Sensor development of CO_2 gas temperature and concentration using 2ｍm DFB semiconductor laser

Y. Ikeda[1], G-M. Choi [2], D-H. Chung[1], K. Fukuzato[1] and T. Nakajima[1]

[1]*Department of Mechanical Engineering, Kobe University*

Rokkodai, Nada, Kobe 657 JAPAN

[2]*NEDO Research fellow,Osaka university*

2-1 Yamada-Oka, Suita, Osaka 565-0871 JAPAN

Abstract

A laser diode absorption method to measure CO_2 gas temperature and concentration was developed using a 2.0μm DFB(Distributed Feedback) laser. The optics was fabricated in a pigtail fashion and the entire optical interferometer filter, and a fiber ring interferometer was all developed for the-system. The measurement sensitivity at different sweep frequencies and pre-set CO_2 concentrations was evaluated using a test cell. The results showed that the system has a 2% error over a wide range of operating frequencies and concentration measurements were made close to the flame front of a premixed laminar flame. The instantaneous gas flame temperature measured using a 2-line absorption scheme was compared to that determined with a thermocouple.

The application of the developed CO_2 sensor for exhaust gas measurement in a practical engine was done. The results indicate the time variation of the absorption lines for 2 wavelength coincided each other that demonstrated the CO_2 variation period could be measured.

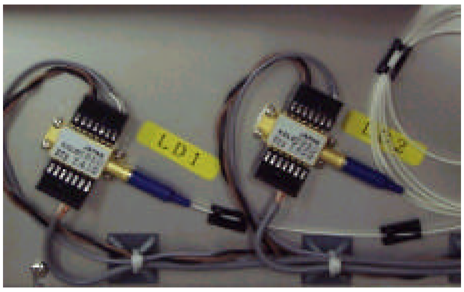


Fig. 1 Pigtail DFB laser module

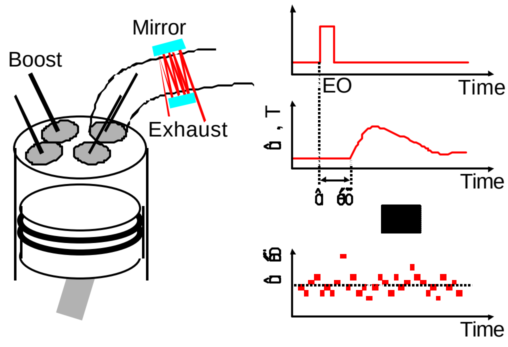


Fig. 2 The Application to 2 stroke engine measurement

1 Introduction

It is required to measure gas temperature and its concentration in a real time and control in a practical combustion system for energy utilization and reduction of CO_2 gas. One of the problem in SI engine development is exhaust gas treatment in cold starting, that is, much UHC and undesirable matters are contains in an exhaust gas because a catalyst is not warm up yet. In addition, the flow dividing ratio of EGR in an each cylinder is also not the steady, hard to control and monitor. In order to solve these problems and develop a new device, the real time monitoring system of temperature and concentration of exhaust gas should be performed so as to control intake flow rate and its fuel/air ratio with high temporal resolution. Although, CO_2 is a major gas species in combustion, the conventional measurement technique could not allow us to measure those over 1kHz in response time. If CO_2 temperature and concentration in exhaust pipe and in-cylinder can be measured over 10kHz, new techniques to control engine combustion can be achieved.

There are various researches on laser absorption methods. The targeted gas species were H_2O [e.g. Hanson et al., 1993 and Kessler et al., 1996], NO [e.g. Tanoura et al., 1999 and Sonnenfroh et al., 1997], NO_2 [Mihalcea et al., 1996], CH_4 [Hanson et al., 1996 and Chou et al., 1996], CO [Skaggs et al., 1996 and Mihalcea et al., 1998], and CO_2 [Mihalcea et al., 1998 and Sonnenfroh et al., 1997]. Those developments were conducted using semiconductor laser used in telecommunication. Then, the wavelength was about 1.3-1.6μm, in which much absorption line can be existed [Rothman et al., 1996]. But the strength of absorption line is not so strong in comparison of that in mid-infrared absorption. To increase sensitivity and reduce measurement path length, a longer wavelength is needed even though this semiconductor laser development itself is hard task. The stronger absorption line can be found in the longer range, e.g., the absorption line strength around 2 micron is about 70 times stronger than that of around 1.5 micron. Because of the telecommunication purposes, there is no need to develop the semiconductor laser of this longer wavelength, furthermore, optics should be developed for this wavelength such as optical fiber, isolator, optical filter receiving optics and so on.

