Optik 126 (2015) 2394–2397

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Multi-point optical fibre oxygen sensor based on laser absorption spectroscopy

Y.B. Wei [a,b], J. Chang [a,*], J. Lian [a], T.Y. Liu [b]

[a] School of Information Science and Engineering and Shandong Provincial Key Laboratory of Laser Technology and Application, Shandong University, Jinan 250100, PR China
[b] Laser Research Institute of Shandong Sciences Academy, Jinan 250014, PR China

ARTICLE INFO

Article history:
Received 25 April 2014
Accepted 2 June 2015

Keywords:
VCSEL laser
Optical fibre sensor
Oxygen sensor
Absorption spectroscopy
Gas detection

ABSTRACT

Based on laser absorption spectroscopy and optical fibre sensing technology, this study proposed an optical fibre oxygen detection sensor. Moreover, using a vertical cavity surface emitting laser (VCSEL) with a wave length of 763 nm as the light source, a Herriot principle-based optical fibre long-optical path detection air chamber was developed, which resulted in the stable, long-term operation of the system. This oxygen detection system covered the full possible measuring range of 0–100% with a detection error of less than 0.15%. Moreover, it realised multi-channel detection at maximum of 3 km. The results showed that the oxygen sensor showed good performance and stability and was applicable to on-line detection in an environment containing multiple- and long-distance targets.

1. Introduction

As a component accounting for 20.9% of the air by volume, oxygen is an important essential gas both for humans and industry. Oxygen sensors are widely applied to: environmental monitoring, industrial combustion processes, chemistry, medical treatment, security, etc. Traditional oxygen sensors are mainly produced on the basis of the operating principles of a thermo-magnet, primary cell, zirconia, fluorescence spectrum, etc. [3,4,7]. However, traditional technologies show defects, including live line measurement, cross-interference, a need for frequent calibration, short operating life, an inapplicability to long-distance on-line monitoring, etc. Optical detection technology, especially laser absorption spectroscopy-based gas monitoring technology, effectively overcomes the aforementioned problems attributable to long-distance measurement, passivity, low- or zero-maintenance regimes, and long-term on-line detection. As such, it has come to lead research and development trends in gas detection technology [1,2].

In recent years, laser absorption spectrum-based gas monitoring technology has seen rapid development from research to industrial application. In situ laser gas measurement technology has been applied to metallurgy, electrical power generation, cement processing, etc. Research into optic fibre oxygen sensors using laser absorption spectroscopy has not been reported [5]. Based on laser absorption spectroscopy and optical fibre sensing technology, this study proposed a type of multi-point optical fibre oxygen sensor. Moreover, using a coupled VCSEL with a wave length of 763 nm as the light source, an optical fibre, cable, splitter, and fibre collimator at a wave band of 760 nm was developed for a Herriot principle-based optical fibre long-optical path detection air chamber that supported long-term, stable operation. The oxygen detection system achieved steady measurement of oxygen concentration from 0 to 100% (v/v) at an error rate of less than 0.15%. Moreover, it displayed three channels and a detection distance of up to 3 km. The test results showed that the oxygen sensor system performed well, was stable, and applicable to on-line detection in long-distance, multi-target environments.

2. Basic principles

Under different conditions, the wavelength, intensity, polarisation, etc. of the spectra emitted (or absorbed) by a material are coherently correlated to the structural characteristics of the material at a molecular level. The structure of different gas molecules corresponds to different absorption spectra; under different concentrations, the same gas also presented inconsistent absorption intensities at certain absorption peaks. Therefore, by detecting the absorption intensity of gas under light with a specific wave length,

* Corresponding author. Tel.: +86 18660182568.
E-mail addresses: wyb9806@163.com (Y.B. Wei), changjun@sdu.edu.cn (J. Chang).

http://dx.doi.org/10.1016/j.ijleo.2015.06.013
0030-4026/

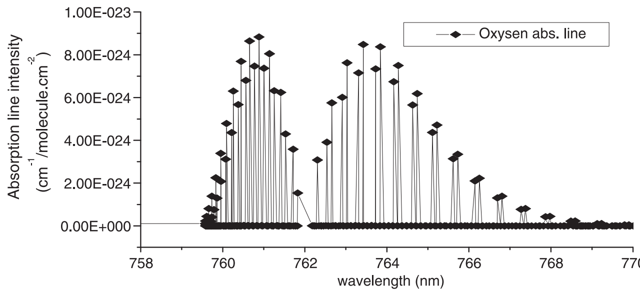

Fig. 1. The absorption line of oxygen near 763 nm.

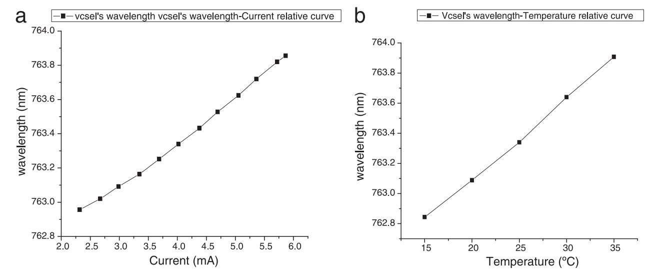

Fig. 3. (a) Current–wavelength relationship for the laser. (b) Temperature–wavelength relationship for the laser.

the determination of the constituents and concentration of gas becomes possible [5,6,8].

