Special Feature: Sensors

Research Report

Alcohol Detection in Exhaled Air Using NDIR Absorption Method

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ABSTRACT In recent years, the increase in traffic accidents associated with drunk driving has become a serious social issue. Therefore, there is a need for an in-vehicle system that can detect the fact that the driver is under the influence of alcohol. One possible approach is the use of non-dispersive infrared (NDIR) absorption to identify the presence of alcohol in the breath of the driver. However, since the sensor is designed to be placed at some distance from the driver, the alcohol content will be significantly diluted, and it is necessary for the sensor to have a high sensitivity to low alcohol levels. In the device developed in the present study, a quantum cascade laser was used as a highly intense infrared light source, and an infrared hollow fiber of the type used in medical treatment was utilized as a gas absorption cell. Since the core of the fiber is hollow, gas could be introduced for analysis. The flexibility of the fiber allowed it to be looped so that a 2-m-long fiber could be formed into a compact coil with a diameter of 29 cm. By measuring changes in the transmitted light intensity, it was found that ethanol concentrations as low as 1 ppm could be detected.

KEYWORDS NDIR Absorption Method, Alcohol Detection, Exhaled Air, Quantum Cascade Laser, Infrared Hollow Fiber

1. Introduction

In recent years, the increase in traffic accidents associated with drunk driving has become a serious social issue. Therefore, there is a need for an in-vehicle system that can detect the fact that the driver has consumed alcohol and lock the controls so that the vehicle cannot be operated.(1-3)

In most US states, breath alcohol ignition interlock devices (BAIIDs) using a fuel cell type sensor have been used for driving under the influence of alcohol (DUI) offenders for more than ten years, and there is evidence that they have helped to reduce DUI recidivism. A BAIID analyzes exhaled breath to estimate the blood alcohol concentration (BAC) of the driver. It prevents the vehicle from starting until a breath sample has been given, and the ethanol content is found to be below a programmed limit. When attempting to start a vehicle, a driver must take a deep breath and blow long and hard through the mouthpiece of the alcohol detector. At present, BAIIDs are secondary interlock devices that are enforced only following a DUI offence. To develop a primary interlock device, not only accuracy but also convenience is required – it should have the ability to estimate alcohol levels with very little effort or wasted time. In addition, it should not be capable of been fooled by a person other than the actual driver, who has not been drinking. In order to prevent false positives, it should be able to distinguish alcohol from other substances such as acetone or perfume. Finally, the device should not be excessively expensive or require regular maintenance.

The device proposed in the present paper is based on non-dispersive infrared (NDIR) absorption, which has been shown to be a highly selective gas detection method.(4-6) The device is designed to be mounted close to the steering wheel, and uses suction to sample the driver's exhaled breath, so there is no need to blow into it. Since the analysis can be carried out periodically while the vehicle is being driven, it is not possible for a person other than the driver to fool it. Since the gas selectivity of the NDIR absorption method is very high, erroneous judgments can be prevented. Furthermore, unlike in a fuel cell type sensor, since no chemical reactions are involved, the sensor does not deteriorate, so regular maintenance is not required.

However, since the intake nozzle is not directly in front of the driver's face, the driver's breath is very diluted, so that extremely high sensitivity is required. This can be achieved by increasing both the incident infrared light intensity and the optical path length.

This paper describes the principle involved in gas detection using NDIR absorption, the design of the proposed device, and the results of an evaluation of its ability to detect low levels of ethanol in air, to assess the feasibility of using this approach to monitor the breath of a driver.

2. Gas Detection Based on NDIR Absorption

2. 1 In-vehicle Measurement System

Figure 1 shows a schematic diagram of the proposed in-vehicle alcohol detection system based on NDIR absorption. A suction nozzle is installed near the steering wheel and a pump is used to suck the driver's exhaled breath through a pipe into the sensor. In addition to alcohol, the sensor measures the humidity or the CO_2 concentration. This data is used to determine the degree of dilution of the driver's breath. From the measured alcohol concentration and the degree of dilution of the driver's breath, it determines whether the driver has been drinking. Since expiration inhales a suction type and it is diluted by the atmosphere to a nozzle, alcohol concentration falls to about 1/10.(7) Therefore, in order to realize this in-vehicle measurement system, increasing the sensitivity of the NDIR absorption method is required.

