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Temperature and current coefficients of lasing wavelength in tunable diode laser spectroscopy

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Abstract

The factors determining temperature and current coefficients of lasing wavelength are investigated and discussed under monitoring CO₂-gas absorption spectra. The diffusion rate of Joule heating at the active layer to the surrounding region is observed by monitoring the change in the junction voltage, which is a function of temperature and the wavelength (frequency) deviation under sinusoidal current modulation. Based on the experimental results, the time interval of monitoring the wavelength after changing the ambient temperature or injected current (scanning rate) has to be constant at least to eliminate the monitoring error induced by the deviation of lasing wavelength, though the temperature and current coefficients of lasing wavelength differ with the rate.

1 Introduction

Optical sensing using tunable diode laser spectroscopy (TDLS) has been widely used in various engineering fields and researched for new users ranging from micro-scale to large-scale applications [1]. For example, optical sensing is being used for bio-sensing, environmental monitoring, etc. Laser diodes are key devices for those applications and are indispensable for building sensing equipment. Edge- and surface-emitting laser diodes are used for those purposes. 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.

The lasing wavelength of these laser diodes is ordinarily controlled by varying the ambient temperature and injected current in TDLS. These variables corresponding to bandgap change due to ambient temperature and the band-filling effect induced by carrier injected into the active

layer of the 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-coefficient of lasing wavelength. However, the correlation between the physical properties and the temperature- and current-coefficient has not been discussed in detail. This paper discusses the physical mechanisms of temperature and current control of the lasing wavelength for TDLS.

2 Samples

Several kinds of edge-emitting InGaAsP/InP Fabry–Perot and DFB laser diodes lasing at 1300, 1550, and 2006 nm were used in this study. The active layers of these laser diodes were composed of bulk, quantum well, and strained quantum well grown by metal organic vapor phase epitaxial (MOVPE) method. The cavity length of these lasers was about 0.3 mm and was defined by cleavage from wafers. After the cleavage, the front and rear facets were respectively coated with an anti- and high-reflecting dielectric film. These laser diodes were mounted in a junction-up or junction-down configuration on silicon or ceramic heat sinks as shown in Fig. 1 and then installed in TO-can packages.

Typical current-light output power characteristics are shown in Fig. 2 for a 2000-nm-band laser diode. The threshold current was about 6 mA. The output power was more than about 20 mW at an injected current of 100 mA and at temperatures below 40°C. The 2000-nm-band as well as the other-band laser diodes showed stable operation with a single longitudinal mode at temperatures ranging from below 0 to above 60°C. The side-mode suppression ratio (SMSR) of all the DFB laser diodes used were more than 40 dB for 1300- and 1550-nm-band laser diodes and more than 25 dB for 2000-nm-band laser diodes at 10 mW and 25°C. Figure 3 shows an example of a lasing spectrum of 2000-nm-band laser diodes at 40°C. A SMSR of more than 25 dB was maintained even at 40°C. The lasing spectral linewidth is not a critical characteristic for spectroscopy and 1300- and 1550-nm-band laser diodes used showed sufficiently narrow linewidth, for example, less than a few MHz at 10 mW for 1550-nm-band laser diodes. This value corresponds to less than 0.1 pm in the 1550-nm wavelength band.

3 Experimental setup

3.1 Lasing wavelength scanning system

To analyze the influence of the ambient temperature and injected current on the lasing wavelength of laser diodes, the temperature and current coefficient of lasing wavelength were monitored with the system shown in Fig. 4. The optical output power from the laser diode was reshaped into a parallel beam with a lens and passed through a 4-cm-thick gas cell filled with CO₂ gas at atmospheric pressure and then received by a pin photodiode or an optical spectrum analyzer to monitor the wavelength spectra. The lasing wavelength was automatically scanned by controlling the temperature of the laser diode with a thermoelectric cooler or the injected current of laser diode. Here, the change rates of the temperature and current were controlled with a computer.

