N	dB	carrier-to-noise ratio
$t_{\mathrm{d(on)}}$	s	turn-on delay time
t_{r}	s	rise time
t_{on}	s	turn-on time
$t_{\mathrm{d(off)}}$	s	turn-off delay time
t_{f}	s	fall time
t_{off}	s	turn-off time
f_{c}	Hz	cut-off (modulation) frequency

[a] radiant power change over the defined temperature or current tuning range.

$\Delta P_{\mathrm{t}} = P_{\mathrm{e1}} - P_{\mathrm{e2}}$,

here P_{e1} and P_{e2} is the end and the opposite end of the tuning range, respectively.

[b] maximum range of wavelength in which the ratio of wavelength to current or temperature is kept constant.

[c] required time at which the shift of lasing wavelength becomes constant or within a defined value just after changing in current or temperature.

A.3 Essential ratings and characteristics of TO can laser devices

A.3.1 Type

The TO can laser device consists of the following basic parts:

- semiconductor laser;
- monitor photodiode.

A.3.2 Semiconductor material

Semiconductor laser: InP, GaAs, InGaAs, InAlAs, InGaAsP, etc.

Monitor photodide: Ge, Si, InGaAs, etc.

A.3.3 Structure

Semiconductor laser: Fabry Perot, Distributed feedback (DFB), buried heterostructure (BH), ridge waveguide, vertical cavity surface emitting (VCSEL), quantum well (QW), Multiple QW (MQW), strained MQW, quantum cascade, etc.

Monitor photodiode.

A.3.4 Details of outline and encapsulation

A.3.4.1 ISO and/or IEC and/or national reference number of the outline drawing.

A.3.4.2 Method of encapsulation: glass/metal/plastic/other.

A.3.4.3 Terminal identification.

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A.3.5 Limiting values (absolute maximum system) over the operating temperature range, unless otherwise stated

Table A.2 — Characteristics and requirements of the limiting values

Ref.	Characteristics	Symbol	Requirements		Unit
			Min.	Max.	
	General conditions				
A.3.5.1	Storage temperature	T_{stg}	x	x	°C
A.3.5.2	Operating temperature	T_{case}	x	x	°C
A.3.5.3	Soldering temperature: (at specified soldering time and minimum distance to case	T_{sld}		x	°C
	Semiconductor laser				
A.3.5.4	Reverse voltage	V_{R}		x	V
A.3.5.5	Forward current	I_{F}		x	A
A.3.5.6	CW radiant output power at optical port	ϕ_{e}		x	W
A.3.5.7	Maximum radiant output power at specified pulse width and duty cycle	ϕ_{ep}		x	W
A.3.5.8	ESD-Voltage (both polarities) Human Body model	V_{ESD}		x	V
	Monitor photodiode				
A.3.5.9	Reverse voltage	V_{mR}		x	V
A.3.5.10	Forward current	I_{mF}		x	A
A.3.5.11	ESD-Voltage (both polarities) Human Body model	V_{mESD}		x	V

A.3.6 Electrical and optical characteristics

Table A.3 — Electrical and optical characteristics

Ref.	Characteristics	Symbol	Requirements		Unit
			Min.	Max.	
	Semiconductor laser “Static” characteristics at T_{case} = 25 °C				
A.3.6.1	Threshold current	$I_{\mathrm{(th)}}$	x	x	A
A.3.6.2	Radiant output power at optical port at I_{F} ($I_{\mathrm{(TH)}} + \Delta I_{\mathrm{F}}$) specified (where appropriate for maximum value)	ϕ_{e}	x	x	W
A.3.6.3	Forward current at ϕ_{e}	I_{F}	x	x	A
A.3.6.4	Differential efficiency at $\phi_{\mathrm{e}} \pm \Delta\phi_{\mathrm{e}}$ specified or at $I_{\mathrm{F}} \pm \Delta I_{\mathrm{F}}$ specified	η_{d}	x	x	W/A
A.3.6.5	Linearity of radiant output power between ϕ_{e1} and ϕ_{e2} specified (where appropriate)	L_{d}		x	%
A.3.6.6	Radiant output power at optical port at $I_{\mathrm{(TH)}}$ (where appropriate)	$\phi_{\mathrm{(TH)}}$		x	W
A.3.6.7	Forward voltage at ϕ_{e} or I_{F} specified	V_{F}		x	V
A.3.6.8	Differential resistance above threshold (where appropriate)	R_{d}	x	x	Ω/A
A.3.6.9	Side mode suppression ratio	SMS	x		dB

NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.

