

The SWDAS Sensor for Stand-off Detection of Methane

Zhang Shuai⁺, Liu Wen-qing, Zhang Yu-jun, Ruan Jun, Wang Li-ming, You Kun, Liu Jian-guo

Key Laboratory of Environmental Optics & Technology, Anhui Institute of Optics & Fine Mechanics,
Chinese Academy of Sciences, Hefei, China

Abstract. Natural gas pipeline leak detection is significant in terms of security, environmental protection and security of state property. However, the leak detection is difficult, because of the pipeline's covering many areas, operating conditions and complicated environment. Quantitative remote sensing of natural gas leakage and location research, with laser absorption spectroscopy, will be faster, safer, more accurate and intelligent. This standoff Scanned-wavelength Differential absorption spectroscopy (SWDAS) sensor is enabling novel applications for remote gas sensing and non-contact process monitoring. SWDAS is feasible and applicable in natural gas leak detection by analyzing the experimental results, which will become a new diagnostic method for leak detection.

Keywords: standoff sensing; remote sensing; leak detection; Scanned-wavelength Differential absorption spectroscopy (SWDAS)

1. Introduction

With increasing the pipeline, using the pipeline and having been destroyed by erosion-corrosion, the pipeline leakages have been occurred frequently, which have caused tremendous threat to the people's life and property safety. In particular, Leakages not only cause economic loss, but polluting the environment, even arouse fire and explosion. According to the statistics, our pipeline leakages have many times higher than developed countries'. It can effectively reduce losses and damage if we detect leaks in time, and accurately locate the leak.

Leak detection technology mainly includes: cable fiber leak measurement, acoustic leak method, pipeline leak detection based on model, pressure gradient measurement, the mass balance method, negative pressure wave method and the magnetic flux leak method. Pipeline leak detection technology is combination of multi-disciplinary knowledge. Various methods have their own characteristics, advantages and disadvantages. Recently, leak detector has become increasingly important due to the widening interest in environmental problems. SWDAS provides one of the best methods as it has many advantages over conventional techniques based on gas chromatography or mass spectroscopy^[1,3,4,5]. For example, SWDAS provides real-time measurement, remote and non-destructive sensing, good molecular selectivity and good sensitivity. At one end, SWDAS platforms address novel niche market applications with lower cost, simpler, and configurable designs. At the other end, SWDAS is being applied to increasing difficult applications demanding sensing of multiple target gases in complex gas mixtures and extremely harsh environments. This paper focuses on emerging standoff SWDAS applications, i.e. those where the SWDAS measurement path is defined by the combination of a transceiver that illuminates and receivers light scattered from a diffuse surface. This corresponds to an ability to locate natural gas leaks resulting in path-integrated concentrations. We simulated natural gas leak outside, which demonstrates the feasibility and applicability by using SWDAS.

2. Swdas Method

⁺ E-mail address: zhangshuai@aiofm.ac.cn

Differential absorption detection and harmonic detection are the most commonly used methods for the detection of weak absorption. Both methods can be realized by a linear variation in injection current to simultaneously scan DFB diode lasers in intensity and wavelength^[4,6]. SWDAS can achieve the minimum detectable absorption, i.e. the detection limit of methane will be $7 \text{ ppm} \cdot \text{m}$, for molecular absorption lines at $1.65 \mu\text{m}$, molecular absorption intensity of $8.7 \times 10^{22} \text{ cm}^{-2} \text{ atm}^{-1}$, line width of 0.05 cm^{-1} .