3.2 Junction temperature monitoring system

As described in the next section, the change in lasing wavelength by controlling ambient temperature or injected current mainly resulted from the temperature change in the active layer of the lasers. To analyze the thermal conductance of each sample, a junction temperature monitoring system was used [2]. The concept of the pn-junction-temperature estimation is depicted in Fig. 5. This method has often been used in the estimation of thermal resistance of diodes and transistors. The active layer temperature (or pn-junction temperature), T_j can be expressed with the equation

$$T_j = T_a + R_{th} I_F V_F, \quad (1)$$

where T_a is the ambient temperature, R_{th} is the thermal resistance in units of $^{\circ}\text{C}/\text{W}$, I_F and V_F are the operating current and voltage, respectively. If operating current is quickly changed from I_F to a small current, I_f , at which Joule heating can be ignored, the junction voltage is lowered by ΔV_f , which is determined by Joule heating due to the operating current, I_F , and then reaches a constant value under the small current, I_f (see Fig. 5). The monitoring delay time, t_d should be small to eliminate monitoring error. Ideally, ΔV_f is obtained by $V_f - V_M$ with $t_d = 0$. Consequently, the temperature dependence of the pn-junction voltage is estimated from the voltage change, ΔV_f . If the temperature dependence of the junction voltage is expressed with $K = -dV_f/dT_a$, the temperature change, ΔT_j can be given by

$$\Delta T_j = T_j - T_a = \Delta V_f / K, \quad (2)$$

where K can be calculated as the slope of the junction-voltage vs. ambient temperature under very small forward current injection which scarcely influences the temperature rise of the junction. The behavior of the active layer temperature can be estimated with this method. If the width of pulse current, T_p increases, the heat generated at the active layer diffuses to the laser chip, heat sink, package stem, package, etc. in response to the thermal conductance of each part. This behavior can be monitored with the systems shown in Fig. 5.

4 Lasing wavelength

Several factors govern the change in lasing wavelength of laser diodes as shown in Fig. 6. 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–Pérot (FP)-mode in FP-lasers. This phenomenon is induced by the plasma effect related to carrier density in semiconductors [3]. 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 bandgap 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 laser diodes. Among them, the change in lasing wavelength by controlling ambient temperature under a constant current is mainly generated by bandgap 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 bandgap 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-coefficient of lasing wavelength is analyzed in DFB lasers from the viewpoint of thermal conductivity in the following sections.

4.1 Wavelength change due to current injection

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 depend on the mounting configuration and packaging structure. This behavior was analyzed with the system indicated in Fig. 5. Figure 7 shows the active layer temperature increase as a function of the current pulse width for a 1300-nm-band FP laser diode. The pulse current, I_F , and the monitoring current, I_f , were set at 100 and 1 mA, respectively. The temperature of each point in the figure was calculated by $V_f - V_M$ with $t_d = 1 \mu\text{s}$. The temperature coefficient of the junction voltage, K , was about 1 mV/°C. 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 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 behaviors are closely related to the rate and range of wavelength change under current modulation. In Fig. 8, the horizontal axis indicates modulation frequency and the vertical axis corresponds to the frequency deviation, which is equal 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 behavior is also recognized in Fig. 7, in which the current pulse width corresponds to the modulation frequency of the laser diode from the viewpoint of heat conduction. A dip appears after 100 kHz in Fig. 8. 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 fiber communication field [4]. The frequency range used for TDLS is below the dip frequency and the frequency at which the influence of heat is dominant (red shift).

4.2 Wavelength change due to ambient temperature

Heat is inversely transmitted from the ambient to the active layer of the laser diode 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 Fig. 7.

4.3 Current coefficient and temperature coefficient

The temperature and current coefficients of lasing wavelength were monitored at a specific interval after changing the package temperature and the injected current. The spectral characteristics were scarcely degraded and responded well to CO₂-gas absorption under these conditions.

