Research on the distributed optical remote sensing of methane employing single laser source

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A design and testing of a cost-effective distributed optical remote sensing methane system, which will help one to detect gas leaks from multi-coal face in mines simultaneously, is presented. The fundamentals of the remote detection are based on frequency-modulation spectroscopy (FMS) and harmonic detection. By utilizing fiber-optic splitting technique and reference-signal restoring circuit, the remote sensing system is feasible to employ single laser source to get multi-spot measurement in the near infrared region so that the system described here shows sufficient sensibility, considerably increased reliability and marketability over the presently available system. The minimum measurable path-integrated concentration is estimated to be about 423 ppb-m by experimentation.

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Methane (CH_4) is an inflammable and explosive gas and a major constituent of mine gas. Hence, methane monitoring is indispensable for safety in mines. Conventional CH_4 gas sensors, such as flame ionization and electrochemical detectors, are not capable of remote detection. Moreover these detectors cannot distinguish methane from some of the other chemical species.

Laser remote measurement of gas concentration has progressed significantly during the nearly past 40 years[1,2]. Unlike other types of CH_4 gas detectors, the laser-based remote sensor can detect a gas leak in real time and does not need to be immersed within the gas leak. Remote methane-detection using an external-cavity diode laser (ECDL) with frequency-modulation spectroscopy (FMS)[3−5] has been described in Ref. [6]. According to Ref. [6], the detected gas range-integrated concentration C_R is given by

$$C_R \approx K(P_{2f}/P_f),$$

where, P_{2f} and P_f are powers of $2f$ and f signal of radiation backscattered from topographic targets respectively, K is a coefficient that will be determined by calibration experiment.

However, using laser-based device in mines will bring other safety problems. Meanwhile, when we organize these sensors to constitute a total distributed remote sensing system (TDRSS), excessive laser sources will be required. This means facility cost is increased, and reliability trends badly. Hence, extensive application of laser remote sensing is limited.

This paper describes a new distributed optical remote sensing methane system by employing only one single laser source which, when fully developed, will facilitate detection mine gas leaks from multi-coal face simultaneously in coal mine. Figure 1 shows the configuration of the system. It is composed of four primary components: 1) a laser source and control electronics (they may be placed in safety area, for example, outside of mines); 2) a light splitting and optic-fiber propagation unit; 3) a number of local sensors (their detecting principle was discussed in Ref. [6]); and 4) a computer module. The diode laser source offers a probe light for those sensors through fibers and couplers that primarily designed for telecommunication. In order to perform FMS, the injection current to ECDL is sinusoidally modulated by control electronics. The basic remote sensor contains of two primary components: optical section and electronic section. The basic optical configuration of remote sensor combines a GRIN collimating lens as transmitting section with a Fresnel lens as radiation receiver section. Laser energy was approximatively uniformly distributed to remote sensors by 1 × 4 fiber-coupler splitting and optical fiber propagation. The basic electronic devices of remote sensor comprise PD (photodetector), PSD (phase-sensitive detection) and reference-signal restoring circuit section. The computer module (not shown in Fig. 1) was a Pentium class industrial rack mounted computer that was outfitted with a National Instruments PCI-MIO-64E-1 data acquisition (DAQ) board and National Instruments LabView graphical software programming language (Ver. 6.1). The DAQ board was used to digitize output signals from each sensor and to record these signals and the Labview software was used to control the DAQ board.

In order to evaluate the performance of the system described above, a laboratory prototype was built. And the experimental work was performed using four sensors and one ECDL. The detecting optical beam of every sensor was all directed towards the wall of laboratory as the topographic target and the space distance between the sensor and the next sensor is 1-meter apart both in vertical and horizontal directions. The distance between sensor and wall surface is 6 meters (it is limited by available space in the laboratory). We operated the Littrow-external-cavity laser (Model TEC100+MLD1000, Sacher Co., Germany) at constant temperature of 25° and a constant injection current of 95 mA, with a nominal output power of 2.5 mW and center frequency of laser is locked to the R (6) absorption line of methane in $2\nu_3$ band[7,8] by active stabilization (using PI1000 AS Module, Sacher Co., Germany). The sinusoidal modulation signal was