2. 2 Principle of Gas Detection

NDIR absorption can be used to identify gas molecules that absorb light in the infrared region, and it offers high selectivity.(4-6) The basic setup for NDIR absorption measurements is shown in **Fig. 2**. Infrared light enters a cell filled with the gas to be measured, and the gas concentration is determined from the amount of absorption at a specific wavelength.

If the initial light intensity is I_0, the transmitted intensity I_t is given by the following equation.

$$I_t = I_0 \cdot \exp(-C \cdot d \cdot \varepsilon) \qquad (1)$$

Here C is the gas concentration, d is the optical path length, and ε is the absorption coefficient for the gas to be measured. From Eq. (1), the change in light intensity due to the presence of the gas is given by the following equation.

$$I_s = I_0 - I_t = I_0 \cdot \{1 - \exp(-C \cdot d \cdot \varepsilon)\} \qquad (2)$$

Thus, higher sensitivity can be achieved by increasing I_0 and d.

Figure 3 shows the optical absorption spectrum for ethanol, which is the substance that would indicate that a driver had consumed alcohol. It is seen to have strong absorption peaks at wavelengths of 3.4 and 9.5 μm, associated with C-H and C-O stretching vibrations, respectively. However, since many other substances

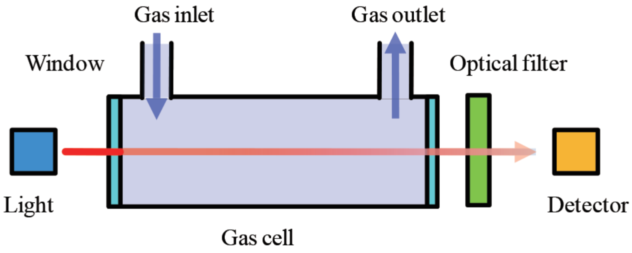


Fig. 2 Setup for NDIR absorption method.

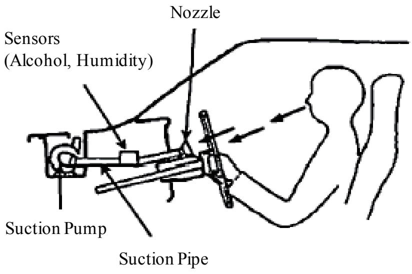


Fig. 1 Schematic of suction type measurement system.

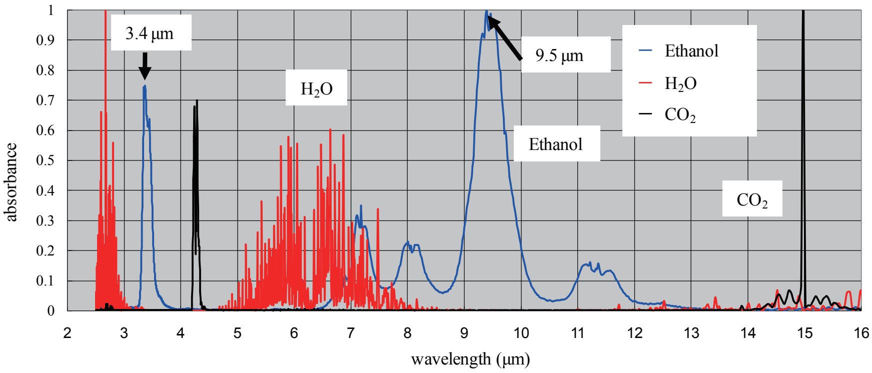


Fig. 3 Infrared absorption spectra for different substances.

exhibit peaks in the region around 3.4 µm, and this peak is also weaker than that at 9.5 µm, the latter peak is most suitable for high-sensitivity detection of ethanol.

2. 3 Methods for Increasing the Measurement Sensitivity

In Japan, the legal breath alcohol concentration for drivers is 0.15 mg/L.(8) This is equivalent to a volume ratio of 80 ppm at 25°C. As mentioned earlier, using the setup shown in Fig. 1, this is expected to drop to 8 ppm at the inlet nozzle of the sensor system. To achieve the required level of sensitivity, a highly intense light source and a long optical path are therefore required. In the present study, the light source was a quantum cascade laser with high wavelength stability. In addition, an infrared hollow fiber of the type used in laser-based dentistry was utilized as the gas cell.