A beam of parallel incident light of intensity I_0 would be attenuated when it reaches the gas being measured. According to the Lambert–Beer law, the relationships between output light intensity $I(t)$ and input light intensity $I_0(t)$ and gas concentration may be expressed by:

$$I(t) = I_0(t)\exp[-\alpha(v)CL] \quad (1)$$

where, $\alpha(v)$ is the gas absorption coefficient, namely, the absorption line-type of the gas at frequency v; L refers to the length of the absorption path; C is the concentration of the gas being measured.

According to the HITRAN database [9], there are intensive absorption bands of oxygen near 763 nm. Fig. 1 shows the absorption lines of oxygen in the near-infrared band. However, moisture and carbon dioxide in the atmosphere show weak absorption intensity in the near-infrared band. Thus the narrow laser scanning range effectively avoided cross-interference. In the proposed system, 763.4 nm was set as the target absorption line at an absorption intensity of $8.48 \times 10^{-24}\ \mathrm{cm}^{-1}/(\mathrm{molecule} \times \mathrm{cm}^{-2})$.

3. The structure and configuration of the sensor system

Fig. 2 shows the configuration of optic fibre oxygen monitoring system. Firstly, laser-transmitted scanning signals were sent under the modulation of an injection current. The laser output was divided into two beams in the ratio 5:95 through a fibre optic splitter. The beam with fewer lasers was used as a reference signal for the light source, while the other beam was further divided into two beams. One of the beams therein reached the detector via a 20 cm long optical reference pool, while the other beam was transmitted into the absorption pool using a single-model optical fibre before being sent to the detector after gas absorption. Through photoelectric conversion by the detector, electrical signals were subjected to A/D conversion after transmission to the data acquisition card. Finally, the concentration of the gas was derived after processing the data recorded.

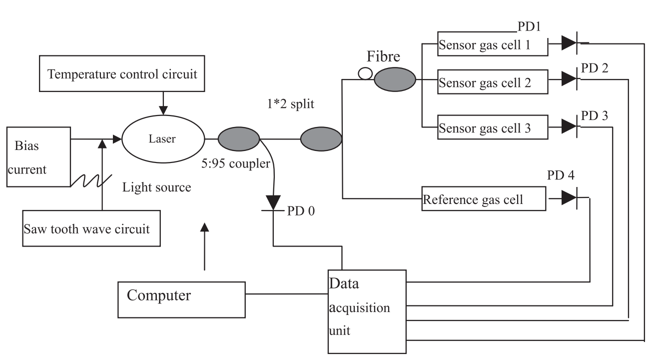

Fig. 2. Schematic of the multi-point optic fibre oxygen detection system.

In the sensor system, the control circuit of the laser included two parts, namely, the temperature control circuit and the injection current control circuit. The former stabilised the working temperature of the chip in the laser and thus maintained a stable output wavelength; the latter, composed of a bias current circuit, saw-tooth wave circuit operating at 50 Hz, and a current driver circuit, controlled the wavelength of the scanning laser.

The optical part of the system mainly involved: a laser, a detector, and the absorption pool used as the sensor. Considering the absorption spectrum of oxygen, cost, and performance, a VCSEL operating at 763.4 nm was selected as the light source. The laser used a single-mode optical fibre coupling output mode at a power output of approximately 0.5 mW. Fig. 3(a) shows the relationship between current and wavelength: the output wavelength of the VCSEL was sensitive to the current, with a sensitivity coefficient of 0.26 nm/mA. Fig. 3(b) shows the relationship between temperature and wavelength at a temperature coefficient of 0.054 nm/K. The low temperature sensitivity and high current sensitivity were conducive to improving the detection speed and stability of the system. Since the wavelength was set to 763 nm, the Si detector with a response wavelength range of 400–1100 nm was used.

The optical fibre used a high-performance low-cut-off wavelength, 780-HP single mode fibre produced by the Nufern Company. Through optimisation in the near-infrared band, the two-order mode of the fibre exhibited a cut-off wavelength of 730 nm and an operating wavelength of between 780 nm and 970 nm. Tests proved that the devices made from such fibre were more stable. However, this fibre had an attenuation at a wavelength of 760 nm of approximately 4 dB/km; the detection distance could not therefore be too long otherwise, the error in the detection result would be increased due to signal attenuation.

Since the absorption line of oxygen merely shows a weak intensity at a magnitude of 10^{-24} near 760 nm, it called for a long optical path to satisfy the performance requirements. The method of production for long optical path gas chambers mainly includes white pool and Herriot pool techniques. The white pool requires a large volume and is difficult to adjust. Moreover, its three-mirror structure diminishes its temperature stability. In contrast, the Herriot pool, with a two-error structure, is simpler and more stable than its white pool counterpart. Therefore, an optic fibre coupling Herriot pool was developed for this current study. This pool had a light path of approximately 3.1 m and an insertion loss of less than 3 dB over the temperature range of 0–60 °C.

4. Experimental work

4.1. Data processing

In the sensor system, to eliminate the influences of light fluctuations and obtain the necessary absorption spectrum signals, the detection signals in each sensing chamber were normalised by removing the PD_0 of the light source. Oxygen, at a known