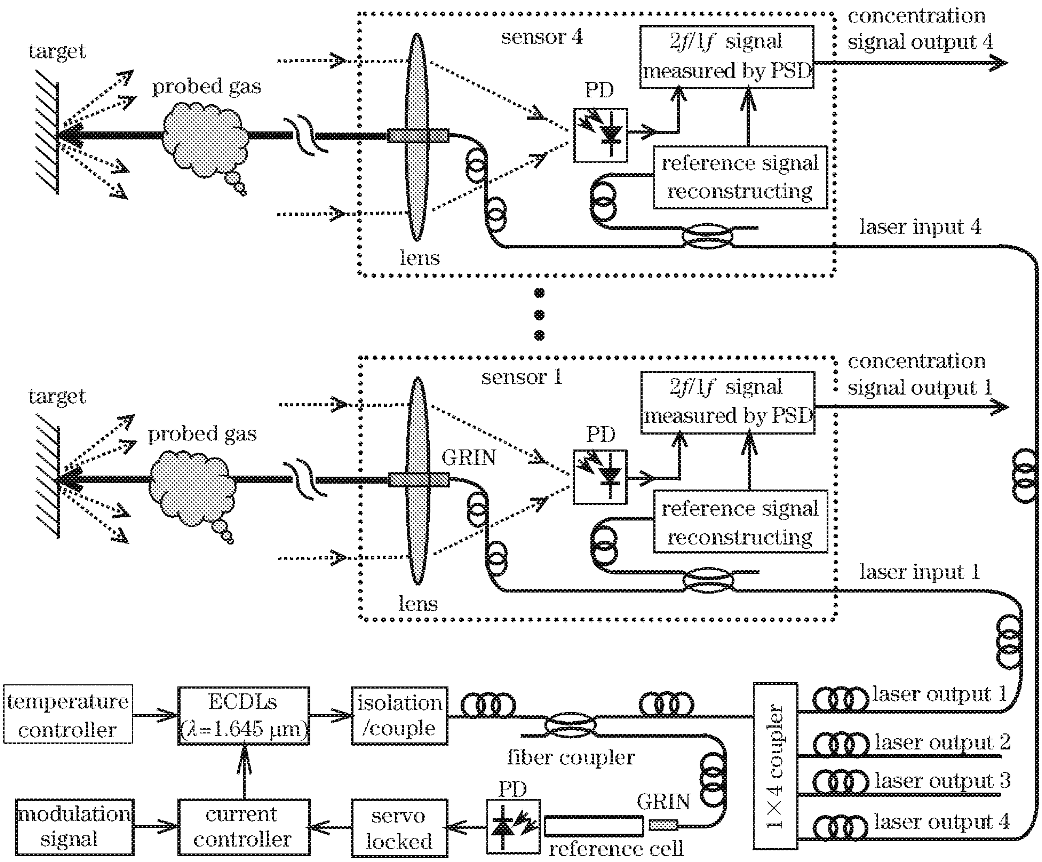

Fig. 1. Schematic diagram of distributed optical remote sensing methane system employing single laser source. Laser energy was approximatively uniformly distributed to remote sensors by 1 × 4 fiber-coupler splitting and optical fiber propagation. Pure (99.99%) CH_4 at a pressure of 10 Pa was contained in the 5-cm long reference cell. The center frequency of laser was locked to the $2\nu_3$ band $R(6)$ line of methane by active stabilization (approximately at 1.645 μm).

generated by a function generator (Model Agilent 33120A, USA). The frequency and amplitude of the modulation signal were set to 10 kHz and 1.2 V, respectively. The amplitudes of $2f$ and f signals of each sensor output were measured precisely with PSD amplifiers (Model SR830, SRS Co., USA). Note that in the experiment the modulation signal is directly acted as the phase reference signal as required by the PSD amplifiers, the phase reference signal will be provided by the reference-signal restoring circuit with multiplexing in practice.

In order to demonstrate the linear response of laser-based remote sensor, a sensor was randomly selected from the laboratory prototype described above. Figure 2 shows the measured signal amplitudes as a function of the range-integrated methane concentration. The linearity is apparent.

The minimum measurable concentration was determined by the noise level of the sensor with 0-ppm methane (representing the natural background of methane in the laboratory air). In our experiment, the noise level is measured to be $(P_{2f}/P_f)_{\rm noise} = 42.5$ μV. Thus the minimum measurable concentration is estimated to be $C_R^{\rm min} = 423$ ppb-m.

