ЛАЗЕРНАЯ ФИЗИКА И ТЕХНИКА

ОПРЕДЕЛЕНИЕ ТЕМПЕРАТУРЫ ГАЗА С ПОМОЩЬЮ ДИОДНОГО ЛАЗЕРА С РАСПРЕДЕЛЕННОЙ ОБРАТНОЙ СВЯЗЬЮ, РАБОТАЮЩЕГО НА ДЛИНЕ ВОЛНЫ ПОГЛОЩЕНИЯ КИСЛОРОДА 760 НМ

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Предложено использование метода прямой абсорбционной спектроскопии для мониторинга температуры газа в трубчатой камере сгорания в области температур 300–900 К с интервалом 100 К. Метод измерения основан на существовании температурной зависимости поглощения на двух спектральных линиях. Сведения о температуре газа могут быть получены из данных об отношении интегральных спектральных областей поглощения кислородом излучения лазерного диода с распределенной обратной связью, излучающего в области 760 нм. В сравнении с термопарными методами этот подход позволяет обеспечить также временнóе разрешение. Результаты показывают, что точность измерений низких температур превышает таковую высоких. В дальнейшем предполагается повысить точность метода и продемонстрировать полезность лазерных абсобционных датчиков для одновременной активной диагностики и оптимизации процессов сгорания.

Ключевые слова: *прямая абсорбционная спектроскопия, температура газа, поглощение пар спектральных линий, лазерный диод с распределенной обратной связью.*

DETECTION OF GAS TEMPERATURE USING A DFB LASER AT O_2 ABSORPTION WAVELENGTH – 760 NM

© 2016 **Z.-R. Zhang**[*], doctor of optics; **P.-S. Sun**[*], graduate student; **H. Xia**[*], doctor of optics; **Z. Li**[*], graduate student; **T. Pang**[*], graduate student; **B. Wu**[*], doctor of optics; **X.-J. Cui**[*], doctor of optics; **F.-Z. Dong**[*,**], doctor of optics

[*]Anhui Provincial Key Laboratory of Photonic Devices and Materials, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, China
[**]School of Environment Science and Optoelectronic Technology, University of Science and Technology of China, Hefei 230026, China

Corresponding author: fzdong@aiofm.ac.cn
First author: zhangzr@aiofm.ac.cn

The direct absorption spectroscopy for gas temperature monitoring in a tube furnace are proposed over the temperature range 300–900 K with interval 100 K. This detecting technique is based on the relationship between two lines' absorption strength and temperature. The gas temperature can be inferred from the ratio of integrated spectral area of the oxygen absorption features with a DFB diode laser near 760 nm. Compared with the thermocouple measured results, the direct absorption spectroscopy approach also provides a temporal resolution. The results show that the accuracy is better at low temperatures than at high temperatures. So in the future, we hope to improve the detection accuracy and demonstrate the utility of the diode laser absorption sensors operating for active combustion diagnostics and optimizations, simultaneously.

Keywords: *direct absorption spectroscopy, gas temperature, line pair absorption, DFB laser.*

OCIS codes: 280.4788, 300.6380, 300.1030

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Introduction

The determination of parameters in combustor is generally relevant to understand its combustion progress. Unfortunately, due to extremely harsh combustion environments (high temperature, high dust and high vapor), many traditional devices, such as thermocouples, have many disadvantages and limited lifetime [1]. As results, non-intrusive, remote-sensing diagnostics are desirable for characterizing the parameters in high temperature. Diode laser absorption-based sensors can offer significant opportunities and advantages for making sensitive, selective and fast in situ measurements. Also, it has been a developing field over the past decade, such as gaseous monitoring [2, 3], velocity measurement [4], food safety [5, 6], medical diagnosis [7, 8], vehicle emission monitoring [9, 10] and engine efficiencies[11, 12].

This paper will cover the theoretical aspects and the temperature detecting experiments using direct absorption spectroscopy (DAS) techniques.

