Appl. Phys. B 90, 269–272 (2008)
DOI: 10.1007/s00340-007-2823-3

Applied Physics B
Lasers and Optics

M. FUKUDA[1,✉]
S. OOYAMA[1]
A. UTSUMI[1]
Y. KONDO[2]
T. KUROSAKI[2]
T. MASUDA[3]

Effect of optical feedback noise on tunable diode laser spectroscopy

[1] Toyohashi University of Technology, 1-1, Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan
[2] NTT Photonics Laboratories, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan
[3] Optoelectronic Industry and Technology Development Association (OITDA), Sumitomo Edogawabashiekimae Bldg., 7F, 1-20-10, Sekiguchi, Bunkyo, Tokyo 112-0014, Japan

Received: 28 August 2007 / Revised version: 11 September 2007

ABSTRACT The effect of optical feedback noise of a laser diode on the stability of gas-absorption spectra was investigated by monitoring the optical absorption of CO_2 gas. Lasing longitudinal mode instability greatly degraded the shape of the absorption spectra, and coherence collapse in the laser diode greatly broadened the spectra. The correlation between the optical feedback noise of the laser diode and the shape of the gas-absorption spectra was clarified on the basis of these spectral behaviors.

PACS 42.62.Fi; 42.55.Px; 42.68.Ca

1 Introduction

Optical sensing has been used in various fields ranging from micro-scale applications such as biosensing to large-scale applications such as environmental monitoring. Several technologies have been developed for these applications and are in use. They include tunable diode laser spectroscopy (TDLS), cavity ring down spectroscopy (CRDS), and photoacoustic spectroscopy (PAS). TDLS is the most basic and widely used spectroscopic method of these technologies. A key device in these applications is the laser diode, and several kinds of laser diodes have been applied. Edge-emitting laser diodes (LDs) are generally used for wavelengths ranging from ultraviolet to near/mid infrared. Most LDs were developed for use as optical sources in optical fiber communication systems and consumer electronic devices such as CDs and DVDs. Wavelength-conversion technology, such as difference-frequency generation using two LDs and optical nonlinear materials, are used to generate light in the mid-infrared wavelength range [1]. For wavelengths of more than about 4 μm, quantum cascade lasers have started to be applied to sensing systems [2].

Single lasing wavelength operation is necessary for the spectroscopy to obtain high sensitivity. Single longitudinal mode behavior is determined by the relationship between the optical gain width and the lasing longitudinal mode spacing, which is mainly determined by the optical cavity length of the laser. Vertical cavity surface emitting lasers essentially operate in single longitudinal mode because of their short optical cavities (large space between cavity modes). For single-mode operation of edge-emitting-type LDs, distributed feedback (DFB) structures are commonly used, and one mode is selected corresponding to the effective pitch of the grating fabricated along the laser cavity. DFB LDs operate stably in equipment, but their stability is easily degraded by optical back reflection from a distant mirror. This optical back reflection strongly affects the sensitivity in optical sensing, although precise analysis of the effect has not been carried out. We have analyzed the effect of optical feedback noise induced in DFB LDs on tunable diode laser spectroscopy for environmental gas monitoring.

2 Laser diodes

2.1 *Structure*

Two types of DFB LDs, one type lasing in the 1550-nm band and the other in the 2000-nm band (KELD1-G5B2TA, NEL Co.), were used in this study. For both types, the light-emitting region was a strained multiple quantum well (MQW) structure etched to form a mesa, and then buried with current-blocking layers. These layers were grown by metal organic vapor phase epitaxy (see Fig. 1). Their cavity length, defined by the wafer cleavage, was about 0.3 mm. After each wafer was cleaved, its front and rear facets were coated respectively with anti- and high-reflecting dielectric films. They were mounted in a junction-up configuration on silicon or ceramic heat sinks. Some 1550-nm-band DFB LDs having bulk-type light-emitting regions were also used to expand the effect of optical feedback noise [3–5].

2.2 *Lasing characteristics*

Typical current–light output power characteristics are shown in Fig. 2. The threshold current was about 6 mA for both types, and the output power was more than about 20 mW at an injected current of 100 mA for both types. These LDs showed stable operation with a single longitudinal mode from below 0 to above 60 °C.