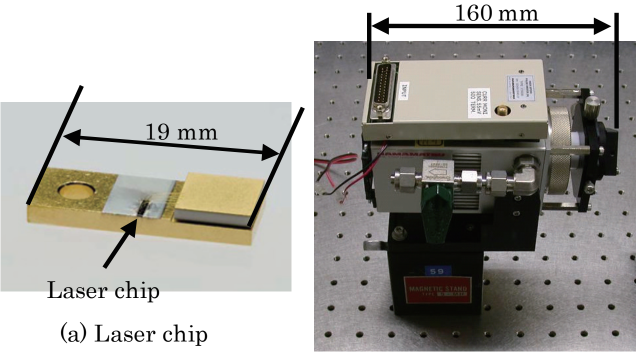
A quantum cascade laser uses electronic transitions between subbands in a semiconductor quantum well, and can emit at infrared wavelengths. The laser used for the present measurements is shown in **Fig. 4**, and its main specifications are given in **Table 1**. Figure 4(a) shows the actual laser chip, and Fig. 4(b) shows its cooling head. It is a Fabry-Perot type laser, emitting at an infrared wavelength of 9.47 µm with a high output power of 5 mW.

The hollow fiber can transmit infrared waves with a wavelength of 2 µm or more with a low loss, which is not the case for solid core silica glass optical fibers. Since the core is hollow, the gas to be detected can be introduced inside it. In addition, because of its high flexibility, a length of 2 m can be easily looped to form a coil with a diameter of about 29 cm (about 2 turns). Furthermore, since the diameter of the hollow core is only 700 µm, just 0.77 cc of gas is required to fill the entire 2-m length. Thus, a long optical path can be achieved with just a small amount of gas. **Figure 5** shows a photograph of the hollow fiber used in the experiment, and **Fig. 6** shows a cross-sectional illustration of the fiber structure. The main specifications of the fiber are listed in **Table 2**. Metal and dielectric thin films are deposited on the inner surface of a glass capillary, to achieve a high reflectance at wavelengths of 2 µm or more.

To use the fiber as a gas cell, it is necessary to introduce the gas and the laser beam. This was achieved using the terminals shown in **Figs. 7** and **8**. The gas to be measured is introduced into the upper part of the inlet terminal, and the laser beam enters the fiber from

Table 1 Specifications of quantum cascade laser.

Manufacturer	HAMAMATSU Japan
Structure	Fabry-Perot type
Driving method	Pulse drive
Wavelength	9.47 µm
Output power	5 mW
Pulse duration	100 nsec
Repetition rate	1 MHz



(a) Laser chip

(b) Cooling head

Fig. 4 Quantum cascade laser.

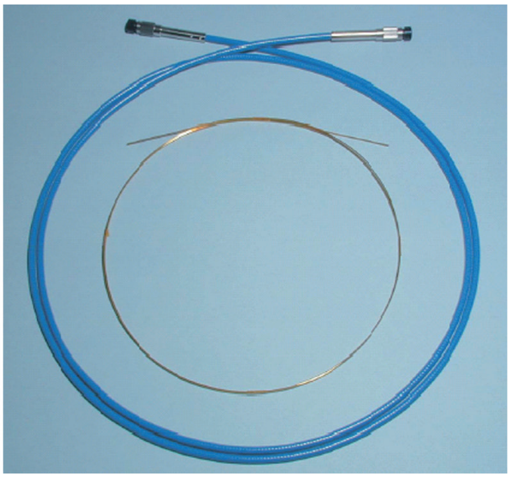


Fig. 5 Infrared hollow fiber (with and without outer jacket).

the side of the terminal, after first passing through a 2-mm-thick BaF_2 window, whose transmissivity at a wavelength of 9.47 μm is about 98%.

2. 4 Detection of Ethanol Gas

Figure 9 shows a schematic overview of the experimental setup. The laser beam was mechanically chopped at 10 Hz and focused using a condenser lens before entering the BaF_2 window. After passing through the gas cell, the beam was focused onto a thermopile (HEIMANN, E21), whose output voltage was measured using a lock-in amplifier synchronized to the reference signal of the mechanical chopper. Ethanol gas with a concentration of 1-100 ppm in dry air, as determined by gas chromatography, was introduced into the gas cell. In addition, a fuel cell type breathalyzer (Alcohol Countermeasure Systems, ALERT J4X.ec) also performed ethanol concentration measurement before each experiment. **Figure 10** shows a photograph of evaluation system.