Molecular oxygen plays a fundamental role in a large variety of natural and industrial process. Atmospheric transmission in the vicinity of the $O_2 X^3\Sigma_g^- \rightarrow {}^{b1}\Sigma_g^+$ near 760 nm absorption feature is important for remote sensing and military applications. And the fast current scanning "finger mark" lines capabilities of laser diodes are exploited to achieve the gas temperature monitoring in the tube furnace under the experimental conditions. Henceforth, the wavelength pair selected rules will be denoted as section 2. And the laser is controlled by the homemade circuit boards to lock the absorption wavelength and scanned by the digital signal board. Also, this paper presents the design of the scanned-wavelength temperature sensor for experiments and demonstrates in a laboratory tube furnace in section 3. We present the results of temperature measurements with the main emphasis on the experiment system and algorithm in section 4. The details of our initial measurements and preliminary results will be discussed.

1. Basic principle

The fundamental theoretical principle for absorption spectroscopy is the Beer-Lambert law. It describes the relationship between gas concentration X_{abs}, optical length L [cm], the outgoing $I(\nu)$ and ingoing $I_0(\nu)$ laser light intensities through

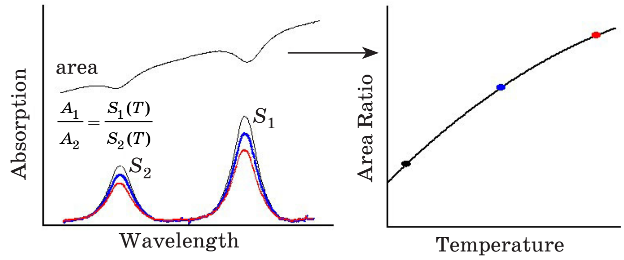

Fig. 1. Temperature inferred from direct absorption area ratio of line pair transitions.

a gas sample, respectively. As Fig. 1 demonstrated, the fractional transmission is

$$\tau_v = \left(\frac{I(v)}{I_0(v)}\right) = \exp(-k(v)L) = = \exp(-PX_{abs}S(T)\phi(v)L), \quad (1)$$

where $k(\nu)$ [cm^{-1}] is the spectral absorption coefficient which is equivalent to an absorption per unit length, $k(\nu)L$ represents the spectral absorbance, P [atm] is the static gas pressure, $\phi(\nu)$ is the gas lineshape function at frequency of ν. The lineshape function, being normalized, will be unity by definition when integrated across all frequency space

$$\int_{-\infty}^{+\infty} \phi(v)dv = 1.$$

And $S(T)$ is the line intensity and can be expressed in term of known line strength at reference temperature $T_0 \approx 300$ K

$$S(T) = S(T_0)\frac{Q(T_0)}{Q(T)}\left(\frac{T_0}{T}\right)\exp\left[-\frac{hcE'''}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]\times \times\frac{1-\exp\left(-\frac{hc\nu_0}{kT}\right)}{1-\exp\left(-\frac{hc\nu_0}{kT_0}\right)}. \quad (2)$$

Except at high T, $\{1-\exp(-hc\nu_0/(kT_i))\}$ is very nearly equal to unity and can be neglected, h [6.63×10^{-34} J s] is Plank's constant, c [3.0×10^{10} cm/s] is speed of light, k [1.38×10^{-23} J/K] is Boltzmann's constant, E'' [cm^{-1}] stands for the low state energy for the given wavelength, $Q(T)$ is the molecular partition function and can be expressed as the following polynomial of temperature

$$Q(T) = a + bT + cT^2 + dT^3. \quad (3)$$

The coefficients of the polynomial expression for various species are included in the HITRAN08 database [13]. The two-line absorption technique is the most widely used method for temperature measurement in modulation spectroscopy. The gas temperature can be inferred from the measured ratio of integrated absorbance for two different temperature-dependent wavelengths. Because the two integrated absorbances are obtained with the same gas pressure, temperature and same path length, the ratio of these two integrals reduces simply to the ratio of line intensities, which eq. (2) is written as

$$T = \frac{\frac{hc}{k}\left(E_2'' - E_1''\right)}{\ln\frac{A_1}{A_2} + \ln\frac{S_2(T_0)}{S_1(T_0)} + \frac{hc}{k}\frac{\left(E_2'' - E_1''\right)}{T_0}}, \qquad (4)$$

where hc/k is the const value 1.438 cm K, A_1 and A_2 are the integrated areas of the absorption lines for DAS. The ratio of the integrated of this pair transitions is only function of gas temperature

$$\frac{A_1}{A_2} = \frac{S_1(T)}{S_2(T)}. \qquad (5)$$

By measuring the two transitions integrated absorbance as shown in Fig. 1, temperature can be inferred with eq. (4) and (5).

