N87-10354

WIDE-AREA REMOTE-SENSING SYSTEM OF POLLUTION AND GAS DISPERSAL BY NEAR-INFRARED ABSORPTION BASED ON LOW-LOSS OPTICAL FIBER NETWORK

Humio Inaba

Research Institute of Electrical Communication
Tohoku University, Sendai 980, Japan

Abstract — An all-optical remote-sensing system utilizing long-distance, ultralow-loss optical fiber networks is studied and discussed for near-infrared absorption measurements of combustible and/or explosive gases such as CH_4 and C_3H_8 in our environment, including experimental results achieved in a diameter more than 20 km.

I. Introduction

Optical fiber sensor technology is being developed currently for a wide variety of applications, and the technical advantages are well recognized so that its impact is now evident. Based on the idea of the first author [1] for a new capability of this technology, an optical network system employing low-loss optical fibers has been analyzed and examined for remote sensing of environmental pollution and spilled dispersals of inflammable, explosive and toxic gases/vapors in various industrial and mining facilities as well as in urban and residential areas by the spectroscopic absorption method [2, 3].

This regime of fiber-optic remote monitoring and detection has various advantages since the optical energy can be concentrated and transmitted in low-loss optical fibers even for long distances over several tens km, instead of the open atmosphere. Hence fully optical, reliable, sensitive, economical with low-power lasers or even incoherent sources, feasible, real-time, nonhazardous, e.g., eye-safe and explosion-free technique can be realized, along with capabilities of little optical interference and of continuous surveillance with easy calibration and selectivity as well as no electrical induction, for various stressing environments and severe conditions. The experimental feasibility of a fiber-optic gas sensor system has been demonstrated for remote absorption measurement of NO_2 in the visible spectrum using an Ar ion laser [3, 4], and CH_4 in the near-infrared region employing InGaAsP light emitting diodes (LED's) [3, 5-7] by our group.

This paper reports and summarizes experimental results of a low-loss optical fiber-based remote-sensing system of CH_4 and C_3H_8 gases which have been investigated in our laboratory, with specific emphasis on the use of a near-infrared wavelength range for this purpose.

II. Near-Infrared Absorption Spectra and Basic Arrangement

Currently, ultralow-loss silica optical fibers exhibiting transmission loss as low as 1 dB/km or less over the range of about 1.05 - 1.7 μm as well as high-quality optical sources and detectors have been developed primarily for long-distance, high-bit-rate optical communications, as shown in Fig. 1. Typical absorption wavelengths of various molecular species present in the atmosphere and environment are also depicted. Consequently, it becomes fairly apparent that the fiber-optic remote gas sensor system should be substantially operated in this near-infrared region to achieve a wide area coverage such as, for instance, a few tens km in diameter [1-3].

From this point of view, we have performed spectroscopic measurements and analyses of combination and overtone bands of a number of molecules such as CH_4, C_3H_8, C_2H_4, C_2H_2, C_2H_6, C_4H_{10}, NH_3, H_2O, those contained in LNG, LPG and city gases, and others in this near-infrared range [3, 5-9].

On the basis of this spectral information, we are pursuing the remote absorption measurements using InGaAsP and InGaP LED's in conjunction with a few to several tens km-long, ultralow-loss silica optical fiber links. Figure 2 shows the basic arrangement of a fully optical remote gas sensor system employing a compact absorption cell as a sensor head. Near-infrared LED's used for the experiment are laser diodes (LD's) operated under threshold current level with output powers less than 0.1 mW. The optical beam from the LED was transmitted through a transmitting multimode optical fiber to a remotely located gas sensor head and then returned to the transmitter/receiver location via the receiving multimode optical fiber. The transmission loss of the silica optical fibers was lower than 1 dB/km in the 1.3 - 1.7 μm region. Absorption measurement was performed by using a grating spectrometer to change the detecting spectral width or a dielectric interference filter for a practical simplification in the system operation [6, 7].