Table A.3 *(continued)*

Ref.	**Characteristics**	**Symbol**	**Requirements**		**Unit**
			Min.	Max.	
Semiconductor laser “Static” characteristics at T_case = 25 °C					
A.3.6.10	Spectral line width FWHM	$\Delta\lambda_\mathrm{L}$		x	m
A.3.6.11	Cut-off frequency	f_c		x	Hz
A.3.6.12	Thermal resistance junction-case (where appropriate)	$T_\text{th(j-c)}$		x	K/W
Monitor photodiode Characteristics at T_case = 25 °C					
A.3.6.13	Reverse dark current at $\phi_\mathrm{e} = 0$ at V_R specified	I_mR0		x	A
A.3.6.14	Monitor photodiode output current at ϕ_e and V_R specified	I_m	x	x	A
A.3.6.15	Linearity of monitor diode current to radiant output power from the optical port over the specified range from I_F1 to I_F2 or ϕ_e1 to ϕ_e2	L_m		x	%
A.3.6.16	Capacitance at V_R and f specified	C_tot		x	F
Semiconductor laser “Dynamic” characteristics at T_case = 25 °C					
A.3.6.17	Central (RMS) wavelength of the maximum spectrum at radiant output power ϕ_e specified	$\bar{\lambda}$	x	x	m
A.3.6.18	RMS spectral bandwidth at a) ϕ_e or I_F specified (under CW conditions) or b) ϕ_e mean or I_F mean and ϕ_e specified (under modulation conditions)(where appropriate)	$\Delta\lambda_\text{rms}$	x	x	W/A
A.3.6.19	Rise time of radiant output power between 90 % and 10 % of the radiant output power ϕ_e or I_F and R_L specified	t_r		x	s
A.3.6.20	Fall time of radiant output power between 10 % and 90 % of the radiant output power ϕ_e or I_F and R_L specified	t_f		x	s
A.3.6.21	Relative intensity noise at ϕ_e or I_F specified, ϕ_e and Δf specified, optical reflection specified (where appropriate)	*RIN*		x	dB/Hz
Semiconductor laser (and monitor photodiode) Characteristics over the operating temperature range specified					
A.3.6.22	Threshold current	$I(\text{th})^+$	x	x	A
A.3.6.23	Differential efficiency at $\phi_\mathrm{e} \pm \Delta\phi_\mathrm{e}$ specified or at $I_\mathrm{F} \pm \Delta I_\mathrm{F}$ specified	η_d^+	x	x	W/A
A.3.6.24	Tracking error at ϕ_e specified referring to T_case = 25 °C	E_R^+		x ±	%
A.3.6.25	Central (RMS) wavelength of the spectrum at radiant output power ϕ_e specified	$\bar{\lambda}^+$	x	x	m
A.3.6.26	Linearity of radiant output power between ϕ_e1 and ϕ_e2 specified (where appropriate)	L_n^+		x	%
A.3.6.27	Temperature dependence of wavelength	$\delta\lambda_\mathrm{T}$	x	x	m/°C

NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.

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Table A.3 *(continued)*

Ref.	Characteristics	Symbol	Requirements		Unit
			Min.	Max.	
Semiconductor laser “Static” characteristics at T_{case} = 25 °C					
A.3.6.28	Current dependence of wavelength	$\delta\lambda_{\mathrm{C}}$	x	x	m/A
A.3.6.29	Wavelength tuning range	$\Delta\lambda_{\mathrm{tr}}$	x	x	m
A.3.6.30	Wavelength tuning time	$\Delta\lambda_{\mathrm{tt}}$		x	s
A.3.6.31	Optical power variation across wavelength (frequency) tuning range	ΔP_{t}		x	W
A.3.6.32	Dark current of the monitor photodiode at V_{R} specified	$IR(D)^{+}$		x	A
NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.					