This laser absorption method based upon the Lambert-Beer theory [Webber et al., 2000] is line-of-sight so that it is difficult to measure gas temperature and its concentration at a local point and the measured results are based upon the averaged in optical path length. In spite of this defect, this method can detect temperature and concentration at very high rate over 10kHz and non-intrusive. It is a trade-off relationship. Computer tomography technique might contribute for two-dimensional profiles of temperature and concentration [Kessler et al., 1998 and Tomiainen et al., 1996].

The purpose of this study is to develop non-intrusive CO_2 gas sensor for temperature and concentration using laser absorption method for researches of combustion, engine, mixing enhancement, CO_2 reduction. For making the sensor robust, mobile, low cost, easy handling and so on, a DFB (Distributed Feed-back) laser was developed here. In order to have high sensitivity, the DFB laser of 2μm was fabricated with optics needed such as isolator, ring interferometer, beam splitter, optical filter, and optical fiber for 2.0μm range. The evaluation tests were examined in a heated constant volume cell, laminar premixed flame and applications for practical SI engine. In this paper, the applicability to SI engine research is focused on.

2 Measurement Principle

The transmission of narrow line width radiates at frequency ν through a uniform and Beer-Lambert relation may describe medium of length L.

$$T = (I / I_0)_n = \exp(-K_n L) \tag{1}$$

Where, T is the spectral transmittance of the medium, I_ν is the spectral intensity at L, I_0 is the incident intensity, and K_ν is the spectral absorption coefficient. The spectral absorption coefficient is

$$K_n = S(T) P_{abs} \Phi_n \tag{2}$$

where, S(T)($cm^{-2}atm^{-1}$) is the line strength, P_{abs} (atm) is the partial pressure of the absorbing species. Φ_n is the frequency dependent line-shape function.

Integrating Eq. 2 over an entire line shape yields an expression for the line intensity, K, and multiplying absorption coefficient by absorption path length becomes absorbance.
Thus, integrating absorbance over an entire line shape, A, yields

$$K = \int_{-\infty}^{\infty} k_n dn = S(T)P_{abs} \tag{3}$$

$$A_i = \int_{-\infty}^{\infty} k_{n,i} L dn = S_i(T) L P_{abs,i} \tag{4}$$

Thus, the partial pressure of a given species may be determined from the measured line intensity and Eq. 3 if the temperature, total pressure and line strength are specified.
The ratio, R, of partial pressure $P_{abs,i}$ / $P_{abs,j}$ yields an expression.

$$\frac{P_{abs,i}}{P_{abs,j}} = \frac{A_i}{A_j}\frac{S_j(T)}{S_i(T)} = 1 \tag{5}$$

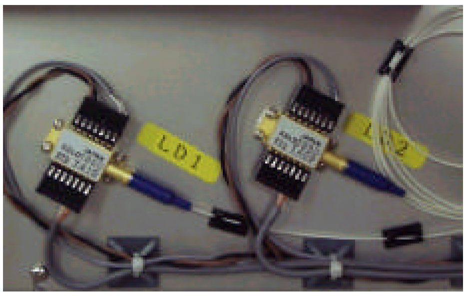
Where, indices j and I denotes the individual transitions within absorption features 1 and 2, respectively. This ratio yields an expression independence of line shape and becomes a function of temperature.
The temperature-dependent line strength of transition I is given by

$$S(T) = \left(\frac{8p^3 NL}{3hc}\right) n_0 \left(\frac{273.15}{T}\right) R \left[\frac{8}{Q(T)}\right]\left[1-\exp\left(\frac{-hcn_0}{kT}\right)\right]\exp\left[\frac{-hcE''}{kT}\right] \tag{6}$$