Characteristics particularly important for diode laser spectroscopy include wavelength tunability by adjusting the in-

---

✉ Fax: +81-532-44-6729, E-mail: fukuda_mitsuo@eee.tut.ac.jp

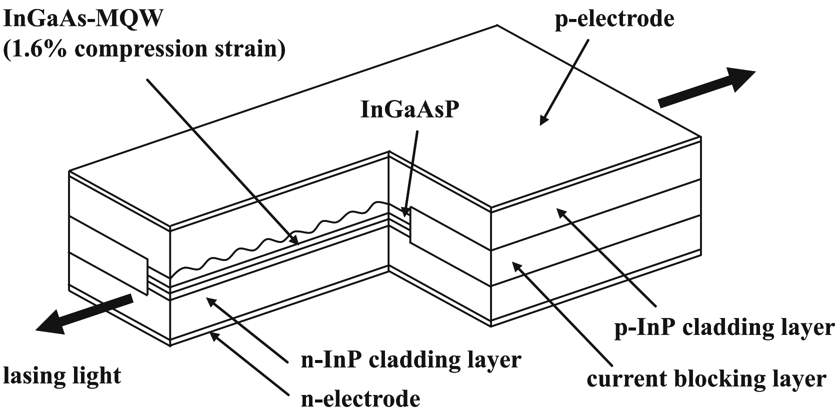

FIGURE 1 Schematic diagram of 2000-nm-band buried heterostructure laser diode used in experiments. The InGaAs-MQW structure is an InGaAsP-MQW one for a 1550-nm-band laser diode

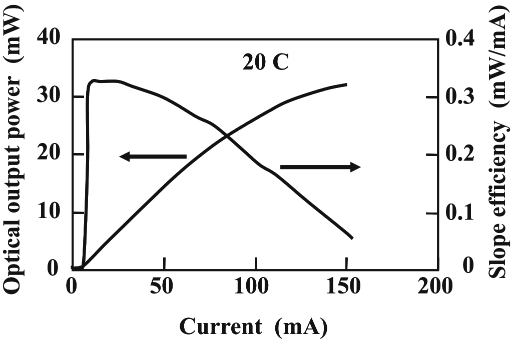

FIGURE 2 Typical current–light output power characteristics of 2000-nm-band laser diodes

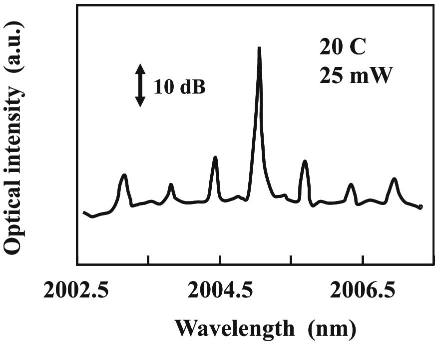

FIGURE 3 Typical spectral characteristics of 2000-nm-band laser diodes

jected current or diode temperature, the spectral line width, and the side mode suppression ratio (SMSR), which is defined by the ratio of the main peak mode to the second mode. The SMSR of more than 40 dB for the 1550-nm-band diodes and more than 25 dB for the 2000-nm-band ones were obtained at the output power of more than 10 mW at 25 °C, as shown in Fig. 3. The lasing spectral line width was not a critical characteristic for the spectroscopy because all the LDs used showed a sufficiently narrow line width; for example, less than a few MHz (less than 0.1 pm) at 10 mW for the 1550-nm-band LDs.

The temperature coefficient of the lasing wavelength variation was about 0.1 nm/K for both types of LDs. Under temperature tuning ranging from below 10 to 60 °C, these spectral characteristics were nearly constant and responded well to CO_2-gas absorption.

3 Experimental setup

The experimental setup is shown in Fig. 4. The optical output power from the LD was coupled to a tapered 1550-nm single-mode silica fiber, the top of which was coated with an anti-reflective coating film, and the coupled light was separated into two optical paths with an optical fiber coupler. One of the two paths led to the variable reflector controlling