3. Results

Figure 11 shows the change in the output voltage of the thermopile for ethanol concentrations in the range 10-100 ppm and 1-5 ppm. The vertical axis represents the percentage change relative to the case without any ethanol. Each measurement was performed five times. It can be seen that a roughly linear relation was obtained for both concentration ranges. The rate of change in the output voltage was – 0.154% / ppm, with a standard deviation of 0.04%.

The detection limit was 1 ppm, which is eight

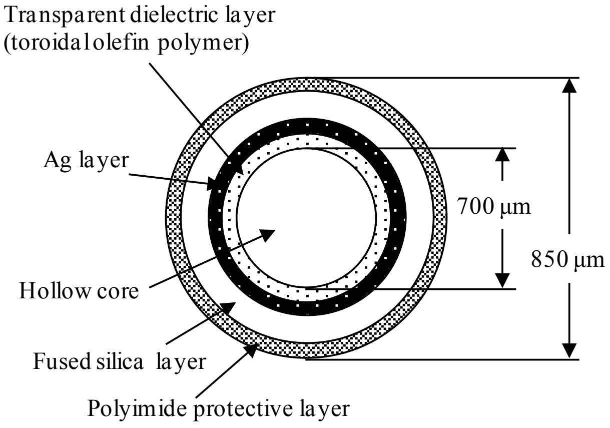


Fig. 6 Cross-sectional structure of infrared hollow fiber.

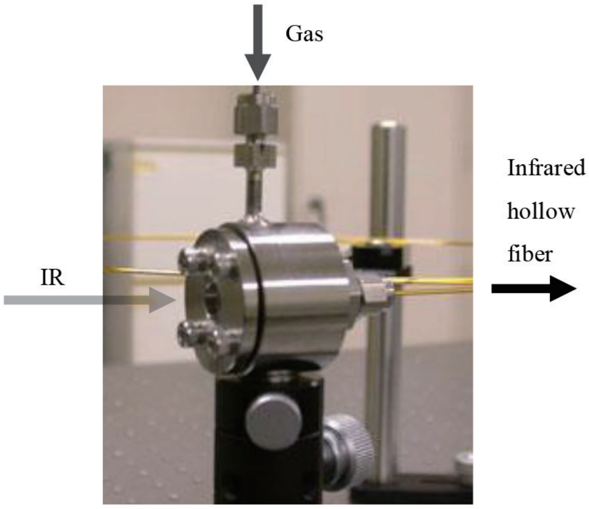


Fig. 7 Terminal used to introduce infrared light and gas.

Table 2 Specifications of infrared hollow fiber.

Manufacturer	Hitachi Cable
Structure	Ag mirror and toroidal olefin polyer
Length	2 m
Inside diameter	700 μm
Outside diameter	850 μm
Permeability	81%

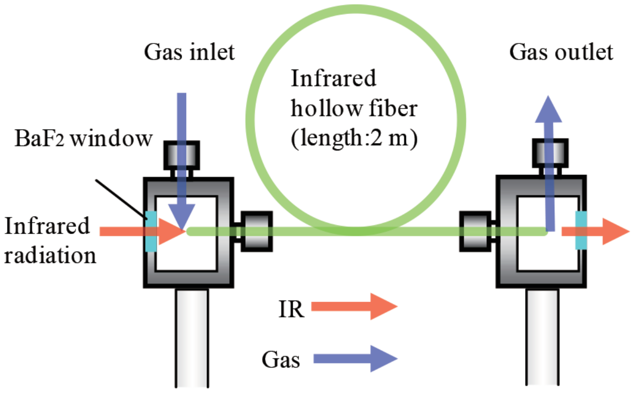


Fig. 8 Setup for introducing gas and infrared light into hollow fiber.

times smaller than the required value, thus indicating the potential of the proposed system for practical applications.

4. Conclusions

For the purpose of reducing traffic accidents caused by drunken driving, an alcohol sensing system based on NDIR absorption was investigated. This system differs from a conventional BAIID in that the driver does not need to blow into it. Instead, suction is used to sample the driver's breath during driving. However, because of the distance between the inlet nozzle and the driver, considerable dilution of the driver's breath occurs. For this reason, a very high detection sensitivity is needed, and the degree of dilution should also be determined. The sensitivity of the system was optimized by using a high-intensity quantum cascade laser, and a gas cell with a 2-m-long long optical path formed from an infrared hollow fiber.

