Gas Temperature Analysis of Laser Gain Medium in a Slab-type Radio-frequency-discharge-excited CO_2 Laser

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An optical method of temperature measurement to analyze CO_2 laser active medium based on near-infrared absorption spectroscopy with a 1.6-μm distributed-feedback (DFB) semiconductor laser is described in this paper. The method was used to measure gas temperatures in the range 400 K to 530 K for discharge electrode distances of 5 and 7.5 mm. Real-time temperature monitoring of CO_2 was achieved by using the DFB semiconductor laser. Such near-infrared absorption spectroscopy has the potential to be a practical method for diagnostic of the active medium of a CO_2 laser.

Key Words: DFB laser, Absorption spectroscopy, CO_2 absorption lines, CO_2 gas temperature

1. Introduction

High-power CO_2 lasers are frequently used in industrial applications such as cutting, welding and microfabrication. Compact, high-power and highly efficient CO_2 lasers can be produced by using systems in which wide discharge electrodes are installed adjacent to each other with a separation of a few millimeters and excitation is performed using a radio-frequency (RF) power source (this kind of system is referred to as a slab-type RF-discharge-excited laser).[1, 2] In such slab-type RF-discharge-excited lasers, the gas medium is discharged to cause lasing, and the medium is cooled by diffusion heat transfer to the adjacent discharge electrodes. In such systems fewer impurities are introduced and stable operation for a longer period of time can be achieved compared with other systems that are cooled by forced-convection during gas exchange.[3] Conventionally, most slab-type RF-discharge-excited lasers have output powers of about 1 kW or less, and most research into optimizing the electrode distance and the RF-discharge excitation aimed to achieve this power level. Recently, these lasers are expected to be used as light sources for generating extreme UV (EUV).[4] Accordingly, researchers and developers have been aiming to achieve the powers of several kilowatts to dozens of kilowatts.

Generally, the performance of a CO_2 laser can be almost completely determined when information on gain measurement and translational temperature is obtained. The temperature of the discharge medium of a slab-type RF-discharge excited laser, which is the focus of this study, is largely determined by the distance between the discharge electrodes that cool the medium. In addition to measuring the gain of the medium, it is important to analyze and monitor the control over the medium temperature. In particular, measuring and checking the medium temperature in a short time period is an effective method for diagnosing faults with the laser system.

The laser medium of high-power CO_2 lasers used in industrial applications such as material processing is a mixture of CO_2, N_2 and He, of which CO_2 accounts for about 10%. Also, gas pressures of between 10 to 50 Torr are used during laser operation. Conventionally, the translational temperature of a continuous-oscillation CO_2 laser is determined by measuring several (e.g., three to five) laser gains for the P-branch laser transition, which have different rotational quantum numbers in the 10-μm-wavelength-region, and then analyzing the results using thermal analysis.[5, 6] This method requires an accurate knowledge of the laser medium's temperature. However, the accuracy of temperature measurements under off-line analysis after performing several gain measurements depends largely on the accuracy of the gain measurements. It is thus unsuitable for real-time assessment of the laser performance. Moreover, there are technical difficulties associated with reproducibly operating a probe laser by mechanically controlling its wavelength using a grating. It is difficult to generalize such a measurement method.

We, therefore, measured an absorption line of CO_2 gas in the 10-μm-wavelength region by laser absorption spectroscopy using a 1.6-μm-wavelength distributed-feedback (DFB) laser in order to determine the laser medium temperature. This absorption is caused by a transition of overtone and combination bands of the CO_2 molecule, and it has a relatively small absorption cross-section of 10^{-23} cm^2. However, sufficient absorbance between 10^{-3} and 10^{-4} can be obtained when the concentration of CO_2 is 10% with the optical path in excess of 0.5 m. It is possible both to analyze temperature by measuring a single absorption transition and to perform on-line analysis. The DFB laser used as the light source is employed in optical communications and it is compact, highly reliable, and has good wavelength reproducibility. Therefore, by generalizing the measurement method, it will be possible to develop a sensor for assessing CO_2 laser system [7-10].