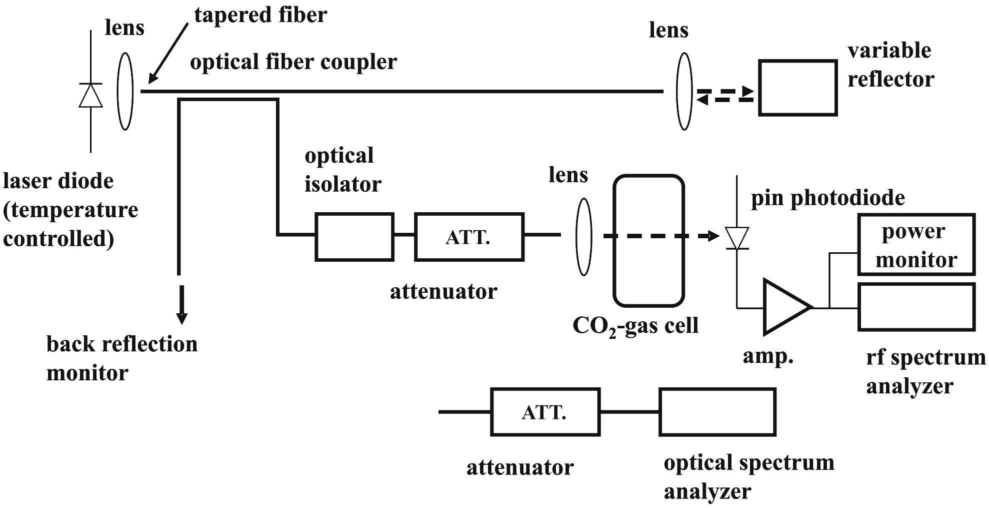

FIGURE 4 Schematic diagram of experimental setup

optical back reflection. The back-reflected light was returned to the LD through the coupler and the tapered fiber. The magnitude of the optical back reflection was also controlled by adjusting the optical coupling between the LD and the tapered optical fiber. The other path led to an output port at which the light carried in the fiber was emitted into the air. The emitted light was reshaped into a parallel beam with a lens and passed through a 4-cm-thick gas cell filled with CO_2 gas and then received by a pin photodiode or an optical spectrum analyzer to monitor the wavelength spectra. The distance between the output port of the fiber and the photodiode was set at about 20 cm. The electrical output from the photodiode was monitored and recorded. The lasing wavelength was scanned by controlling the temperature of the LD with a thermoelectric cooler.

4 Effect of optical feedback noise on characteristics of laser diodes

To analyze the effect of the optical back reflection on the characteristics of the LDs, relative intensity noise (RIN) of the diode was monitored under test. The electrical power output from the photodiode was amplified, and its frequency noise spectrum was monitored with an rf spectrum analyzer. The RIN was calculated by using the equation

$$\mathrm{RIN} = (P_{\mathrm{noise}} - N_{\mathrm{n}})/G R_{\mathrm{L}} I_{\mathrm{R}}^2 \Delta f \,, \tag{1}$$

where P_{noise} is the measured noise power, N_{n} is the noise power from the photodetector (shot noise) and amplifier (thermal noise), G is the amplifier gain, R_{L} is the load resistance, I_{R} is the photocurrent of the photodiode, and Δf is the measurement frequency bandwidth of the rf spectrum analyzer.

A typical change in relative intensity noise at 100 MHz under dc operation is shown in Fig. 5 as a function of the magnitude of the optical back reflection for a 1550-nm-band LD. The effect of the back reflection on the diode can be separated into five regimes corresponding to the magnitude of the back reflection [3–5]. In the present study, three regimes – lasing in single longitudinal mode without optical back reflection, lasing with mode hopping between two peaks separated by a few hundred MHz (a few pm), and lasing during coherence collapse – were generated corresponding to the optical feedback power. The output power was nearly constant in the mode-hopping regime. The optical feedback level in the transition area from one regime to another depends on the LD structure and characteristics, but the essential trend is the same [4–6].

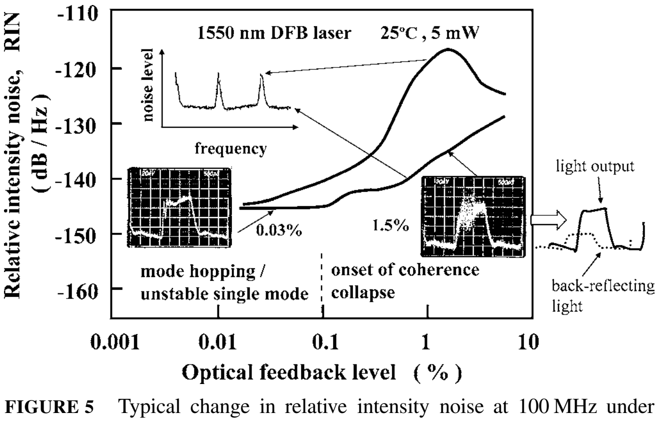

FIGURE 5 Typical change in relative intensity noise at 100 MHz under optical back reflection for 1550-nm-band laser diodes having bulk-type light-emitting regions