For ethanol concentrations in the range 1-100 ppm, The output signal strength was found to be linearly proportional to the ethanol concentration in the range 1-100 ppm. The detection limit of 1 ppm means that the system is practical for detecting alcohol in the breath of a driver.

However, at present, the cost of such a system is still high since quantum cascade lasers are very expensive. However, since these lasers can be produced with any expensive materials or specialized equipment, their cost is expected to be greatly reduced in the future as a result of mass production. Therefore, the proposed in-vehicle alcohol detection system is considered to be promising for practical applications.

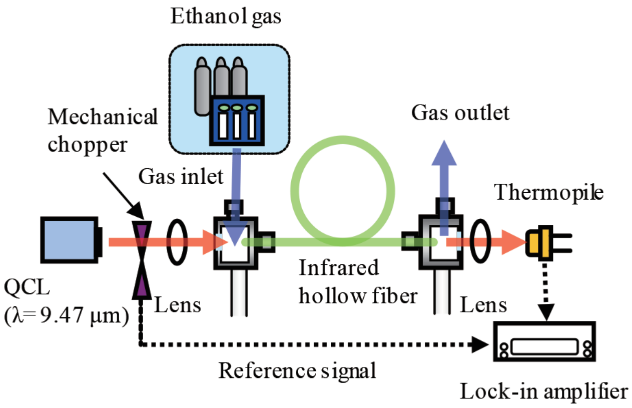


Fig. 9 Evaluation system for ethanol gas.

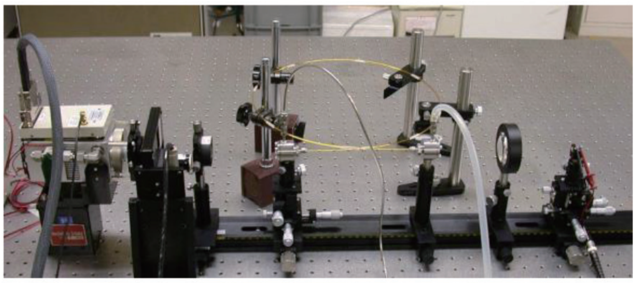


Fig. 10 Photograph of evaluation system.

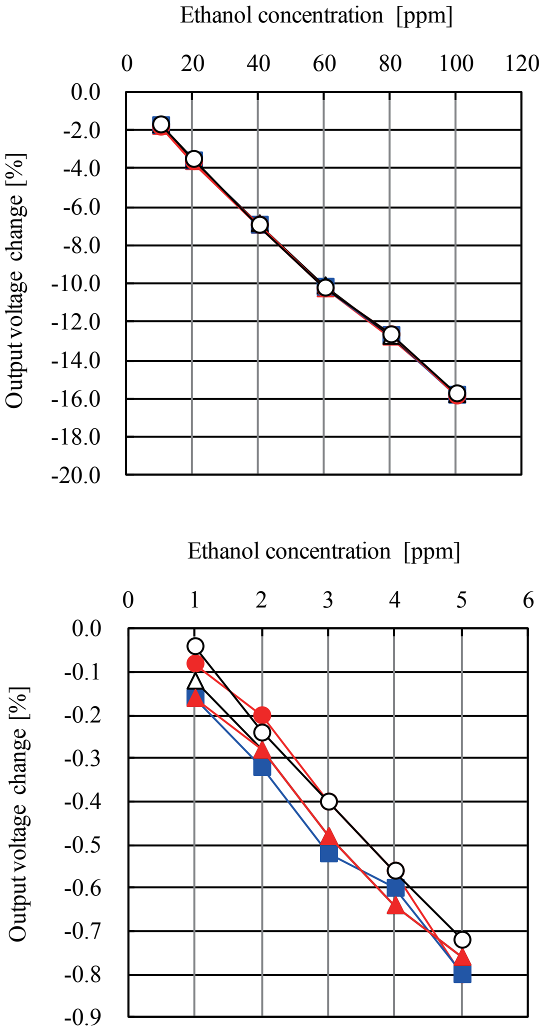


Fig. 11 Output characteristics.

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Fig. 1-11, Table 1, 2
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