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Optics and photonics — Measurement method of semiconductor lasers for sensing

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

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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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.

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.

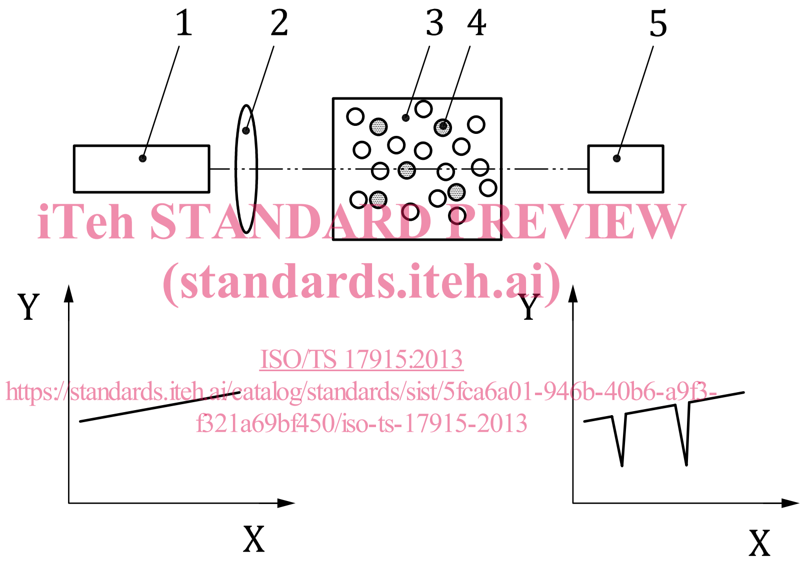
3.3 Common sensing technique and equipment using semiconductor laser

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.



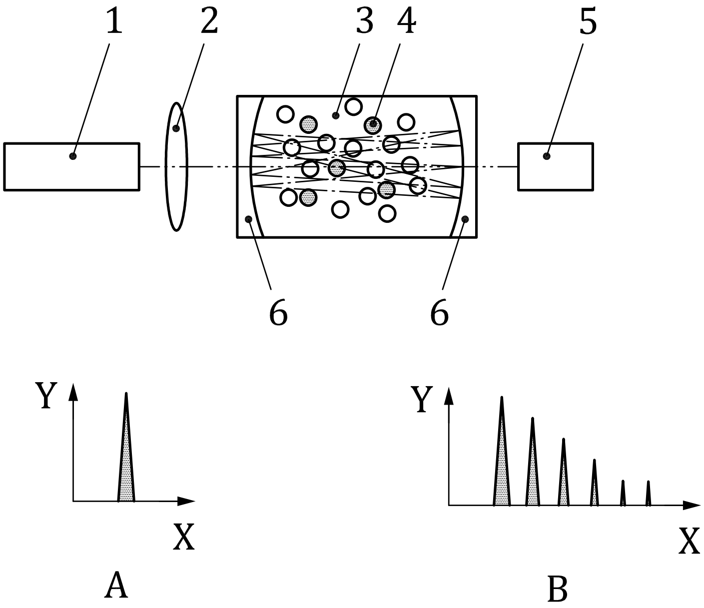
Key

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.



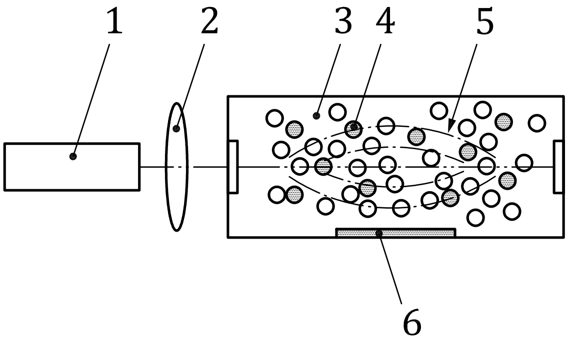
Key

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.