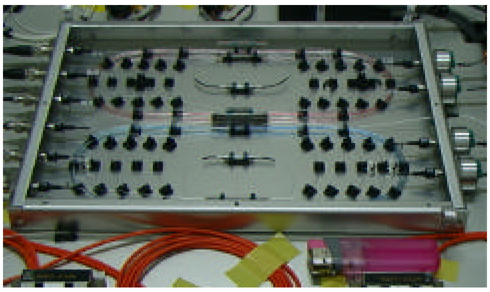
Where, N_L is Loschmidt's number[cm^{-1}], e[esu] and m_e[g] are the electron charge and mass, respectively; c[cm/sec] is the speed of light; Q(T) is the molecular partition function; h[Js] is Plank's constant; k[JK^{-1}] is the Boltzmann's constant; $g_{1,i}$, E_i", and f_i are the lower-state degeneracy, lower-state energy level and the oscillator strength for the transition, respectively.
CO_2 concentration is then determined from the measured absorbance using the known line strengths at the measured temperature.

3 Sensor development

A DFB laser near 2.0μm was developed in pigtail fashion (with isolator and fiber link) as shown in Fig. 3. The developed fiber ring interferometer was also shown in the same figure. The targeted wavelength for CO_2 was determined by HITRAN Database [Rothman et al., 1996]. There are many absorption lines around 2.0μm as shown in Fig. 4 and these strength is over seventy times higher than those found around 1.5μm.



Pigtail DFB laser moduke



Developed fiber ring interferometer

Fig. 3 DFB laser

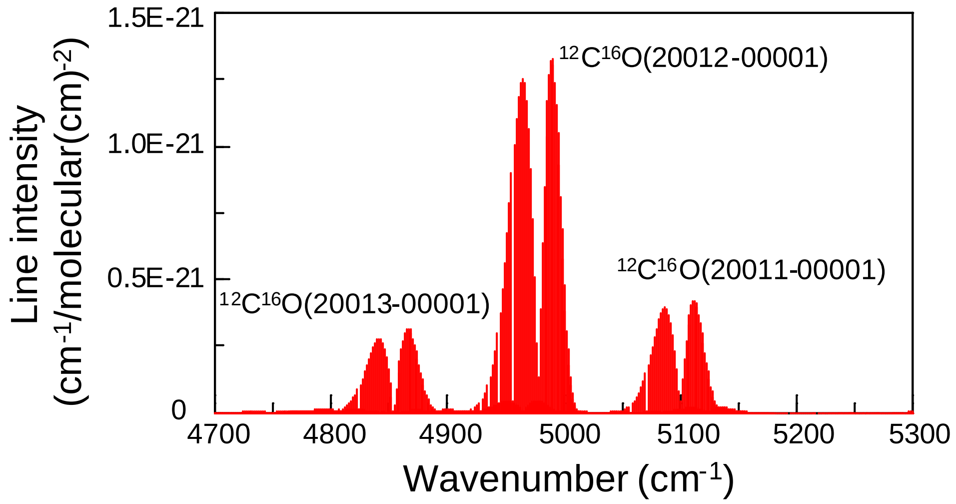


Fig. 4 CO_2 absorption line near 2000nm at 296K(HITRAN96,98)

There are also H_2O absorption lines which cause overlapping problem in the measurement so that a special attention of wavelength selection was taken into account. The wavelength of the developed DFB lasers were 1996 and 2050μm, respectively. We used R(50) and R(30) pair and R(48) and R(32) pair for two-color temperature calculation. The sensitivity can be estimated as shown in Fig. 5 for wide temperature range.

A schematic layout of developed CO_2 sensor system is shown in Fig. 6 with a direct photo of the sensor box. There are two DFB lasers (5mW), the output of each laser was split into three fibers, one for direct absorption measurement, one for reference beam and the other for fiber ring interferometer (FSR=1.09GHz [e.g. Arroyo et al., 1994 and Baer et al., 1994]). The direct absorption measurements are carried out using two optical fibers, one from sensor box and the other is for receiving optics, which is connected to beam splitter (1996/2050) and signal processing.