This paper illustrates how the temperature of laser medium can be measured using laser absorption spectroscopy, by using the discharge excitation frequency of 40 MHz as an example.

2. Principles of Measurement

When light having a frequency v passes through a uniform gas medium, the transmitted intensity I_t through a uniform gas medium of length L [cm] to the incident intensity I_0 follows Lambert-Beer law as;

$$\left(\frac{I_t}{I_0}\right)_v = \exp(-k_v L) \tag{1}$$

where k_v [cm^{-1}] is the spectral absorption coefficient. For an absorption transition i

$$k_v = P\chi_{abs} S_i(T)\varphi_v \tag{2}$$

where χ_{abs} is the mole fraction of the absorbing species, $S_i(T)$ [cm^{-2} atm^{-1}] the line-strength of the transition, and φ_v[cm] the line-shape function. The product k_vL is known as the spectral absorbance α_v:

$$\alpha_v \equiv -\ln\left(\frac{I_t}{I_0}\right) = k_v L = P\chi_{abs} S_i(T)\varphi_v L \tag{3}$$

φ_v is the line-shape function normalized over the frequency.

The line-strength, in the unit of cm^{-2}/atm, is then expressed as a function of temperature:

$$S(T) = S(T_0)\frac{Q(T_0)}{Q(T)}\left(\frac{T_0}{T}\right)\exp\left[-\frac{hcE''}{k_B}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$$
$$\times\left[1-\exp\left(\frac{-hc\nu_0}{k_B T}\right)\right]\left[1-\exp\left(\frac{-hc\nu_0}{k_B T_0}\right)\right]^{-1} \tag{4}$$

where h [J s] is Planck's constant, c [cm/s] is the speed of light, k_B [J/K] is Boltzmann's constant, the partition function, $Q(T)$, of CO_2 is taken from HITRAN database,[11), †] T_0 [K] is the reference room temperature, ν_0 [cm^{-1}] is the frequency at absorption line-center, and E'' [cm^{-1}] is the lower-state energy of the transition. The lower-state energy E'' determines the equilibrium population fraction in the lower state as a function of temperature.

Therefore absorption signal on the particular transition are influenced as a function of temperature.

Figure.1 shows the energy levels of a near-infrared absorption transition. When near-infrared absorption spectroscopy is used, absorption is measured between much higher energy levels than the laser transition, which is in the vicinity of 10.6 μm.

A wavelength in the region of the 1.6-μm band was selected to measure an absorption line of CO_2. Concerning this measurement of the CO_2 laser medium, although the line intensity in this region was weak, it was independent of other CO_2 gas absorption lines and it also had little interference from other gas molecular species. This wavelength region was therefore considered to be suitable for accurately measuring the absorption. The absorption line that was measured in this study was between the ro-vibrational energy levels of (0,0,0) and (3,0,1).

Each absorption line has a linewidth of about 1.5 GHz, with Voigt line shapes and it was possible to detect about six transition lines using the current system. To measure one absorption line, we selected the absorption transition (P8) between the rotational quantum numbers J"=8 and J'=7, in which appropriate absorption signals could be obtained. The center wave number of this absorption line corresponds to 6221.477 cm^{-1}. The absorption cross-section at the absorption line is 1.183×10^{-23} cm^2.

Figure 2 shows the relationships between the temperature and the transmission. Transmissions that changed depending on temperature were calculated using the HITRAN database. Based on the measurement conditions (i.e., typical laser gas mixture conditions), the pressures of laser gas is changed between 1.33 kPa add 6.66 kPa, while the CO_2 concentration

