ガスセンシング用分布帰還型半導体レーザ

Distributed Feedback Laser Diodes for Laser Gas Sensing

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1 INTRODUCTION

Tunable diode laser absorption spectroscopy (TDLAS) have many advantages for monitoring trace amounts of gases when compared to conventional methods of detection such as mass spectroscopy, gas chromatography, or Fourier transform infrared absorption. The advantages include compact size, remote sensing (safety from explosions), in-situ monitoring, no need for pre-treatment of the gas sample, and little interference from absorption bands of constituent gas species. One of the limiting factors of TDLAS is the wavelength of the laser diodes. Most gas species of interest in combustion and environmental measurement applications have strong absorption bands due to the fundamental molecular vibrations in the mid-infrared region. However, the laser diodes available for this wavelength region, such as the quantum cascade, the lead-salt, or the antimonide-based laser diodes, still have problems to overcome, for example, low output power, need for liquid nitrogen cooling, and poor reliability.

Although the wavelength of InP-based lasers have a practical limit of 1,200 nm to 2,000 nm, high-performance and reliable devices developed for optical fiber communication systems are available. Moreover, recent progress in strained multiple quantum well (MQW) technology, as well as signal processing technology, has made it possible to detect a wide range of gases with sufficient sensitivity for practical applications using InP-based distributed feedback laser diodes (DFB-LD)[1-3] .

In this report, the characteristics of the 1,550-nm, 1,650-nm, and 1,800-nm wavelength DFB-LDs are discussed. These wavelength cover the absorption region of gases such as CO, CO2, CH4, HCl, and NOx as shown in Fig.1[4, 5] . Methane gas detection using the 1,650 nm DFB-LD, with sensitivity up to 100 ppb-m, is demonstrated. The detection method is the either the differential absorption technique or the second harmonic detection technique.

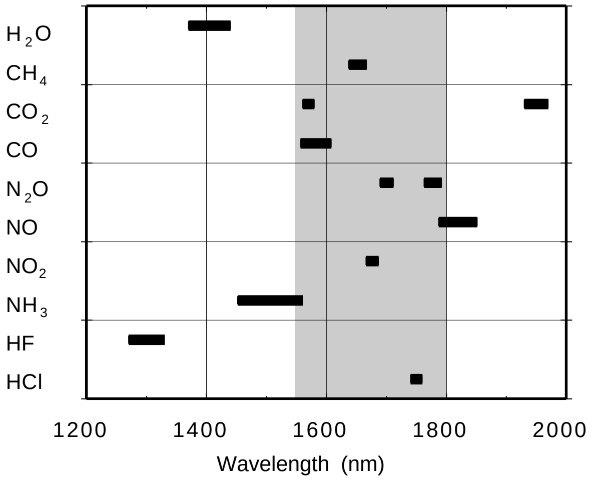

Fig. 1 Absorption wavelength of various gases

2 DEVICE CHARACTERISTICS

The DFB-LDs are buried-heterostructure index-coupled DFBs fabricated by a conventional four step epitaxial growth sequence; the growth of the active region, the cladding layer after first order grating fabrication, and two buried-heterostructure (BH) growth steps. Figure 2 shows a schematic diagram of the device structure. The active region of the DFB-LDs are strained MQW, with

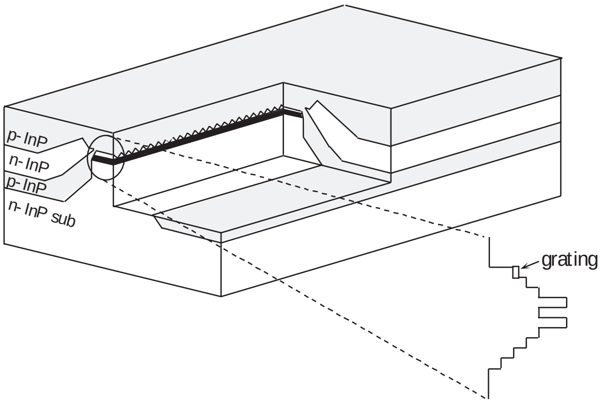

Fig. 2 Schematic structure of DFB-LD

compressive strained wells of either InGaAsP (for wavelength 1,650 nm or shorter) or InGaAs (for wavelength longer than 1,650 nm). All epitaxial growth are performed by MOVPE.

Figure 3 shows the spectrum and I-L characteristics of the 1,800-nm DFB-LD. All data are for CW operation at 25 °C. The typical characteristics for the 1,800-nm DFB-LD are power output of 12 mW at 100 mA, threshold current of 20 mA, and slope efficiency of 0.15 mW/mA. Theoretically, it is possible to fabricate DFB-LD anywhere from 1,200 nm to 2,000 nm, the short and long wavelength limits of InP-based LD. The successful development of the 1,800-nm DFB-LD should lead to the fabrication of DFB-LD with even longer wavelength. A summary of typical characteristics for the DFB-LD at various wavelength that we have developed are shown in Table 1. The DFBs typically have a threshold current of 20 mA and spectral linewidth of less than 10 MHz. The output characteristics of the 1,800-nm DFB is comparable to those of DFBs at other wavelengths, although the linewidth could not be determined due to the limitations of the measuring equipment.