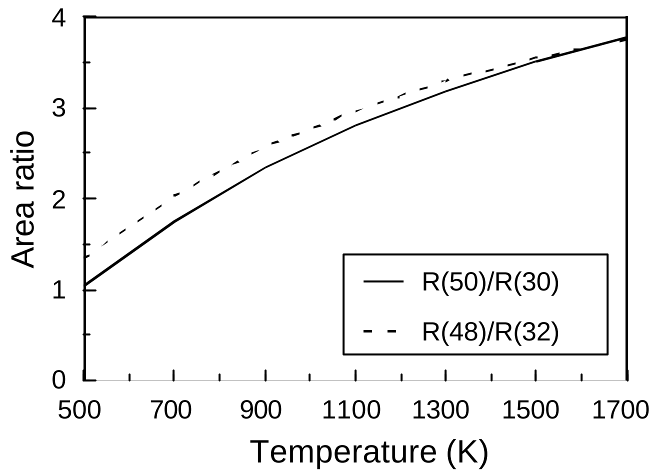


Fig. 5 Temperature dependence of the integrated intensity ratio

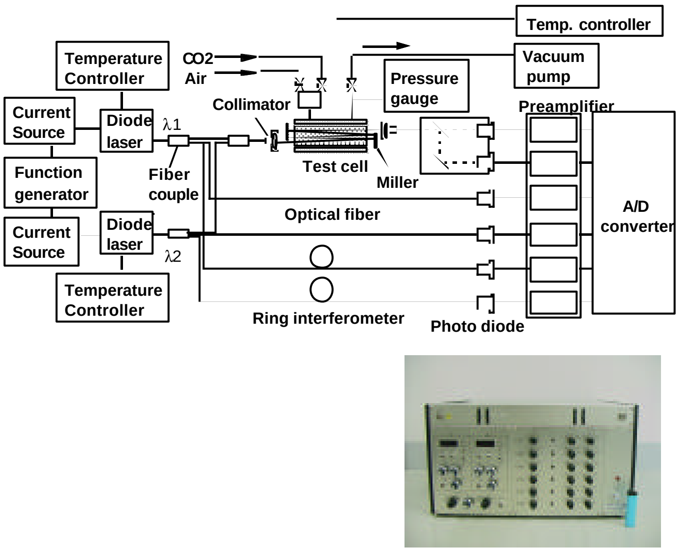


Fig. 6 Schematic layout of developed sensor system

4 Measurement

Direct absorption of CO_2 gas in a cell was measured using these two lasers as shown in Fig. 7 in comparison with HITRAN database. There is no significant difference in 1996nm, while large discrepancy was observed around 2050nm. This is due to that HITRAN database needs some correction in a certain condition, especially high temperature. We have to measure these absorption line strength by ourself for various temperature range in order to increase measurement accuracy.

Measured signals in a cell are shown in Fig. 8 for various sweep frequency. A ramp signal was used in this study. It is clearly observed that the absorption signals were measured in all repetition rates up to 20kHz. The top figures are for 1996nm, the second are for 2050nm, and then the bottoms are from the fiber ring interferometer.

The CO_2 concentration measurement was examined in a pre-set cell in cell in which CO_2 concentration was set up by controlling supply CO_2 pressure. Fig. 9 indicates the comparison of the pre-set and the measured. The accuracy was about less than 3% in all range. It is needed to examine more detail accuracy by adjusting accurate CO_2 supplying. But in this experiment, we assumed that the developed CO_2 sensor could be applicable for practical system.