Distributed monitoring simulated methane leak was performed using the laboratory prototype described above. In the experiment, a methane cylinder was attached to a gas valve that could be opened and closed

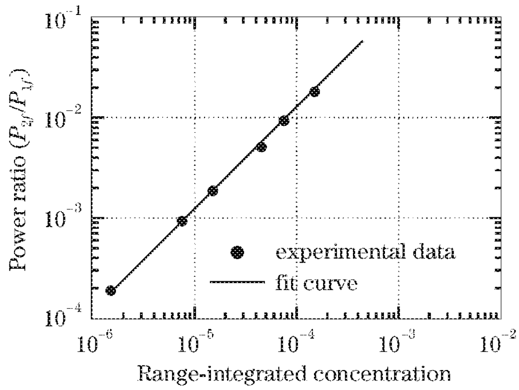

Fig. 2. The remote sensor outputs versus the range-integrated methane concentration.

quickly. One end of a length of hosetube was attached to the gas valve and the other end was placed in the vicinity of the inspection site. When the gas valve was opened for a short period (about 1 s), methane is released and outputs of the four sensors were recorded by the computer module. Figure 3 shows the results for a simulated methane leak. Since the time duration that gas valve opened was very short, the security of the laboratory is assured.

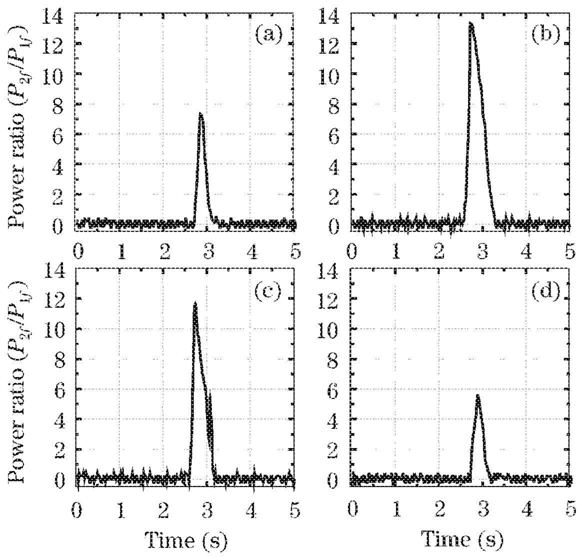

Fig. 3. Distributed simulated methane leak detection. Chart (a), (b), (c) and (d) respectively show output of four sensors that in Fig. 1 for a simulated methane leak.

In conclusion, we have developed a distributed optical sensing methane system using a single ECDL. By using a single ECDL and components originally designed for the telecommunications industry, the system can detect gas leaks from multi-coal face simultaneously in mines and will enable a cost-effective, reliability and marketability. The system shows sufficient sensibility, considerably increased reliability and marketability over the presently available system. It results in a large potential for applying extensively to various strategic points within the environment.

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References

1. P. Werle, Spectrochimica Acta Part A **54,** 197 (1998).
2. D. Lognoli, G. Cecchi, I. Mochi, L. Pantani, V. Raimondi, R. Chiari, T. Johansson, P. Weibring, H. Edner, and S. Svanberg, Appl. Phys. B **76,** 457 (2003).
3. J. Reid and D. Labrie, J. Appl. Phys. B **26,** 203 (1981).
4. D. S. Bomse, A. C. Stanton, and J. A. Silver, Appl. Opt. **31,** 718 (1992).
5. A. N. Dharamsi, J. Phys. D: Appl. Phys. **29,** 540 (1996).
6. W. B. Yin, J. M. Zhao, W. G. Ma, C. Y. Li, L. T. Xiao, and S. T. Jia, Chin. J. Lasers **30,** 928 (2003).
7. L. S. Rothman, R. R. Gamache, R. H. Tipping, C. P. Rinsland, M. A. H. Smith, D. C. Benner, V. M. Devi, J.-M. Flaud, C. Camy-Peyret, A. Perrin, A. Goldman, S. T. Massie, L. R. Brown, and R. A. Toth, J. Quantum Spectrosc. Radiat. Transfer **48,** 469 (1992).
8. J. S. Margolis, J. Appl. Opt. **27,** 4038 (1988).