The wavelength of a DFB-LD can be tuned either by the temperature of the LD or by the injection current. Figure 4 shows the wavelength tuning characteristics of the 1,650-nm DFB-LD. For the 1,650-nm DFB-LD, wavelength tuning by temperature is 0.1 nm/°C, and wavelength tuning by injection current is 0.003 nm/mA. For gas sensing applications, temperature is used to lock the wavelength to the absorption line, and the current is used to modulate the wavelength as necessary.

Table 1 Typical characteristics of various DFB-LD

Wavelength (nm)	Output* (mW)	Threshold Current (mA)	Slope (W/A)	Linewidth (MHz)	Gas Species[4,5)
1,550	18	20	0.23	5	NH_3, CO
1,650	10	20	0.13	2	CH_4
1,800	12	20	0.15	NA	HCl, NOx

∗Output at 100 mA
NA: not available

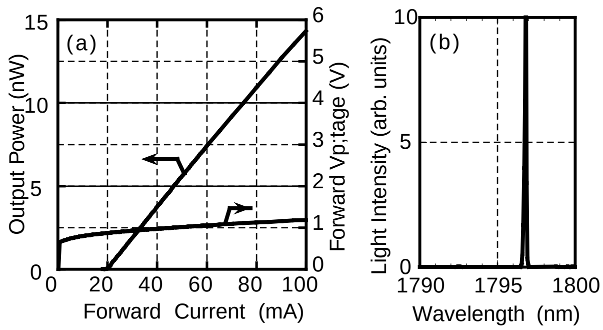

Fig. 3 Characteristics of 1,800-nm DFB-LD
(a) I-L and I-V curve and (b) optical spectrum

The wavelength precision of the DFB-LD is an extremely important parameter for gas sensing applications. The DFB-LD fabrication by MOVPE technology enables the precise control of the wavelength. The actual wavelength of what we generally call 1550-nm band DFB-LD covers the wavelength region from 1530 nm to 1565 nm. As shown in Fig.5, the difference between the requested wavelength (either for gas sensing or optical communication applications) and the actual wavelength of the device is quite small, with a standard deviation of 0.216 nm.

The reliability of these DFB-LDs are also confirmed. The result of the aging test for the 1,550-nm DFB-LD is shown in Fig.6. The aging conditions are automatic power control (APC) at 10 mW and temperature of 70 °C. When the end-of-life for the LD is defined as a 50 % increase in the operating current, and the activation energy is assumed to be 0.4 eV, the mean time to failure at 25 °C is estimated from this result to be 2,240,000 hours.

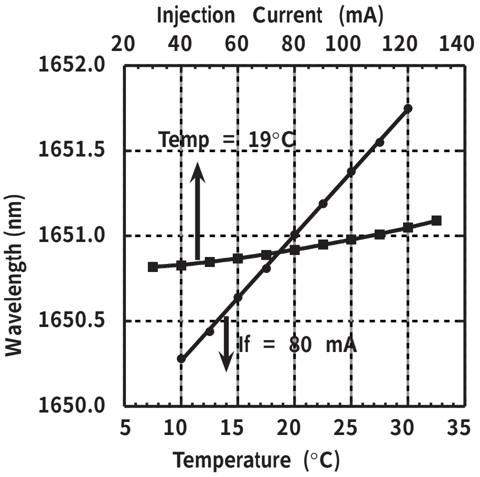

Fig. 4 Wavelength tuning characteristics of 1,650-nm DFB.
Tuning by temperature is 0.1 nm/°C, and tuning by current is 0.003 nm/mA

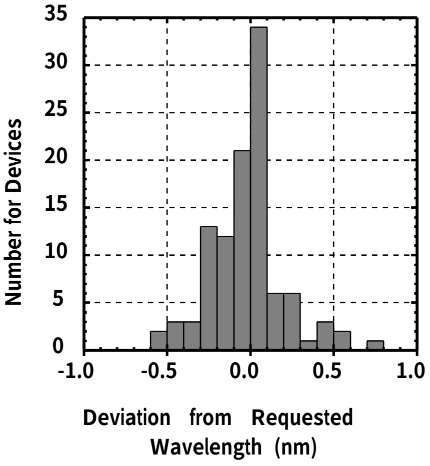

Fig. 5 Wavelength accuracy of 1,550-nm DFB
The standard deviation is 0.216 nm.

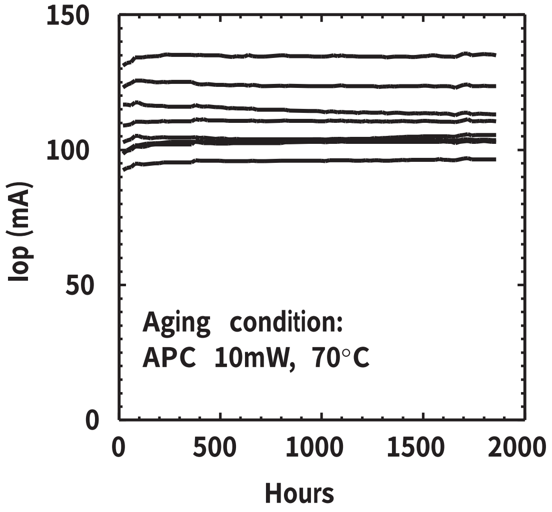

Fig. 6 Aging test of 1,550-nm DFB-LD.
Assuming an activation energy of 0.4 eV,
mean time to failure at 25 °C is 2,240,000 hours.