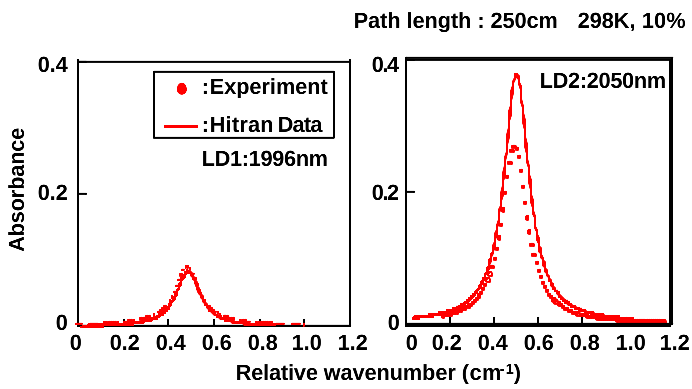


Fig. 7 Direct absorption measurement using developed two DFB laser

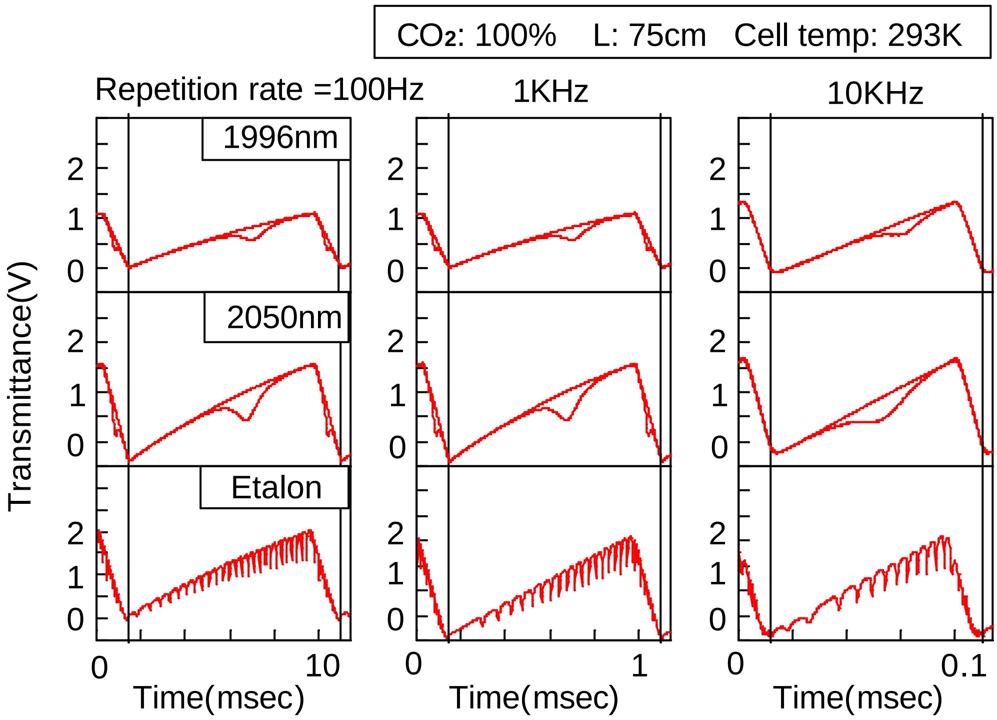


Fig. 8 Measured signals for variations sweep frequency

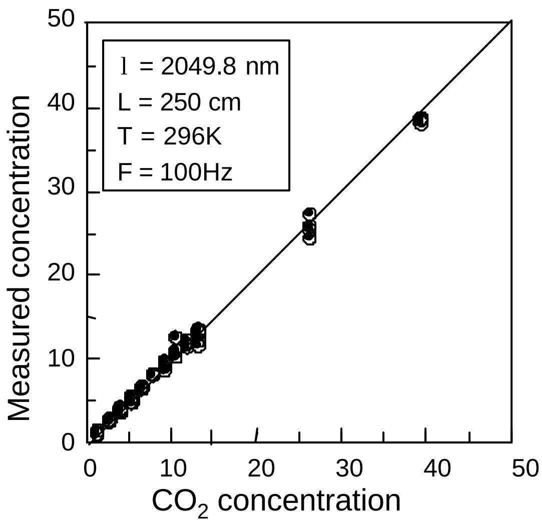


Fig.9 Comparison of measured CO2 concentration to absolute value

An actual temperature measurement was carried out in premixed laminar flame [Kojima et al., 2000], in Fig. 10. The results indicate that the CO_2 sensor can measure flame temperature and exhaust gas temperature. The measurement accuracy will be examined and the resolution is modified in the next paper.

Because one of our purposes in this sensor development was to detect CO_2 temperature and concentration in time, for cycle-resolved temperature variation in a practical engine, then these two experiment results were sufficient enough, even though the accuracy in temperature was not well improved.