A.3.7 Hazard

See IEC 60825.

A.4 Essential ratings and characteristics of modules with pigtail fibre

A.4.1 Type

The laser module with pigtail fibre consists of the following basic parts:

- semiconductor laser;
- monitor photodiode;
- pigtail fibre.

A.4.2 Semiconductor material

A.4.2.1 Semiconductor laser: InP, GaAs, InGaAs, InAlAs, InGaAsP, etc.

A.4.2.2 Monitor photodiode: Ge, Si, InGaAs, etc.

A.4.3 Structure

Semiconductor laser: Fabry Perot, Distributed feedback (DFB), buried heterostructure (BH), ridge waveguide, vertical cavity surface emitting (VCSEL), quantum well (QW), Multiple QW (MQW), strained MQW, quantum cascade, etc.

Monitor photodiode.

A.4.4 Details of outline and encapsulation

A.4.4.1 ISO and/or IEC and/or national reference number of the outline drawing.

A.4.4.2 Method of encapsulation: glass/metal/plastic/other.

A.4.4.3 Terminal identification.

A.4.4.4 Information on pigtail fibre: type of fibre, kinds of protection, connector, length, etc.

A.4.4.5 Information on the heatsinking of the package.

A.4.5 Limiting values (absolute maximum system) over the operating temperature range, unless otherwise stated

Table A.4 — Characteristics and requirements of limit values

Ref.	**Characteristics**	**Symbol**	**Requirements**		**Unit**
			Min.	Max.	
General conditions					
A.4.5.1	Storage temperature	T_{stg}	x	x	°C
A.4.5.2	Operating temperature	T_{case}	x	x	°C
A.4.5.3	Soldering temperature: (at specified soldering time and minimum distance to case	T_{sld}		x	°C
A.4.5.4	Minimum bending radius of pigtail (at specified distance from case)	r	x		m
	Tensile strength along cable axis:				
A.4.5.5	Untight structure: - fiber tensile strength - cable tensile strength	F F		x x	N N
or **A.4.5.6**	Tight structure: - cable tensile strength	F		x	N
Semiconductor laser					
A.4.5.7	Reverse voltage	V_{R}		x	V
A.4.5.8	Forward current	I_{F}		x	A
A.4.5.9	CW radiant output power at pigtail output	ϕ_{e}		x	W
A.4.5.10	Maximum radiant output power at specified pulse width and duty cycle	ϕ_{ep}		x	W
A.4.5.11	ESD-Voltage (both polarities) Human Body model	V_{ESD}		x	V
Monitor photodiode					
A.4.5.12	Reverse voltage	V_{mR}		x	V
A.4.5.13	Forward current	I_{mF}		x	A
A.4.5.14	ESD-Voltage (both polarities) Human Body model	V_{mESD}		x	V

A.4.6 Electrical and optical characteristics

Table A.5 — Electrical and optical characteristics

Ref.	**Characteristics**	**Symbol**	**Requirements**		**Unit**
			Min.	Max.	
Semiconductor laser “Static” characteristics at $T_{\mathrm{case}} = 25$ °C					
A4.6.1	Threshold current	$I_{\mathrm{(th)}}$	x	x	A
A.4.6.2	Radiant output power at pigtail output at I_{F} ($I_{\mathrm{(TH)}} + \Delta I_{\mathrm{F}}$) specified (where appropriate for maximum value)	ϕ_{e}	x	x	W
A.4.6.3	Forward current at ϕ_{e}	I_{F}	x	x	A
NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.					