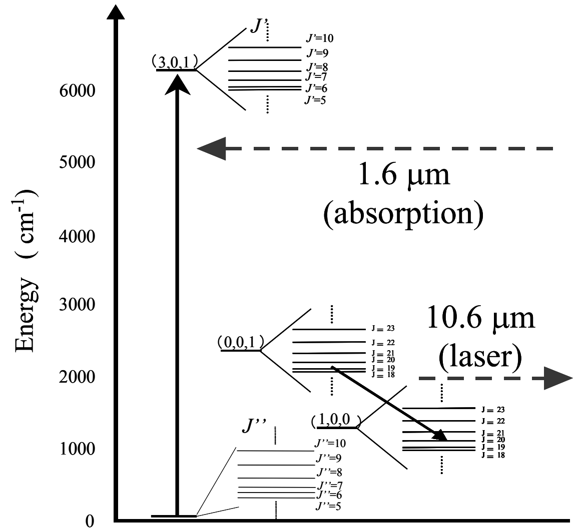

Fig.1 A part of energy levels of the CO_2 absorption transition and CO_2 laser transitions

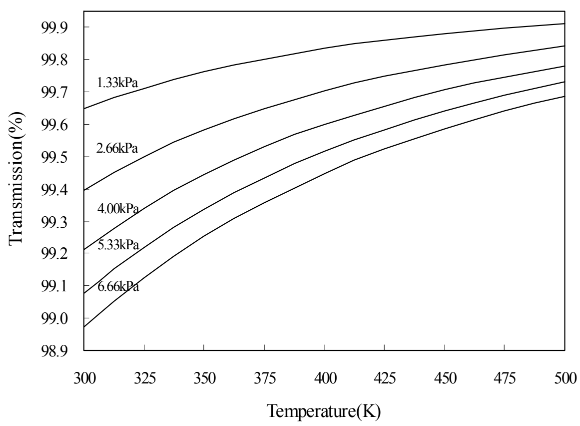

Fig.2 Relationships between the temperature and the transmission of the laser gas medium as a function of gas pressure.

† HITRAN web site: http://cfa-www.harvard.edu/HITRAN/

is taken to be 10% and the absorption light path length was taken to be 1.38 m. The absorption signals are calculated to be up to 1% at room temperature. On this transition, the absorption is reduced to 0.2~0.5 % at elevated temperature of around 500K.

3. Measurement Method and Experimental System

Figure 3 shows a configuration diagram of the slab-type RF-discharge-excited CO_2 laser used in this study. The experimental system principally consists of an oscillator main body, an RF power source, cooling equipment and a gas mixer. In the main body of the laser unit, two plate electrodes are installed adjacent to each other within a chamber and laser excitation is performed by high-frequency discharge between the electrodes. The electrodes were 344 mm long and 50 mm wide. In this structure, the distance between the electrodes can be varied between 5 mm and 7.5 mm. The RF power source fires a RF discharge by applying an alternating voltage with high frequency of 40 MHz between the electrodes. Furthermore, since the output impedance of the RF power source is 50 Ω, in order to transmit high-frequency electric power to an arbitrary load, the load impedance (mainly that of the electrode plates within a vacuum chamber) needs to be matched. Therefore, a matching box was used to stably supply RF electric power to the electrode plates. It performs matching adjustment of the load impedance and the output impedance of the high-frequency power source. The gas mixer is used to control the gas pressure and the vacuum in the vacuum chamber. The cooling equipment circulates water within the chamber to cool the discharge medium and to increase the cooling efficiency.

Figure 4 shows a schematic diagram of the experimental system used for the near-infrared laser absorption spectroscopy measurements. A DFB laser module (NTT Electronics, Model: NLK1L5EAAA) was used as the light source for measuring absorption. It is subject to current modulation to measure the absorption line, and it is possible to measure the density and temperature of the gas. An InGaAs photodiode detector was used for light detection in the measurement system, while a calcium fluoride window with wedges was used as a window for the laser cavity. Interference at the window was suppressed by the wedges. The output signals from the detector were observed using an oscilloscope. The data was stored on a computer, and analysis of the absorption line was performed.