Figure 11 illustrates how this CO_2 sensor can be applicable for exhaust gas measurements. The temperature in exhaust pipe can be increased by combustion gas and its time delay and temperature increase are parameter to evaluate engine combustion status. This kind of application can be done to measure intake gas temperature, exhaust gas temperature and in-cylinder gas temperature and CO_2 concentration due to self-EGR ratio, for conventional SI engine and new HCCI engine.

The CO_2 measurements were done in an exhaust pipe of practical two-stroke engine of 100cc [Ikeda et al., 1994], in Fig. 12. The absorption measurements results are shown in the same figure, which demonstrate some level of valley. The measurement absorption area is small but clearly observed. This CO_2 sensor can measure up to 20kHz.

This CO_2 variation in time in the exhaust pipe was measured as shown in Fig. 13. In this experiment, the engine was operated at 3000 rpm. The target of this measurement was to detect CO_2 variation in time, accuracy of the CO_2 measurement was not sufficient enough but it was found to be applicable. The results were before calculation for temperature and concentration at 1996nm and 2050nm. It was found that these two time variations had the same period. The accuracy will be improved in the next paper. But the applicability of this CO_2 sensor in practical engine combustion diagnostics was proven.

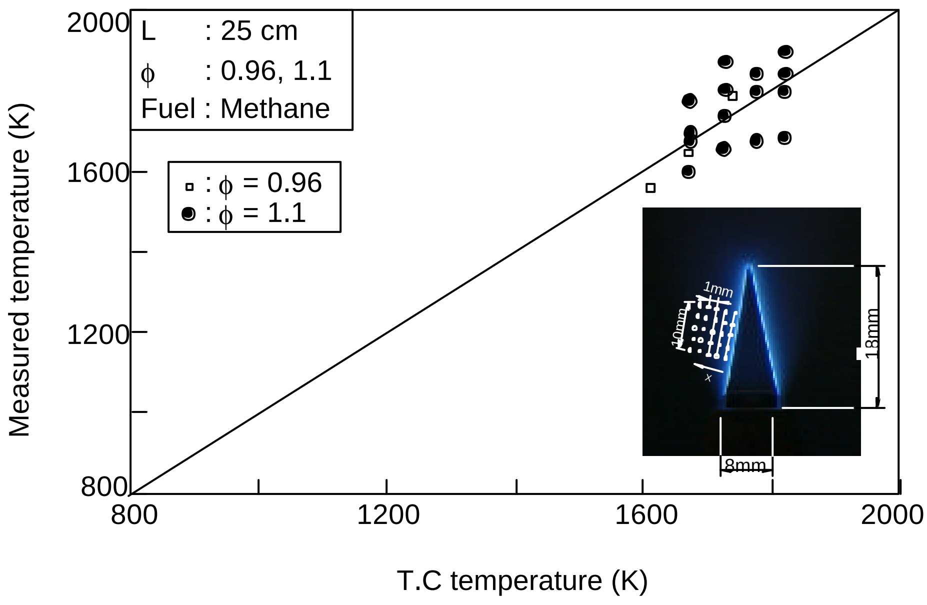


Fig.10 Comparison of temperature measured in the CH4 + air flame Determined from 2-color method and type-R thermocouple