With low optical back reflection, the RIN level was sufficiently low and was determined by the noise of the whole system, as shown in Fig. 5. As the optical back reflection was increased, the periodic noise peaks in the frequency spectra began to appear and their height increased in the noise spectra. This is caused by phase matching between the mode within the laser cavity and that within an external cavity formed by the distant mirror (reflecting point) [7]. The frequency of the peaks can be expressed by

$$f = m/tr = mc_0/2n_{\mathrm{ext}}l_{\mathrm{ext}} \,, \quad m = 1, 2, 3, \ldots, \tag{2}$$

where c_0 is the light velocity in vacuum, n_{ext} is the refractive index of the medium (silica fiber in Fig. 4), and l_{ext} is the distance between the laser facet and the distant mirror (nearly the fiber length). The spacing of the noise peak, δf, is therefore given by

$$\delta f = c_0/2n_{\mathrm{ext}}l_{\mathrm{ext}} \,. \tag{3}$$

The spacing shown in the inset in Fig. 5 is about 34 MHz, which coincides with that for a fiber length of 3 m (refractive index of about 1.45).

As the optical back reflection was further increased, the RIN ground level began to increase. This corresponds to the onset of coherence collapse [8], and a large intensity fluctuation occurred in the LD. This situation is evident in Fig. 5. Both inset photographs show light output shapes when the LD was modulated at 300 MHz with a 50% duty ratio. Clear modulated outputs are evident in the low optical feedback range. After onset of the coherence collapse, a large optical intensity fluctuation was observed in the region in which modulated optical back reflection was partially superimposed onto the modulated lasing output power. This coherence collapse greatly degraded the lasing spectral line width of the LD and quickly broadened the spectral line width from less than 0.1 pm to sub-nanometers.

5 Effect of optical feedback noise on diode laser spectroscopy

The absorption spectra of CO_2 gas were monitored for various magnitudes of the optical back reflection. Three typical spectra are shown in Fig. 6. The wavelength was changed by adjusting the temperature with a step of 0.2 K while keeping the current constant at about 60 mA, so the signal intensity gradually decreased as the wavelength increased in correspondence to the decrease in laser output power. The pressure of the CO_2 gas in the cell was set at about atmospheric pressure to monitor strong CO_2-gas absorption, so the absorption spectra without the effect of optical back reflection showed wide absorption peaks because of Doppler shift due to gas-molecule collisions. When the optical feedback was negligible, clear spectra were monitored and sharp absorption peaks of CO_2 gas were observed, as shown in Fig. 6a. The background spectrum without the CO_2 gas cell is also shown in Fig. 6. The monitored power gradually decreased as the lasing wavelength lengthened according to temperature rise. The

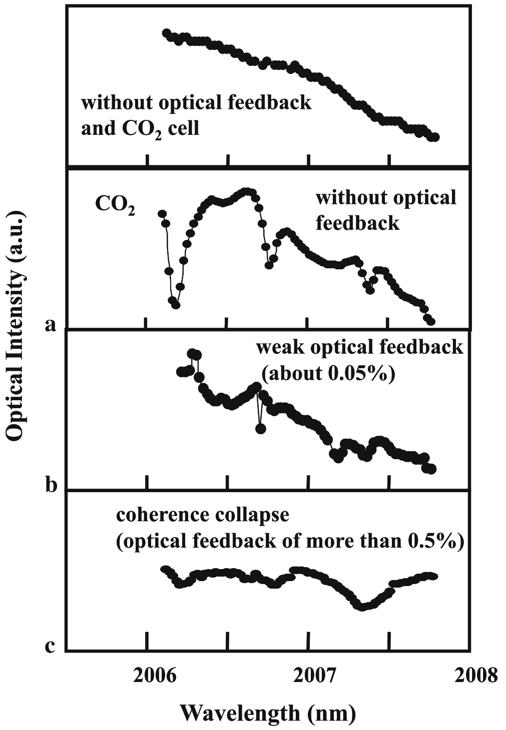

FIGURE 6 Absorption spectra of CO_2 gas under three optical back-reflection conditions (**a**–**c**), and background spectrum without CO_2 gas cell and optical feedback, monitored using 2000-nm-band laser diode

small hollows were observed at the wavelength corresponding to CO_2-gas absorption. As the optical back reflection was increased, the absorption peaks in the spectra became less clear, as shown in Fig. 6b. With an even further increase in the optical back reflection, clear CO_2 gas absorption peaks were no longer evident – only broad, weak peaks were detected, as shown in Fig. 6c.