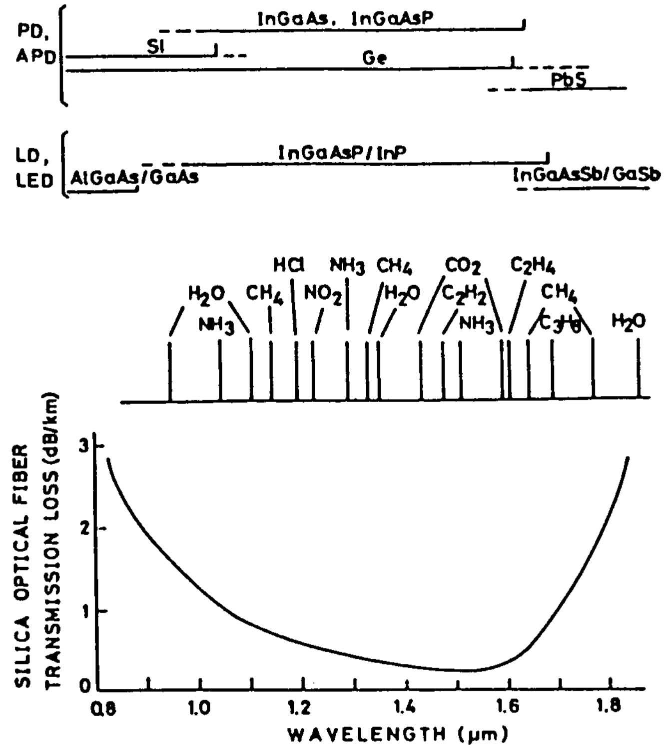

Fig. 1 Currently available high-quality semiconductor light sources (LD and LED) and detectors (PD and APD) in conjunction with ultralow-loss silica optical fibers in the near-infrared region, and typical absorption wavelengths of various molecular species present in the atmosphere and environment.

III. Remote Monitoring of Methane Gas at 1.33 and 1.66 μm

The experimental demonstration of remote detection of low-level CH_4 gas was carried out for the first time employing a 2-km-long low-loss silica optical fiber link and a 50-cm-long compact absorption cell incorporating InGaAsP LED's operated around 1.34 and 1.61 μm. We observed that the detec-

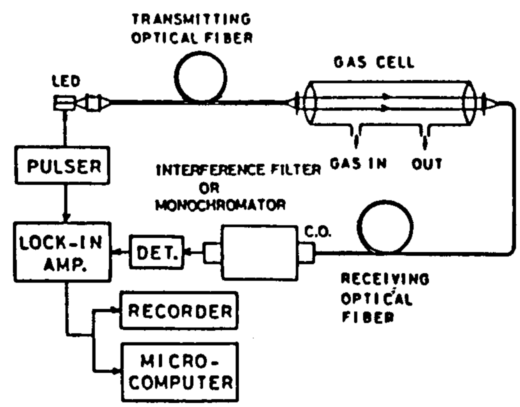

Fig. 2 Block diagram of an all-optical fiber-based remote-sensing system for absorption measurement of low-level combustible, explosive and toxic gases/vapors in the near-infrared region.

tion sensitivity of CH_4 gas in air is approximately 4 % of the lower explosion limit (LEL) at the 1.331-μm Q-branch of the $\nu_2 + 2\nu_3$ band using a grating monochromator with the spectral resolution of 0.3 nm [5], and about 1.3 % of the LEL at the 1.666-μm Q-branch of the $2\nu_3$ band employing a dielectric interference filter with the spectral width of nearly 3 nm [6], respectively.

A compact and reliable remote-sensing system was also realized by utilizing the power-balanced, two-wavelength differential absorption method [10], which enables one direct detection of differential absorption signals for the specific substance to be monitored [7]. Thus we confirmed that this technique is capable of achieving the sensitivity of about 0.8 % of the LEL of CH_4 density in air with easy calibration, using two dielectric interference filters centered at 1.666 μm as the on-absorption filter and at 1.528 μm as the off-absorption filter, respectively [7].