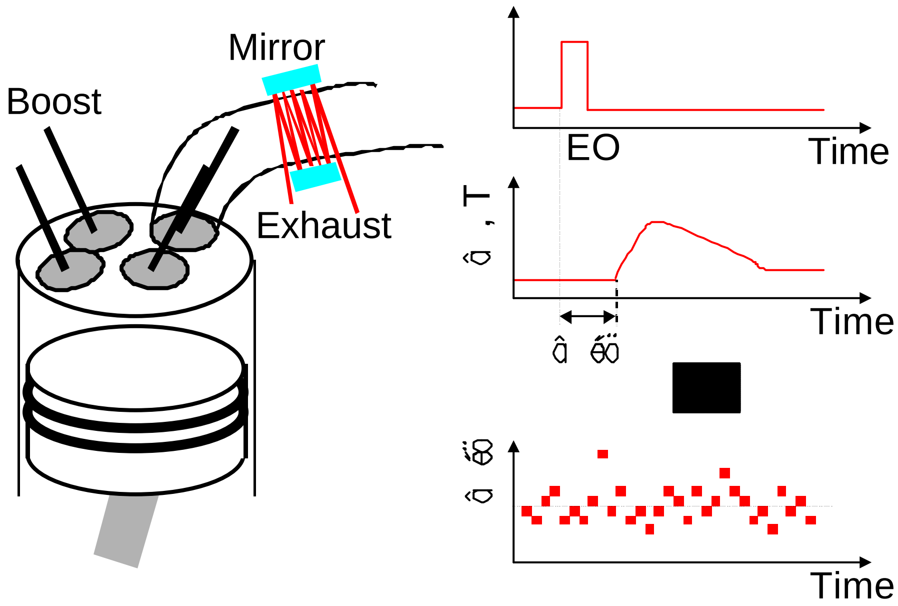


Fig. 11 Gas temperature and hot gas arrival time

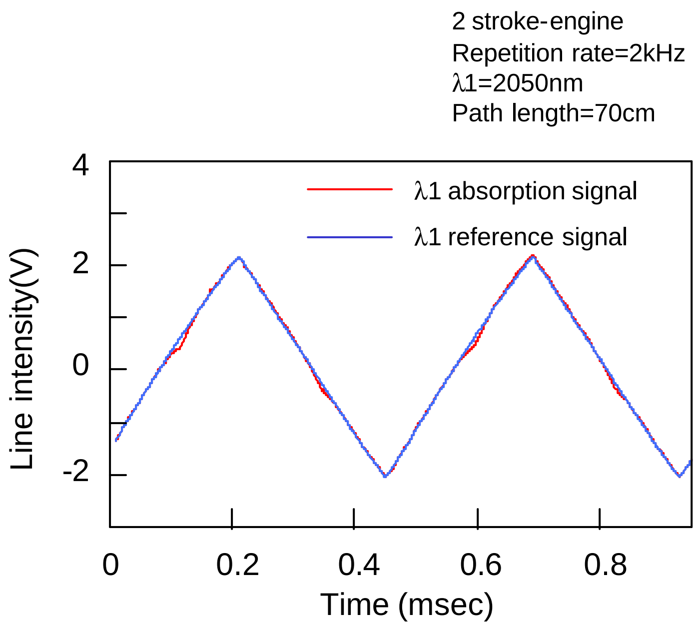


Fig. 12 Direct absorption measurement in exhaust pipe gas of 2 stroke engine

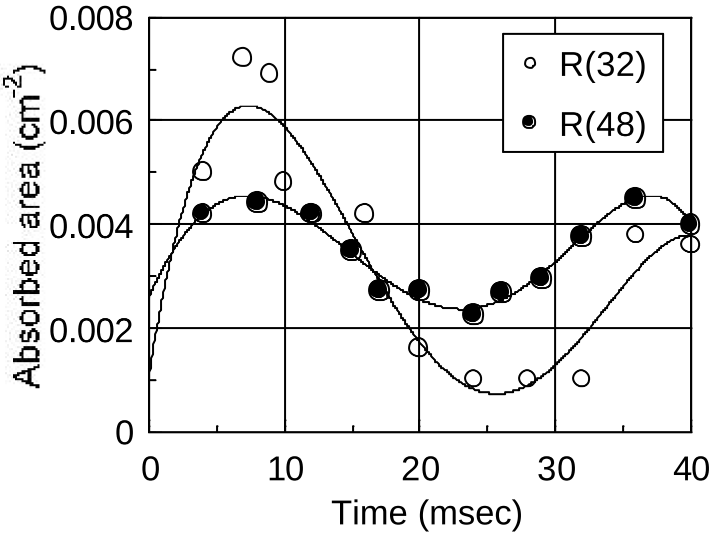


Fig. 13 Absorbed area change in exhaust pipe gas of 2 stroke engine

5 Conclusion

We have developed the laser absorption sensor system of CO_2 gas temperature and concentration using 2.0μm DFB laser. The system evaluation was done in a cell for various CO_2 gas concentrations. This sensor was examined with laminar flame burner and application for practical exhaust gas measurement of engine. The measured results indicate that this sensor can measure CO_2 gas temperature and concentration with 5% uncertainty. It was found that the cycle–resolved CO_2 measurement could be performed in engine combustion diagnostics.

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