The lasing spectral line width of normal DFB LDs is not so important if the optical back reflection from distant mirrors is negligible. This situation is evident in the gas-absorption spectrum shown in Fig. 6a. As the magnitude of the optical back reflection was increased, the shape of the spectra changed, as shown in Fig. 6b and c. Before the onset of coherence collapse in the LD, the periodic noise peaks increased in the frequency noise spectrum (see Fig. 5), and the LD operated in mode-hopping mode between the two peaks or in single mode. The hopping frequency was about 1 MHz [3]. The single-mode wavelength in this regime is selected from the two peaks, whose wavelength corresponds to the larger optical gain between them. Consequently, this single-mode operation is not sufficiently stable against optical back reflection and environmental perturbations such as gas absorption, temperature changes, and mechanical vibration. This spectral instability greatly degraded the absorption spectra, and the CO_2 gas absorption peaks in the spectrum vanished due to a large optical intensity fluctuation (see Fig. 6b). If the pressure of the gas is low and the absorption spectrum is sharp, the spectral mode hopping will degrade the sensitivity much more.

Under strong optical back reflection and the generation of coherence collapse, the ground level of the relative intensity noise increased, and the lasing spectral line width broadened to sub-nanometers (about 0.2 nm or a few tens of GHz in the frequency range), although the mode hopping was suppressed because of the decline of coherency. This broadening was beyond the spectral absorption line width and degraded the resolution of the absorption spectra. This situation is indicated in Fig. 6c. Only broad, weak peaks were detected.

The shape of the absorption spectra was determined by the absorption line width and the lasing spectral line width. When the absorption line width was narrower than the lasing spectral line width, the shapes of the absorption spectra were strongly affected by the lasing line width and its stability. When the gas absorption line width was sufficiently broader than the lasing line width, as in the present study, the shape of the absorption spectra is clearly monitored. Under optical back reflection, however, the shape of the absorption spectra was greatly affected by the stability of the lasing spectra. The stability of the lasing spectra is of primary importance, and optical feedback noise is a key factor affecting the shape of gas absorption spectra. The optical feedback noise must be suppressed or eliminated to avoid mode hopping between two peaks and coherence collapse, at least for detecting clear gas absorption peaks.

6 Conclusion

The correspondence between the shape of gas-absorption spectra and noise induced by optical back reflection in a laser diode has been investigated by using two types of strained quantum well laser diodes lasing at 1550- and 2000-nm-wavelength bands. The effect of the optical feedback noise was separated into two regimes: mode hopping between two peaks, including operation in single mode, and coherence collapse generation. The absorption spectra were greatly degraded by mode hopping and broadened with the onset of coherence collapse. The effect of optical feedback noise in the LD on tunable diode laser spectroscopy has been clarified on the basis of these behaviors.

REFERENCES

1 K. Gallo, G. Assanto, J. Opt. Soc. Am. **16**, 741 (1999)
2 J. Faist, F. Capasso, D.L. Sivco, C. Sirtori, A.L. Hutchinson, A.Y. Cho, Science **264**, 553 (1994)
3 R.W. Tkach, A.R. Chraplyvy, J. Lightwave Technol. **4**, 1655 (1986)
4 N. Schunk, K. Petermann, IEEE J. Quantum Electron. **QE-24**, 1242 (1988)
5 T. Kurosaki, T. Hirono, M. Fukuda, IEEE Photon. Technol. Lett. **6**, 900 (1994)
6 M. Fukuda, *Optical Semiconductor Devices* (Wiley, New York, 1999)
7 R. Lang, K. Kobayashi, IEEE J. Quantum Electron. **QE-16**, 347 (1980)
8 D. Lenstra, B.H. Verbeek, A.J. Den Boef, IEEE J. Quantum Electron. **QE-21**, 674 (1985)