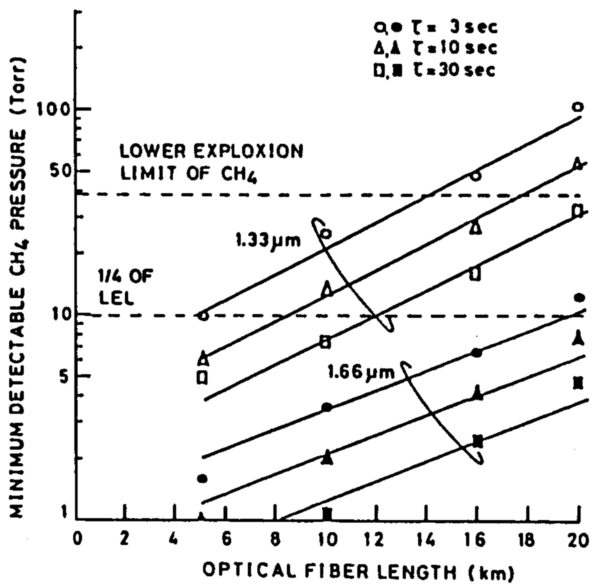

Fig. 3 Minimum detectable pressure of CH_4 gas in air at 1.331 and 1.666 μm as a function of the optical fiber length and the detection time in the all-optical remote measurement employing 5 - 20 km-long ultralow-loss silica optical fiber links in conjunction with InGaAsP LED's and a 50-cm-long absorption cell as the gas sensor head.

Based on these experiments demonstrating the feasibility of low-level CH_4 gas remote sensing employing very low-loss optical fiber links, we planned to extend the length of optical fibers to achieve a capability of a wider area coverage of this fully optical system. Figure 3 summarizes the measured result for the silica optical fiber links of the length of 5, 10, 16 and 20 km. The minimum detectable pressure of CH_4 gas in air was measured for each optical fiber link at 1.33 and 1.66-μm bands using a dielectric interference filter with the transmission center at 1.331 μm and about 2.5 nm spectral width, and a similar filter around 1.666 μm as mentioned above, respectively. It was verified that the detection sensitivity of 25 % of the LEL of CH_4 gas density in air, which is normally required for any practical CH_4 gas sensor, can be realized up to a 20-km-long optical fiber link with the detection time longer than 3 sec for 1.666-μm band, and also up to nearly 12 km with the detection time of 30 sec for 1.331-μm band. We should note that since the absorption of CH_4 molecules in 1.66-μm region is usually stronger than that in 1.33-μm region, higher sensitivity or longer detectable range for the fiber-optic CH_4 gas remote sensing is achievable in 1.66-μm region as is seen in this figure.

IV. Remote Monitoring of Propane Gas at 1.68 μm

As a further extension of our all-optical fiber-based remote gas sensing scheme, we have performed the remote measurement of low-level C_3H_8 gas in 1.68-μm region for the first time [11]. This gas is known to be the predominant component of LPG, and an inflammable and explosive species.

From the spectroscopic measurement using InGaAsP and InGaP LED's, C_3H_8

molecules were found to have absorption spectra in 1.3 - 1.7 μm region and the strongest absorption at 1.6837 μm [9, 11]. Then remote detection of C_3H_8 gas was pursued employing the experimental setup shown in Fig. 2 incorporating an InGaP LED and a 50-cm-long compact absorption cell.

Figure 4 shows the measured dependence of absorbance at the wavelength of 1.6837 μm on C_3H_8 partial pressure in the cell using a 2-km-long low-loss silica optical fiber link. Here, I_0 and I represent the intensity of optical signal which passed through the evacuated and C_3H_8-air mixture contained absorption cell, respectively. The spectral resolution was 1.0 nm and the detection time was 3 sec. In this measurement, the minimum detectable pressure of C_3H_8 gas in air was confirmed to be lower than 2 Torr, which corresponds to nearly 12 % of the LEL.

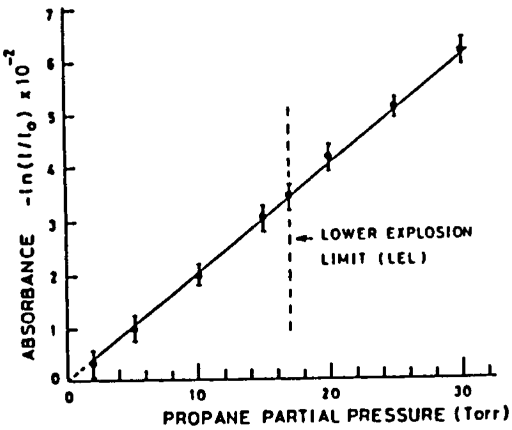

Fig. 4 Measured dependence of the absorbance at 1.6837 μm on C_3H_8 partial pressure in 1 atm. C_3H_8-air mixture contained in a 50-cm-long gas sensor head using a 2-km-long very low-loss silica optical fiber link.