2. Selection of O_2 pairs

Selection of the optimum absorption transitions is the first important step in the development of two-line absorption spectroscopy based on the DAS [14, 15]. For this work, we use the HITRAN08 database for sensor design. It contains the oxygen vibrational lines in the infrared and here we concern ourselves with the overtone transitions in the region between 0.5 and 2 µm. The design rules for the line selection are considered as follows.

First, the selected O_2 wavelength should be limited to the near infrared (NIR) region of 0.7–2 µm, where the fiber-coupled lasers are commercially available at low fiber loss. There are 988 oxygen lines listed in the HITRAN08 database within above region.

Second, the absorption strength must be large enough to guarantee a good signal-to-noise ratio (SNR). There are 43 oxygen lines selected in the step one.

Third, the wavelengths of both absorption lines lie within a single laser scan, and should be minimize interference from nearby transitions.

Fourth, the line pairs should have sufficient different line strength and lower state energy *E*” to yield a DAS peak height ratio that is sensitive to temperature as Fig. 2.

Fifth, the line pair’s ratio should be single valued with temperature and the lines strengths should have the same magnitude. If one transition is much stronger or lower, the stronger transition will influence on the monitoring of the weak transition. This rule ensures that these two lines have similar SNR [16]. As this said, the selected two lines sample is shown in Fig. 3.

The spectroscopy parameters for the two selected O_2 lines have been systematically measured in the tube furnace for temperatures region of 300–900 K. Considering the selected line pairs could be recorded in a single scan of the diode

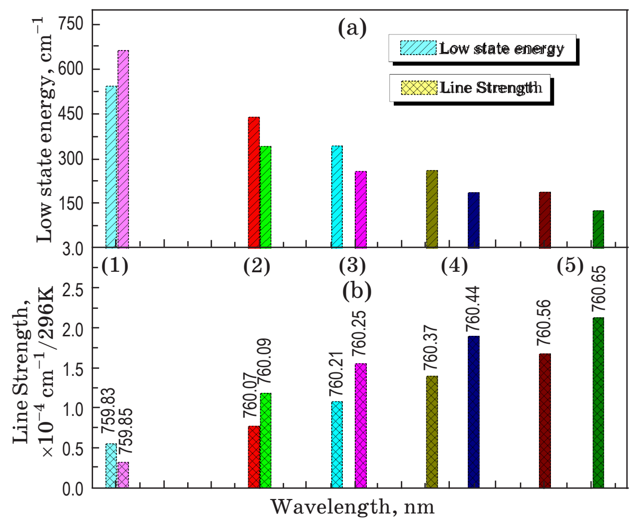

Fig. 2. The selected oxygen 5-pair lines and low state energy based on the HITRAN08 database. (a) Low state energy, (b) Line strength.

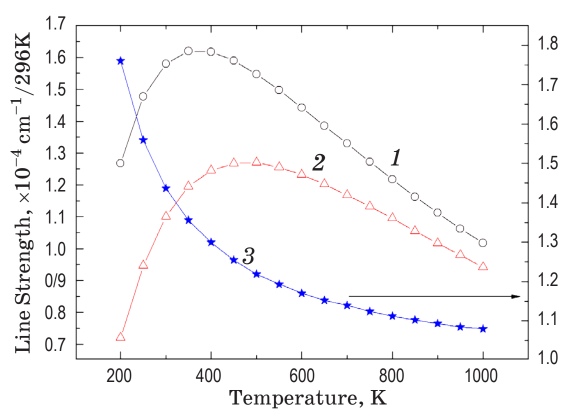

Fig. 3. The scheme of the selected lines strengths (wavelength λ_1 = 760.26 nm (*1*), wavelength λ_2 = 760.21 nm (*2*)) and its ratios (*3*) for temperature.