3 MEASUREMENT OF METHANE

Using the 1,650-nm DFB-LD, methane detection by two methods, the differential absorption technique and the second harmonic detection technique, is demonstrated.

3. 1 Differential Absorption Method[1, 2]

The differential absorption technique requires the emission of two different wavelengths. Two emissions of λ1 and λ1 are alternately emitted by modulating the injection current to the DFB-LD. The wavelength of λ1 is fixed to one of the absorption lines of methane while that of λ2 is controlled to an absorption free wavelength. A wavelength difference of 0.1 nm between the two emissions is sufficient, and this can be achieved by about 30 mA modulation of the injected current to the DFB-LD.

The experimental setup is shown in Fig.7. The emission from the rear facet of the DFB-LD is detected by a monitoring photodiode after passing a 2 cm long gas cell for wavelength stabilization of λ1 emission. The emission from the front facet is coupled into a single mode fiber, and a portion of the coupled power is measured by a monitoring photodiode as the reference signal. The remainder of the coupled power is measured by a measuring photodiode (the sample signal) after passing the detection cell at the midpoint of a 60 km long fiber.

Mixtures of methane and nitrogen gas at various concentration were introduced into the 60 cm long detection cell. Methane gas concentration of 100 ppm was detected with S/N ratio of more than 20. Therefore, the minimum detectable amount of methane is estimated to be less than 5 ppm, assuming the detection limit of S/N ratio is 1.

An important aspect for the DFB-LD in this detection method is the transient temperature fluctuation due to the sudden change in injection current. When the injection current changes, it causes a transient change in the temperature of the LD, which in turn causes a transient wavelength fluctuation. Therefore a delay of a few milli-seconds is necessary before the wavelength stabilizes after the change in injection current.

3. 2 Second Harmonic Detection Method[3)]

The experimental setup of the second harmonic detection is shown in Fig.8. In this method, the wavelength of the laser is stabilized at one of the absorption lines of methane gas. The injection current of the laser is modulated at frequency f. When the laser output passes through the gas cell, the signal intensity at the second harmonic, 2f, will change according to the absorption intensity, that is the gas concentration. Fluctuations in the signal intensity due to factors other than the gas absorption can be canceled out by calculating the signal intensity difference between the modulation frequency f and the second harmonic 2f.

Measurement was made using a cell length of 3.5 cm and methane concentration of 100 ppm. From the S/N ratio of this measurement, it was estimated that a sensitivity of up to 100 ppb-m is possible from this experimental setup.

A key parameter of the DFB-LD in this detection method is the second harmonic distortion. The LD has an inherent distortion due to non-linearity in the I-L curve, and this distortion is a source for excess noise to the second harmonic signal. Minimizing the I-L non-linearity is an important requirement for high sensitivity measurements.

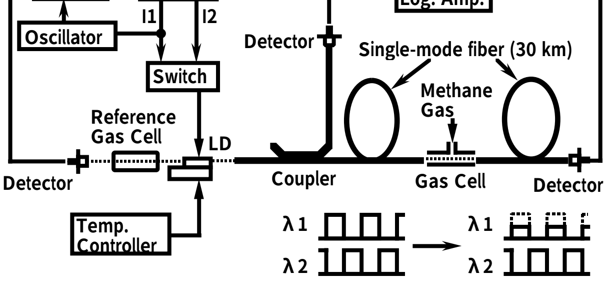

Fig. 7 Schematic diagram of differential absorption method

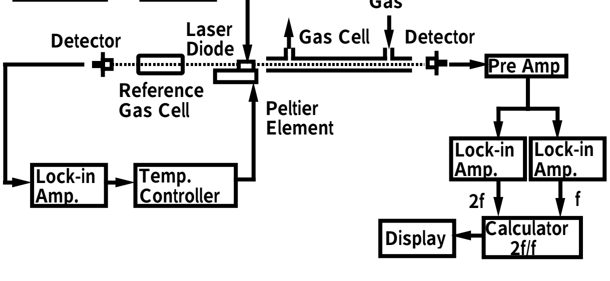

Fig. 8 Schematic diagram of second harmonic detection method

4 CONCLUSION

The characteristics are reported of the 1,550-nm, 1,650-nm, and 1,800-nm wavelength DFB-LDs, which cover the absorption wavelengths of gases such as CO, CO2, CH4, HCl, and NOx. Methane gas detection using the 1,650-nm DFB-LD, with sensitivity up to 100 ppb-m is demonstrated. The successful development of the 1,800-nm DFB-LD should lead to the fabrication of DFB-LD with even longer wavelength, hopefully exceeding 2,000 nm.

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