Moreover, we have realized that the same system utilizing a 5-km-long silica optical fiber link is capable of achieving reproducibly the detection sensitivity of about 2.4 Torr for C_3H_8 gas in air with the resolution of 1.2 - 1.5 nm, i.e., 14 % of the LEL [11]. The similar remote-sensing system is being applied to other gases by suitably selecting the measuring wavelength in the near-infrared region as illustrated in Fig. 1[12].

V. Conclusion

On the basis of the present state of the art of optical electronics technology, this kind of optical fiber network incorporating LED's or LD's and detectors in the near-infrared range should prove a very powerful scheme and provide extensively an all-optical safe way for remote sensing of various dangerous and toxic gases/vapors at strategic points over a wide area within the environment, e.g., industrial complexes, factories, mines, fuel storage yards, tunnels, undergrounds, ships, offices, hospitals, hotels, apartments, and so on.

References

[1] H. Inaba, in Conference Abstracts, 9th International Laser Radar Conference, Munich, July 1979, Invited paper 2 - 2, pp. 61 - 67.
[2] H. Inaba, T. Kobayasi, M. Hirama, and M. Hamza, Electron. Lett. 15, 749 (1979).
[3] H. Inaba, in Optical and Laser Remote Sensing, D. K. Killinger and A. Mooradian, Eds. (Springer, Berlin, 1983) p. 288.
[4] T. Kobayasi, M. Hirama, and H. Inaba, Appl. Opt. 20, 3279 (1981).
[5] K. Chan, H. Ito, and H. Inaba, Appl. Phys. Lett. 43, 634 (1983).
[6] K. Chan, H. Ito, and H. Inaba, IEEE/OSA J. Lightwave Technol. LT-2, 234 (1984).
[7] K. Chan, H. Ito, and H. Inaba, Appl. Opt. 23, 1 Oct. 1984 issue, to be published.
[8] K. Chan, H. Ito, and H. Inaba, Appl. Opt. 22, 3802 (1983).
[9] H. Inaba, K. Chan, and H. Ito, in Dig. Tech. Papers, Conference on Lasers and Electro-Optics (CLEO'84), Anaheim, California, June 1984, Invited paper WN3, pp. 118 - 120.
[10] M. Hamza, T. Kobayasi, and H. Inaba, Opt. and Quantum Electron. 13, 187 (1981) and 14, 339 (1982).
[11] K. Chan, H. Ito, and H. Inaba, Appl. Phys. Lett. 45, 220 (1984).
[12] H. Inaba, in Laser/Optoelectronics in Engineering - Laser 85 Optoelektronik, W. Waidelich, Ed. (Springer, Berlin, 1986) p. 619.

8-bits digitizer units. Signal averaging and system control is handled by an ITT XT computer with a hard disk and a floppy drive for data storage. The computer has graphic capabilities to present data. A printer and a plotter are incorporated for the final presentation of evaluated data. The computer can, on its own, perform a complete measurement sequence once the directions have been entered. System steering is performed with an additional microprocessor, which takes care of stepper motors, chopper, laser etc.

The system has the function of a laboratory when no field campaign is performed. It has a stationary docking place at our institute that makes it possible to walk directly from the fixed laboratories into the bus. So far, the system has participated in two field campaigns, one for SO_2 and one for NO_2. A result from the SO_2 campaign is shown in figure 2.

Future use of the system will be in development of lidar techniques, where we try to widen the range of species that can be monitored. In specific, we will investigate range resolved measurements of NO and mercury. Other experiments are also planned - a monochromator on the detection side allows measurements with the DOAS (Differential Optical Absorption Spectroscopy) technique to be performed. This method, where the absorption of light from a high pressure Xenon lamp is measured in a way that eliminates atmospheric turbulence, gives the average concentration of the monitored species over the measured path. The sensitivity can be made extremely high. Remote laser induced fluorescence activities such as mineral monitoring or monitoring of pollution effects on plants might be considered. Other applications can be to provide a mobile lab or laser source for combustion studies in the industry.

References:

1. K. Fredriksson, B. Galle, K. Nyström, and S. Svanberg, "Mobile lidar system for environmental probing ", Applied Optics 20, 4181 (1981).

2. R. J. Allen and W. E. Evans, Rev. Sci. Instruments 43, 1422 (1972).