The principles are straightforward: Gas molecules absorb energy at specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these absorption lines, there is essentially no absorption. Specifically, when the laser frequency (reciprocal wavelength) is tuned to correspond to a particular absorption transition of the target gas molecule, the transmitted light is attenuated according to the Beer-Lambert relation^[1,2,3,4,5,6]:

$$I(\nu) = I_0(\nu) \exp(-\sigma(\nu)NL) \quad (1)$$

Where, N is the number density, $\sigma(\nu)$ is absorption cross section for the gas molecules. Gas absorption linear can be described by Lorentz under atmospheric pressure. The molecular absorption cross section can be expressed as:

$$\sigma(\nu) = \frac{S}{\pi} \frac{\nu_L}{(\nu - \nu_0)^2 + \nu_L^2} \quad (2)$$

Where S is molecular absorption intensity, ν_L is half-width half-height. The absorption cross section at the center of absorption line can be expressed as:

$$\sigma(\nu_0) = \frac{S}{\pi \nu_L} \quad (3)$$

In the case of weak absorption ($\sigma(\nu)NL \ll 0.05$), the absorption intensity can be expressed as:

$$\frac{\Delta I(\nu)}{I_0(\nu)} = \sigma(\nu)NL \quad (4)$$

This formula describes the absorption light intensity ratio at different frequencies. A complete gas absorption spectrum can be obtained from accumulated absorption by different frequency, described as follows:

$$absorb = \int_{\nu} \sigma(\nu)NL \quad (5)$$

We get absorption spectrum at time-domain, and convert to frequency-domain by etalon. The gas concentration can be detected by the formula 5.

Figure 1 shows the systemic structure, which includes: lasers and laser control circuit, noise cancellation circuit, transceiver telescope, computer control system. The laser was scanned by high-frequency sawtooth of 10 kHz. A linear variation in injection current was used to scan DFB diode lasers simultaneously in intensity and wavelength. The laser was divided into three beams. The first beam passes through the wavelength calibration cell, which was mainly used for wavelength calibration. The second laser beam was not absorbed, which was directly received reversly by a high-sensitivity InGaAs detector. The detection signal was directly entered into the noise cancellation circuit, as the reference signals of noise cancellation circuit. The third laser beam was transmitted into the telescope by an armored single-mode fiber. The echo signal was received frontly by the same detector, and entered into noise cancellation circuit. Noise cancellation circuit resolved automatic gain amplification of signal and noise cancellation. Differential absorption can be realized by noise

cancellation circuit. This approach Weakened the laser self-noise, optical feedback noise and the interference of background signal. Laser light intensity should be normalized because of differential absorption was obtained under different amplification gain coefficient. Differential absorption spectra should be fitted by Lorenz linear under the data processing. It aimed at eliminating the noise which disturbed absorption spectrum, and lead to inaccurate measurements.

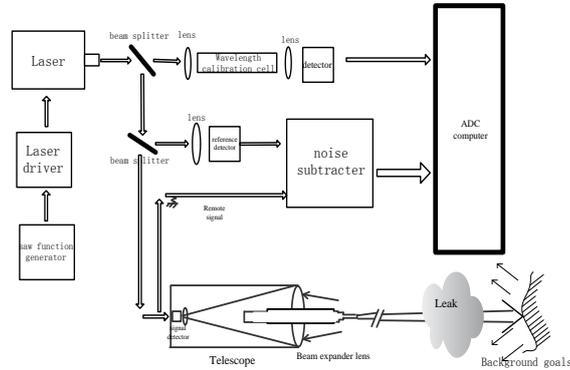


Figure 1. Systemic structure diagram of laser remote sensing of natural gas leaks.

3. Optical Power And Linearity Characterization

The performance of the optical system was initially evaluated using a fiber-coupled tunable diode laser having a nominal wavelength near 1.6 μm , suitable for sensing methane at several spectral lines of varying strength. Data were acquired by remote measurement from a movable target which was made from a 50 \times 50 cm^2 flat section of white corrugated clothe on a tripod. The target position was varied at regularly spaced distances between about 1 and 30 m from the transceiver, the range being limited by available space in the laboratory. The average received remote intensity was measured at each position. Echo signal strength can be calculated as shown by the formula 6^[3]. Figure 2 shows the echo signal strength began to become stronger with increasing space distance, reaching maximum at about 5 meters away, then began to become weaker, and shows the monotonically decreasing phenomenon. On the one hand, due to the changes of telescope blind area. On the other hand, the echo signal intensity is inversely proportional to the square of the distance. Telescope was designed by a coaxial way. Blind area would be larger when the transmitter at close range, and gradually smaller When the diameter of laser beam was larger than the aperture of transmitter.