Spectroscopy parameters for the selected O_2 line pair

λ, nm	Intensity, $cm^{-1}/(mol\ cm^{-2})$ 296 K	E'', cm^{-1}
$\lambda_1 = 760.26$	$6.258E^{-24}$	260.50
$\lambda_2 = 760.21$	$4.337E^{-24}$	345.85

laser wavelength across about 0.07 cm^{-1} spectral interval, so the selected line transitions are listed in table taken from reference [13].

3. Considerations

Absorption spectroscopy technique with modulation had been described in details elsewhere [17]. In this work the butterfly package DFB diode laser with output in the 760 nm, 2 mW range is used which supplied by Nanoplus, Germany. The diode laser is driven by homemade current and temperature controllers to lock the absorption wavelength. The laser is scanned through the chosen absorption two lines by a sawtooth signal at low frequency of 10 Hz from our designed digital signal board. Also, it was synchronized with the oscilloscope used for data acquisition.

The DAS schematic diagram of the experimental system used for preliminary measurements is shown in Fig. 4. The cell is constructed from a quartz tube (total heated length 50 cm, inner diameter 4 cm, and the maximum temperature gradient is determined to be less 0.5%) insert in an electrically heated cylindrical oven supplied by the HEFEI KEJING Materials Technology Co., China. The direct absorption signals are collected by an acquisition card for temperature monitoring extracted from low-pass filter and pre-amplifier using one input channel.

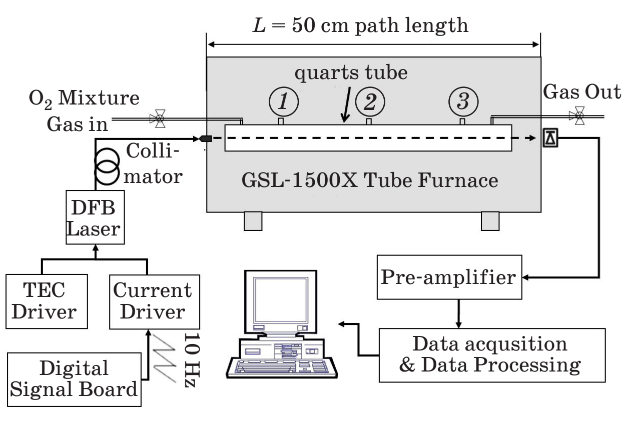

Fig. 4. The experimental schematic of the O_2 temperature measurement system.

The averaging temperature of the absorbing layer is changed by regulation of the electric current of the tube furnace. The strategy for temperature monitoring by DAS is validated over the 300–900 K with intervals of 100 K. After each step of the temperature increased, the temperature stabilized in about 30 min. These measurements are performed inside a tube furnace where the radiative corrections and stability to the thermocouples are minimized within ±10 K errors (as see *1*, *2*, and *3* in Fig. 4). During one measurement cycle signal is recorded, averaged and stored in the personal computer memory. As is well-known, the SNR increases with the increase of average times. But, considering the response time, sensitivity and action effect, we used the 16 scans averaging signals to analyze and calculate the peak heights ratio for temperature monitoring.

4. Results and discussion

As above introduced, we presented applications of DAS to monitoring temperatures with the electrical tube furnace at the experimental conditions. The example results about 20% O_2&N_2 mixture absorption system are discussed in this section.

Figure 5 shows the measurement O_2 absorption spectroscopy of different temperature at T = 300–900 K. A 3-order polynomial fit with non-absorbing wings is performed to extrapolate a zero-baseline for the purpose of creating the absorption profiles in different temperatures. And also the absorption profiles are best-fit using