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

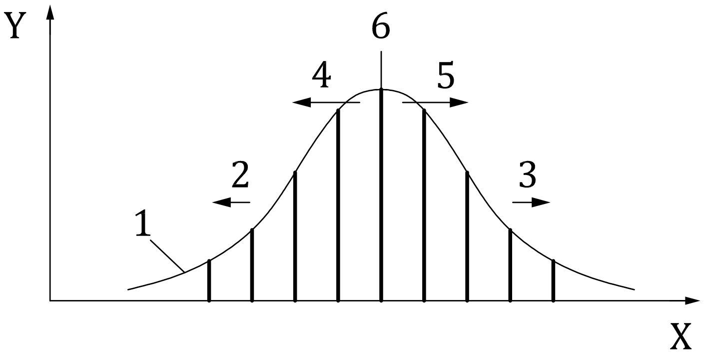
The lasing wavelength of semiconductor lasers is changed by various methods. In external cavity control semiconductor lasers, the lasing wavelength can be selected by controlling the angle of grating if a grating is set as an external mirror. The lasing wavelength is widely scanned by controlling the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

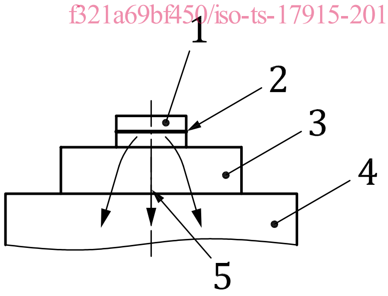
These are basic mechanisms for changing lasing wavelength in semiconductor lasers. Among them, the change in lasing wavelength by controlling ambient temperature under a constant current is mainly generated by band-gap change in FP-lasers and refractive index change in DFB lasers. Controlling the lasing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

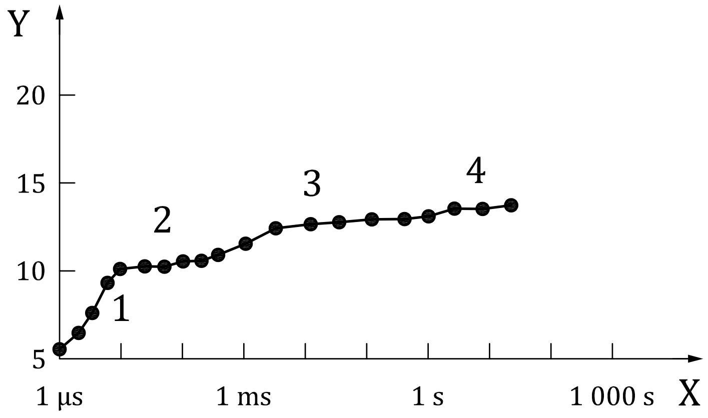
Figure 4 — Main factor of lasing-wavelength change



Key

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

Figure 5 (a) — Sample configuration



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.

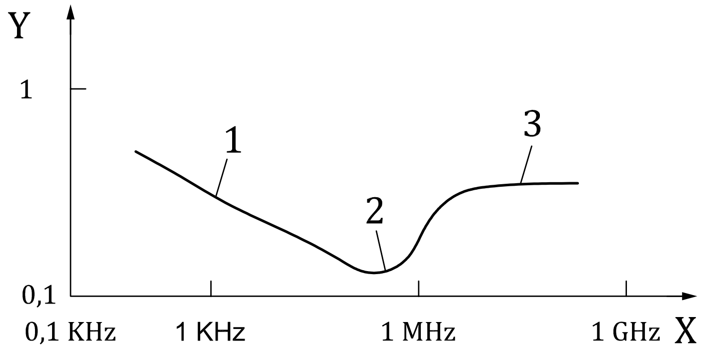
NOTE 2 The sample is a 1 300 nm-band FP semiconductor laser. The labels indicated by 1, 2, 3 and 4 indicate the responsible parts of heat conduction for the heat generated at the active layer.

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