$$P_{DC} = \left(\frac{A_{col} R_{dif} \eta_{opt}}{R^2} \right) P_{out} \quad (6)$$

Where: A_{col} = effective area of optical receiver in m^2 , R_{dif} = differential reflectance of topographic targets, η_{opt} = optical efficiency, R = distance to topographic target in m, P_{out} = laser output power in W.

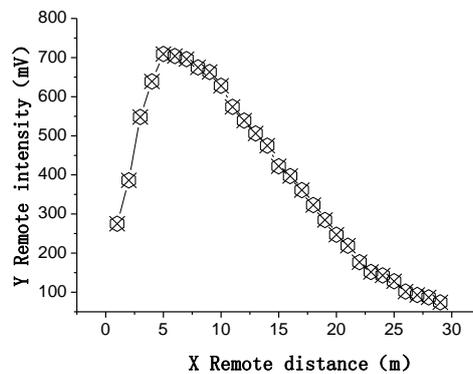


Figure 2. The relationship between remote distance and remote intensity.

Table 1 shows the ranges from which the sensor receives adequate backscattered laser power after implementing the improvements described above. For most topographic targets, the maximum range exceeds the specification value of 30 meters. The topographic targets include: white walls, bricks, leaves, grass, white clothing, clean snow, books, cement road, dirty water, The metal surface, the soil surface, and the dirty snow. Where the biggest remote distance is 37 meters, the minimum distance is only 3 meters.

TABLE I. THE MAXIMUM REMOTE DISTANCE OF THE DIFFERENT TARGET

Surface	Maximum Range (m)	Surface	Maximum Range (m)
White walls	31	Books	28
Brick	37	Cement road	29
Leaves	32	Dirty water	4
Lawn	29	Metal surface	33
White clothing	33	Soil surface	27
Clean snow	20	Dirty snow	16

4. The Minimum Detectable Concentration For A Given Light Level

Those signals obtained from the backscattered laser are independent of methane in the optics path and show clearly the characteristic spectra. A methane concentration of 5%, confined to a 50mm length of the beam, i.e. 2500 ppm*m. The key parameter in determining the smallest amount of gas that can be measured is the amount of backscattered light reaching the detector. Figure 3 shows a graph of the minimum detectable gas concentration (S:N=1:1) as a function of received power. The detection limit scales inversely with the returned light power, indicating that the system has a constant noise floor.

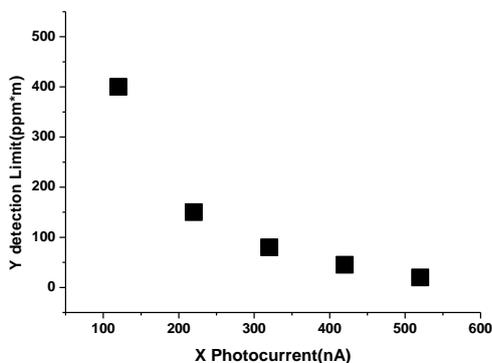


Figure 3. Minimum detectable gas concentration for a given light level

5. Field-testing And Evaluation Of The Sensor

Experiment was carried out in Weihai City. The participants are Key Laboratory of Environmental Optics and Technology, CAS and Harbin Institute of Technology. Experimental device can be shown in figure 4. It consists of A and B: A: natural gas leak detector, B: mobile telemetry device.