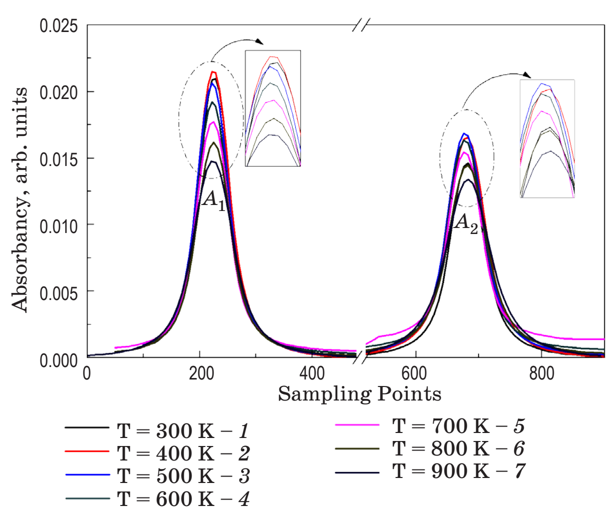

Fig. 5. Expanded view of DAS for selected O_2 line pair in the 760 nm region. *1* – 300, *2* – 400, *3* – 500, *4* – 600, *5* – 700, *6* – 800, *7* – 900 K.

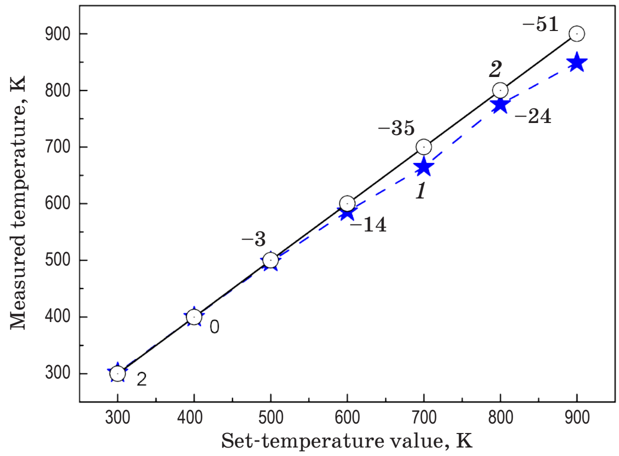

Fig. 6. Comparison of measured temperatures using DAS (*1*) and thermocouple temperatures (*2*).

Lorentz lineshape function and digital smoothing processing. Consequently, the above fitting method introduces some residual noise to the line shape with the temperature increase. Especially, when the absorbing feature is weak, it is difficult to know the correct non-absorbing wings of a signal feature begin and end. So the incorrect baseline fits will lead to the sources of measurement errors. Therefore, only small errors for direct absorption measurement will lead to maximum errors at lower gas concentrations.

The comparison of the measured temperatures and thermocouple data shows good agreement in Fig. 6. The abscissa and ordinate are the thermocouple monitoring temperatures and measured temperatures values, respectively. The five-start line stands for the DAS measured temperatures, and the circle line stands for the thermocouple measured temperatures. The temperatures inferred from the direct absorption profiles are seen to extremely well with the thermocouple measurements (max error value is 51 K).

From this graph, we can draw a conclusion that with the increase of gas temperature, the measured temperatures errors become more obviously. But limited to the experimental conditions, we can only assume that the measuring gas pressure is maintained constant. As the case stands, the temperature changes cause the gas pressure different, and then cause the absorption broadening different, and cause the modulation depth changes, and finally disturbed the measured gas temperature's errors, theoretically. In other words, the integrated absorption profiles increase with the gas pressure and decrease with the gas temperature. Under laboratory existing conditions, these factors will be further discussed in the future experiments.

Conclusions

Diode laser absorption spectroscopy is applied for the remote measurement of temperature, gas pressure, velocity and concentration. We presented an application of DAS to the measurement gas temperature in the tube furnace. Building on this experiment, however, temperature strategies based on absorption spectroscopy in more than two lines may then be derived to yield expanded temperature information, and therefore enable temperature monitoring in a non-uniform conditions.

This procedure greatly simplified the selection of the most important periods of the industry process. And spectrometer is easily extendable to other gases such as CO, CO_2, HCl, NH_3 and H_2S by a simple change of laser diode. Therefore, it has the capability to become a universal tool for industrial gas analysis in advanced combustion control applications. It is should be note that the present sensor provides average temperature for situation in which the temperature distribution along the beam path is uniform. So in the future work, the multi-line light-of-sight temperature distributions, gas concentration distributions and total pressure, respectively, will be inferred from the dynamic absorption spectral division with the "CT" model and complicated algorithms to investigate the detailed internal situations.

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