The current coefficient of wavelength and absorption peak wavelength varied with the time interval of monitoring after changing the current as shown in Fig. 9. The current was changed with a 2-mA step under a constant package temperature (11.7°C). The lasing wavelength was also monitored at the all monitoring points in Fig. 9, and in the extreme case, the current coefficient was estimated to be about 0.008 and 0.006 nm/mA at 3 min and at 10 s, respectively, just after changing the current under a constant package temperature. The difference in the coefficient was caused by the temperature difference at the time interval of 3 min and 10 s which corresponds to the pulse width in Fig. 7. When the package temperature was not controlled, the current coefficient increased about 10% because the package temperature increased. The current-light output characteristics under CO₂-gas absorption therefore differed from the change rate of injected current. 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 coefficient is, therefore, not constant and varies with the rate of current increase. Their coefficients were, however, kept at fixed values if the time interval of monitoring were fixed at the constant values and strongly influenced by the materials used and the chip-mount configuration.

The temperature coefficient of wavelength and absorption peak wavelength will vary depending on the time interval of monitoring after changing the ambient temperature (see Fig. 7). If the change rate of package temperature is set at values of more than 1 second, the temperature coefficient is the same because the change in package temperature diffuses to the active layer. Figure 10 shows examples of the CO₂-gas absorption spectra monitored at several time intervals after 0.2°C-step change in the package temperature. The absorption spectra monitored at the time intervals of 1 and 3 min after 0.2°C-step change nearly coincided with each other as shown in Fig. 10. The temperature rise at the active layer was nearly constant in this time range, and the coefficient was estimated to be about 0.13 nm/°C. When the package temperature was increased and the change rate (time interval) of package temperature was set at values of less than 1 second, the absorption peak tended to be small and shifted to the longer wavelength range against the horizontal axis (package temperature).

These coefficients are governed by the change of each factor discussed in Sect. 4. When ambient temperature is changed, for example, threshold current density and bandgap energy vary simultaneously and lasing wavelength changes complicatedly. The coefficients result from the overall change in the factors. Consequently, the coefficients 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 (package) temperature has to be constant during TDLS to eliminate wavelength error, although the coefficient differs with the change rate.

5 Conclusion

The physical mechanisms determining temperature and current coefficients of lasing wavelength, the band-filling effect, the plasma effect, and the heating effect in relation to the dynamic property of the junction (active layer) temperature have been discussed in detail and clarified for TDLS. The wavelength change after lasing is mainly governed by the temperature in the active layer. The temperature in the active layer depends on the heat conductance between the active layer and package (or ambient). Joule heating generated at the active layer quickly spreads within the laser chip and then gradually diffuses to the surrounding region (heat sink and package), and the current coefficient differed with the monitoring time interval after changing the magnitude of injected current. The thermal conductance also has a strong influence on the temperature of the active layer when the ambient (package) temperature changes. From these results, it can be said that the monitoring time interval after changing the ambient temperature or injected current (scanning rate) should be strictly fixed to eliminate monitoring error related to lasing wavelength, although the coefficients will be different with the scanning rate.

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Fig. 1.
Schematic diagram of a buried heterostructure laser diode used in this experiment and its mounting configuration

Fig. 2.
Typical current–light output power characteristics of 2000-nm-band DFB laser diode

Fig. 3.
Typical spectral characteristics of 2000-nm-band DFB laser diode at 40°C

Fig. 4.
Schematic diagram of the experimental setup

Fig. 5.
Concept of active-layer- (pn-junction-) temperature estimation method

Fig. 6.
Basic mechanisms of lasing wavelength variation in laser diodes

Fig. 7.

(a) Sample configuration and (b) the estimated temperature rise in active layer as a function of pulse width. The sample is a 1300-nm-band FP laser diode. The labels of LD chip, heat sink, package stem, and package in (b) indicate the responsible parts of heat conduction for the heat generated at the active layer. These are estimated by the time constant of the heat conduction

Fig. 8. Lasing frequency (wavelength) deviation for a 1300-nm-band DFB laser diode as a function of frequency. The modulation current was a 0.5-mA peak-to-peak sinusoidal wave and the DC bias was set at 60 mA

Fig. 9. Typical current-light output power relation under CO₂-gas absorption. The ambient temperature was set at the wavelength just before a CO₂-gas-absorption peak. The current was increased with a 2-mA step

Fig. 10.

Typical CO₂-gas absorption spectrum. The laser diode was biased at 60 mA, and the ambient temperature was changed with a 0.2°C step. The time interval between steps was set at 1 and 3 min, respectively