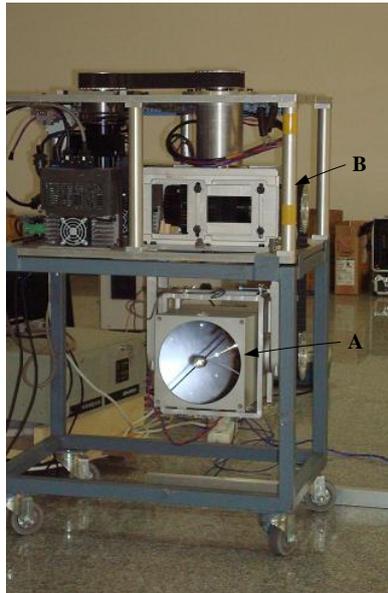


Figure 4. Experimental device (A: natural gas leak detector B: mobile telemetry device)

Figure 5 shows a time-trace of the sensor's output in a natural gas leak detection scenario. Experimental conditions are: 1, methane gas of 5%; 2, standoff sensing range of 30 meters; 3, the gas flow is controlled under 20 Kg / h; 4, northeast of 1 ~ 2. The results can be observed by rotating mobile telemetry device at different angles, which are: 3 degrees, 7 degrees, 13 degrees, 15 degrees, 13 degrees, etc. Sensor can detect path-integrated concentrations of the gas. The concentrations will change with the angles change due to gas diffusion. However, it is important to appreciate that in most 'angle' situations the gas concentration will be strongly different from the vicinity of the leak.

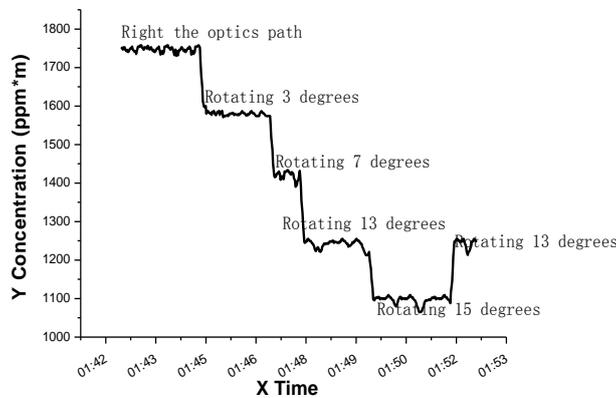


Figure 5. A natural gas leak detection scenario

6. Conclusion

In this paper, SWDAS has been used for remote sensing of natural gas leaks. With field experiments, the system prototype described above has demonstrated its ability to detect natural gas leaks from a mobile telemetry device. The technology has a great potential to reduce the cost and improve the quality of pipeline gas leak survey. In a word, SWDAS can be a new diagnostic method for leak detection.

7. Acknowledgment

This work was supported by the National High Technology Research and Development (863 Program) (No.2008AA06Z208). S. Zhang's e-mail address is zhangshuai@aiofm.ac.cn.

8. References

- [1] F. Hong, G. Xiao ming, B. Jian, W. Xia, H. Teng et al. "Study on Remote Sensing of Methane Leakage Using a Tunable Diode Laser," *Spectroscopy and Spectral Analysis*, 26(8):1423~1426(in chinese), 2006.
- [2] M. B. Frish, M. A. White, M. G. Allen. "Handheld laser-based sensor for remote detection of toxic and hazardous gases," *SPIE Paper*, No. 4199-05, 2000.
- [3] B.V. Well, S.Murray, J.Hodgkinson, R.Pride, R.Strzoda, G.Gibson and M.Padgett. "An open-path, hand-held laser system for the detection of methane gas," *J. Opt. A: Pure Appl. Opt.* 7:S420~S424, 2005.
- [4] Z.Shuai, L.Wen-qing, Z.Yu-jun et al.. "Gas Leakage monitoring with scanned-wavelength direct absorption spectroscopy," *Chin.Opt.Lett* , 8(5):443~446, 2010.
- [5] T. Iseki. "A portable remote methane detector using an InGaAsP DFB laser," *Environmental Geology* , 46:1064–1069, 2004.
- [6] P. Werle , R. Mücke , F. D. Amato et al.. "Near-infrared trace-gas sensors based on room-temperature diode lasers," *Appl. Phys.(B)* , 67(3) : 307~315, 1998 .