4. Results and Discussion

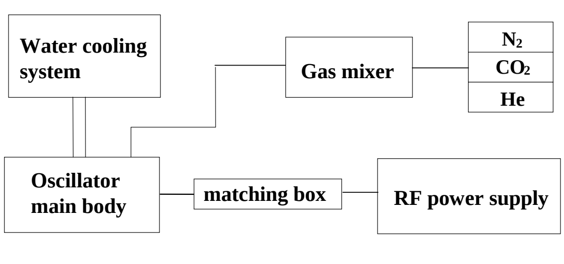

Fig.3 System Configuration of the slab-type RF-discharge-excited CO_2 laser

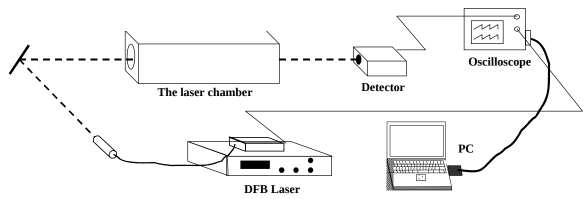

Fig.4 Schematic diagram of the optical measurement system

In the preliminary study before discharge experiments, the verification of measured temperatures by the optical measurement method in comparison with that by thermocouples was performed at elevating temperatures up to 373K in the static gas cell with an electric heater. The measured temperatures showed excellent agreement within ±3K.

Figure 5 shows the changes of CO_2 absorption with and without RF discharge excitation. The measurement conditions in the main oscillator body at that time were a gas mixing ratio of CO_2:N_2:He = 1:1:8, an input electric power of 0.5 kW, and a gas pressure of 2.66 kPa. We then estimated the temperature by comparing the calculated transmission with the experimentally measured transmission.

Figure 6 shows the results of the CO_2 laser medium temperature measurement. When the results for the electrode plate distances of 5 and 7.5 mm were compared, the electrode plate distance of 7.5 mm was found to result in higher temperatures. Furthermore, the temperature increased when the electric power was increased for both distances between the electrode plates. In the CO_2 laser, since the excitation transition is a transition between energy levels that are close to the ground level, when the gas temperature reaches about 500 K or more, the low energy level is thermally excited and the efficiency of the oscillation deteriorates dramatically. Therefore, when the input electric power exceeds a range of 1 kW to 1.5 kW, allowable temperatures reach the limit of obtaining gain.

5. Conclusion

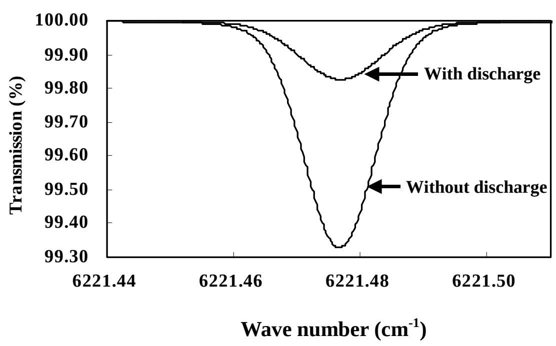

Fig.5 CO_2 absorption lines during RF discharge excitation

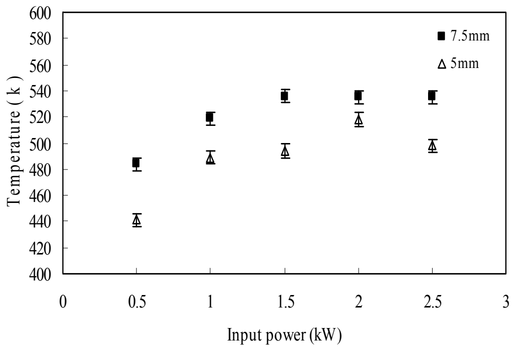

Fig.6 Relation between temperature and input power

In this study, temperatures in a CO_2 laser medium were measured by using laser absorption spectroscopy. By using a 1.6-μm DFB laser, it was possible to determine the temperature in the CO_2 laser medium during discharge. When the results for an electrode plate distance of 5 mm and those for 7.5 mm were compared, it was revealed that using an electrode plate distance of 7.5 mm resulted in higher temperatures in the laser medium. Compared with the method in which medium temperature is analyzed by measuring the small signal gain on CO_2 laser transitions, the measurement accuracy was improved and the measuring time was drastically shortened. This measurement method is capable of not only measuring the temperature and concentration of CO_2 gas, but also detecting other gases like CO and H_2O. Accordingly, this method is anticipated to be used as a failure monitoring system of gas medium for CO_2 lasers in the future.

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