Table A.5 *(continued)*

Ref.	Characteristics	Symbol	Requirements		Unit
			Min.	Max.	
Semiconductor laser “Static” characteristics at T_{case} = 25 °C					
A.4.6.4	Differential efficiency at $\phi_e \pm \Delta\phi_e$ specified or at $I_F \pm \Delta I_F$ specified	η_d	x	x	W/A
A.4.6.5	Linearity of radiant output power between ϕ_{e1} and ϕ_{e2} specified (where appropriate)	L_d		x	%
A.4.6.6	Radiant output power at pigtail output at $I_{(TH)}$ (where appropriate)	ϕ_{TH}		x	W
A.4.6.7	Forward voltage at ϕ_e or I_F specified	V_F		x	V
A.4.6.8	Differential resistance above threshold (where appropriate)	R_d	x	x	Ω/A
A.4.6.9	Side mode suppression ratio	SMS	x		dB
A.4.6.10	Spectral line width FWHM	$\Delta\lambda_L$		x	m
A.4.6.11	Cut-off frequency	f_c		x	Hz
A.4.6.12	Thermal resistance junction-case (where appropriate)	$T_{th(j\text{-}c)}$		x	K/W
Monitor photodiode Characteristics at T_{case} = 25 °C					
A.4.6.13	Reverse dark current at $\phi_e = 0$ at V_R specified	I_{mR0}		x	A
A.4.6.14	Monitor photodiode output current at ϕ_e and V_R specified	I_m	x	x	A
A.4.6.15	Linearity of monitor diode current to radiant output power from the optical port over the specified range from I_{F1} to I_{F2} or ϕ_{e1} to ϕ_{e2}	L_m		x	%
A.4.6.16	Capacitance at V_R and f specified	C_{tot}		x	F
Semiconductor laser “Dynamic” characteristics at T_{case} = 25 °C					
A.4.6.17	Central (RMS) wavelength of the maximum spectrum at radiant output power ϕ_e specified	$\bar{\lambda}$	x	x	m
A.4.6.18	RMS spectral bandwidth at: a) ϕ_e or I_F specified (under CW conditions) or b) ϕ_e mean or I_F mean and ϕ_e specified (under modulation conditions)(where appropriate)	$\Delta\lambda_{rms}$	x	x	W/A
A.4.6.19	Rise time of radiant output power between 90 % and 10 % of the radiant output power ϕ_e or I_F and R_L specified	t_r		x	s
A.4.6.20	Fall time of radiant output power between 90 % and 10 % of the radiant output power ϕ_e or I_F and R_L specified	t_f		x	s
A.4.6.21	Relative intensity noise at ϕ_e or I_F specified, ϕ_e and Δf specified, optical reflection specified (where appropriate)	RIN		x	dB/Hz
Semiconductor laser (and monitor photodiode) Characteristics over the operating temperature range specified					
NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.					

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Table A.5 *(continued)*

Ref.	**Characteristics**	**Symbol**	**Requirements**		**Unit**
			Min.	Max.	
	Semiconductor laser “Static” characteristics at T_{case} = 25 °C				
A.4.6.22	Threshold current	I(th)+	x	x	A
A.4.6.23	Differential efficiency at $\phi_e \pm \Delta\phi_e$ specified or at $I_F \pm \Delta I_F$ specified	$\eta_d{}^+$	x	x	W/A
A.4.6.24	Tracking error at ϕ_e specified referring to T_{case} = 25 °C	$E_R{}^+$		x ±	%
A.4.6.25	Central (RMS) wavelength of the spectrum at radiant output power ϕ_e specified	$\bar{\lambda}^+$	x	x	m
A.4.6.26	Linearity of radiant output power between ϕ_{e1} and ϕ_{e2} specified (where appropriate)	$L_n{}^+$		x	%
A.4.6.27	Temperature dependence of wavelength	$\delta\lambda_T$	x	x	m/°C
A.4.6.28	Current dependence of wavelength	$\delta\lambda_C$	x	x	m/A
A.4.6.29	Wavelength tuning range	$\Delta\lambda_{tr}$	x	x	m
A.4.6.30	Wavelength tuning time	$\Delta\lambda_{tt}$		x	s
A.4.6.31	Optical power variation across wavelength (frequency) tuning range	ΔP_t		x	W
A.4.6.32	Dark current of the monitor photodiode at V_R specified	$IR(D)^+$		x	A
NOTE Characteristics with “+” in the symbol column indicate that minimum and maximum values of the characteristics shall be taken over whole operating temperature range.					

A.4.7 Hazard

See IEC 60825.

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ICS 31.260

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