A CO₂ sensor for capnography, based on a hollow waveguide (HWG) and tunable diode laser absorption spectroscopy (TDLAS), is presented; the sensor uses direct absorption spectroscopy and requires neither frequent calibration nor optical filters, giving it a significant advantage over existing techniques. Because of the HWG, the CO₂ measurement achieved a concentration resolution of 60 ppm at a measurement rate of 25 Hz, as characterized by Allan variance. The length of the HWG was selected to efficiently suppress the optical fringes. This setup is perfectly suited for the detection of CO₂ by capnography, and shows promise for the potential detection of other breath gases.

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where $\alpha(\nu)$ is the absorption coefficient; $C$ is the gas concentration, i.e., the number of molecules per unit volume; and $L$ is the effective optical path length. From Eq. (1), the gas concentration can be measured by analyzing the transmitted laser intensity and the background signal, which is proportional to the incident laser intensity.

Most laser spectrometers suffer from the etalon effect, i.e., optical fringes caused by multiple reflections\cite{17}. When a laser beam passes through plane-parallel surfaces, the optical fringes can be regarded as the fluctuations in the laser transmittance $T(\nu)$ with respect to the laser frequency $\nu$. In actual spectrometers, the reflectivity $r$ of the surface is sufficiently small and the $T(\nu)$ fluctuation is sinusoidal,

$$T(\nu) = 1 - r^2 \left[ 1 - \cos \left( \frac{2\pi \nu}{v_e} \right) \right], \quad (3)$$

where $v_e$ is the width of the optical fringe in frequency, i.e., the free spectral range (FSR). The FSR can be written as

$$v_e = \text{FSR} = \frac{c}{2nd}, \quad (4)$$

where $c$ is the speed of light in a vacuum, $d$ is the distance between the surfaces, and $n$ is the refractive index of the medium.

The experimental setup is depicted in Fig. 1. The capnography probe consists of a 12 cm-long HWG, a breath tube, and a photoelectric diode and mountings. The distributed feedback diode laser (Nanoplus, operating near 2004 nm) is driven by a laser controller (LDC3908). The frequency of the wavelength sweep is 200 Hz and the measurement result is averaged 8 times by a computer. As a result, the effective measurement rate is 25 Hz, i.e., the time resolution is 40 ms in theory. The inner diameter of the HWG is 1 mm; therefore, its volume is about 0.1 cm$^3$. The breath gas is pumped into the HWG by a vacuum pump with a flow rate of more than 5 mL/s. This setup achieves a 50 Hz rate of change of gas in the HWG, which meets the demand for a 40 ms time resolution.

A CO$_2$ absorption line at the wavelength of 2003 nm was selected, and the laser wavelength was scanned from 2002.88 nm to 2003.16 nm. According to the high-resolution transmission (HITRAN) database, the line-width at half-maximum is 57.9 pm at 300 K and 1 atm. In the range of the wavelength scan, H$_2$O gas absorption is a factor of 10$^3$ smaller than CO$_2$ absorption in the exhaled gas; therefore, it can be ignored for the purposes of CO$_2$ detection.

The CO$_2$ absorption line and the background signal were measured while the laser wavelength was swept over an adequate range, and the absorption signal was derived from Eq. (1). Since direct tunable diode laser absorption spectroscopy is an absolute measurement method, the gas absorbance is measured accurately and is not influenced by the drift of the laser intensity; this means that the sensor does not need frequent calibration.

Optical fringes commonly appear in laser spectrometers, particularly in compact devices. In order to decrease the potential negative influence of optical fringes, the distances between the surfaces in the sensor were selected carefully. The distance between the PD window and collimating lens was about 125 mm (the gaps between the HWG, the PD, and the lens are included). From Eq. (4), plane-parallel surfaces separated by 125 mm should correspond to an optical fringe width of 16 pm, which is much narrower than the CO$_2$ absorption line-width. Such narrow potential optical fringes in the CO$_2$ sensor can be suppressed efficiently by low-pass filters, line-shape fitting, or other algorithms.

Figure 2 shows the absorption signal averaged over the course of 40 ms while 4% CO$_2$ was being pumped into the HWG. Here it can be seen that the CO$_2$ absorption signal is close to 2003 nm. The measured absorption signal was processed by least-squares fitting to a standard absorption signal derived from the HITRAN database. Optical fringes

![Fig. 1. Schematic of the experimental setup.](image1)

![Fig. 2. Least-squares fitting of the measured absorption signal.](image2)
with a width of 16 pm exist in the absorption signal as a result of reflections between the PD window and the collimating lens. Those fringes can be suppressed efficiently by line-shape fitting because their width is much narrower than the width of the gas absorption line itself.

To validate the precision of the CO2 sensor, a constant concentration of 1% CO2 was delivered to the HWG continuously and we performed a CO2 detection experiment. Fig. 3 shows the measured CO2 concentration results of the least-squares fit on absorption signals with and without averaging. With averaging over 40 ms (8 sweeps), the sensor achieved a measurement rate of 25 Hz and the fluctuation of the measured concentration decreased to about 150 ppm.

Allan variance is widely used to characterize the detection limit of spectrometers\(^{17,18}\). The measured concentration, characterized by the Allan variance, was investigated. Fig. 4 indicates that the sensor achieved a concentration resolution of 60 ppm, which corresponds to an absorption of \(10^{-4}\), with a measurement rate of 25 Hz. This result is clearly sufficient for clinical applications. In addition, the detection limit reaches 10 ppm with the optimal integration time of 3 s. Therefore, the concentration resolution can be improved, if necessary, by reducing the time resolution, i.e., increasing the integration time.

We performed a CO2 detection experiment using real breath cycles and the result is shown in Fig. 5. The time dependence of the measured concentration throughout the course of an exhalation is similar to that described in the literature\(^{21}\). The measured concentration decreases rapidly at the end of exhalation, which is consistent with the high time resolution of this sensor.

With the experimental results shown above, we have demonstrated two advantages of using a HWG instead of some other small-volume cell for the detection of breath gases. (i) HWG has a longer absorption path, which facilitates the detection of gases at low concentration. (ii) The optical fringes created in the HWG are more easily suppressed, since the length of the HWG can be selected flexibly to make the width of the optical fringes noticeably different from the gas absorption linewidth.

A CO2 sensor for capnography based on TDLAS and HWG has been designed, constructed, and tested. The sensor does not need frequent calibration or an optical filter, since the CO2 absorption line as well as the laser background is measured using direct absorption spectroscopy. Taking advantage of HWG, the CO2 measurement achieved a concentration resolution of 60 ppm at a measurement rate of 25 Hz. This setup is well-suited for the detection of CO2 by capnography as well as being potentially useful for the detection of other breath gases.

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