

# Improving the measurement accuracy of hydrogen cyanide sensor by using DSP technique

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Finite impulse response digital filter is used to improve the measurement accuracy of hydrogen cyanide gas sensor. Simulation and experimental results show that the minimum detectable gas concentration of about 0.1ppm is achieved by using direct spectroscopy technique at the wavelength of 1537.299 nm while the input power of the light source is 1 mW.

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**Keywords:** Hydrogen cyanide gas sensor, Finite impulse response digital filter, Direct spectroscopy technique, Measurement accuracy

## 1. Introduction

Gas detection systems have become increasingly important for safety and environmental monitoring in industry. However, the wavelength and intensity detection accuracy are usually limited by various kinds of noises, such as interferometric noise, thermal noise, and 1/f noise [1]. High-sensitivity measurements were achieved through the use of wavelength modulation and multi-pass intracavity spectroscopy techniques, with the minimum detectable gas (acetylene) concentrations of 781ppm and 1000ppm respectively [2, 3]. Whereas, both of their setups were complex and the measurement errors were always induced by the intensity fluctuations due to the instability of the pump laser sources and optical noises from other components, such as the EDFA, optical filter, photodetector (PD), etc [2,3]. In this paper, the use of digital signal processing technique to enhance the measurement accuracy of hydrogen cyanide (HCN) gas sensor is reported. The results of computer simulation are shown in Section 2, experimental results are presented in Section 3, and a conclusion is given in Section 4.

## 2. Background theory and simulation results

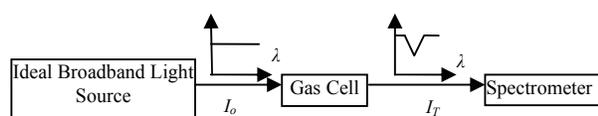


Fig. 1. Block diagram of direct absorption spectroscopy technique.

The block diagram of the direct absorption spectroscopy technique is shown in Fig. 1. The light from an ideal broadband light source is passed through a HCN

gas cell. By Beer's Law, because of the absorption of the gas molecules, the output intensity after the gas cell is

$$I_T = I_o \exp(-\alpha_m l C) \quad (1)$$

where  $I_o$  and  $I_T$  respectively denotes the input and output intensity,  $l$  is the length of the gas cell,  $C$  is the gas concentration and  $\alpha_m$  is the molar absorption coefficient, related with each individual absorption line, which could be obtained from Malathy's model [4]. For trace gas monitoring at a low pressure, the absorption line could be described as a Lorentzian function (press-broadened line) [5]. So the absorption coefficient of HCN gas  $\alpha(\lambda)$  could be rewritten as

$$\alpha(\lambda) = \frac{\alpha_m}{\left\{ \left( \frac{\lambda - \lambda_o}{\Delta\lambda/2} \right)^2 - 1 \right\}} \quad (2)$$

where  $\alpha_m$  is the molar absorption coefficient at the central absorption wavelength  $\lambda_o$  and  $\Delta\lambda$  is the full-width-half-maximum (FWHM) of the absorption line at  $\lambda_o$ . Concerning in a practical gas multiplexing system [6], an optical input power for each gas cell is quite small, i.e. the corresponding signal-to-noise-ratio (SNR) is quite small, and hence this will increase the measurement error. Moreover, the noise from the laser source is regarded as white noise [1], which will contribute significant errors in the detection. In order to improve the measurement accuracy of gas detection system, an effective technique is to employ a digital filter to remove these noises [7] in such system. Compared to its real optical counterparts, the attraction of the digital filter comes from key advantages such as no drift in performance with the ambient environment and great flexibility without the need to modify the hardware. In this simulation, R(7), the strongest absorption line of HCN gas in the near infrared

region (NIR), is used for analysis, while the molar absorption coefficient  $\alpha_m$  is equal to  $2.4488 \times 10^{-4} \text{ Pa}^{-1} \text{ m}^{-1}$ . The central wavelength  $\lambda_0$  and corresponding FWHM  $\Delta\lambda$  of the absorption line are 1537.299 nm and 60 pm respectively, the length of the gas cell  $l$  is 121000 ppm and the gas concentration  $C$  is 22.5 cm. The input power of the laser source is assumed to be 1 mW, while the absorption of the light intensity by HCN molecules is about 3 dB as shown in Fig. 2. The amplitude of noise is set to be 0.2 mW, so the signal-to-noise-ratio (SNR) is about 5, which is much smaller than in some practical cases. To design appropriate parameters of the filter, the frequency spectrum of the signal with noises is obtained by using discrete Fourier transform (DFT) analysis [7]. The DFT spectrum demonstrates the maximum signal frequency  $f_a$  is at 1 mHz. Therefore, a digital finite impulse response (FIR) low-pass filter is designed by the optimal method [8]. Compared with an infinite impulse response (IIR) filter, FIR filter has an exactly linear phase response and is realized nonrecursively, so its stability is better guaranteed. The chosen passband (PB) frequency and stopband (SB) frequency of the filter are 1 mHz and 400 mHz respectively and the number of order (N) is 7. The simulation result is illustrated in Fig. 2. The SNR of the signal after the FIR filter is about 48, 6.82 dB larger than the signal with noise without any filtering.

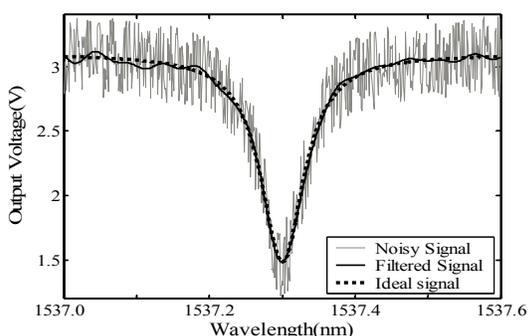


Fig. 2. Spectra of R(7) absorption line.

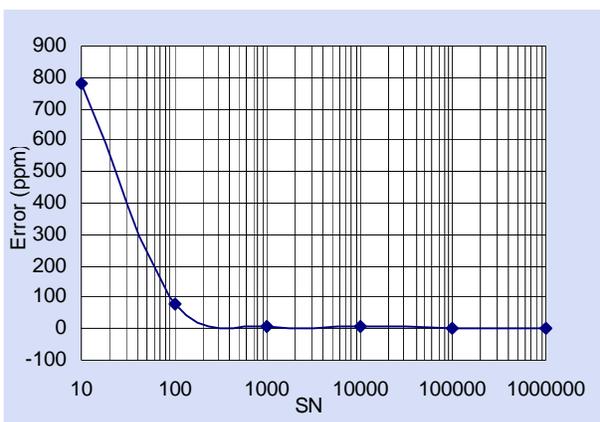


Fig. 3. Signal-to-noise ratio vs. detection errors of gas concentration.

In some practical cases, SNR should be around 10000~100000, dramatically larger than that simulation study. The relationship of SNR after filtering and the error in terms of the gas concentration is shown in Fig. 3, where the aforementioned filter is used for this simulation. It demonstrates clearly that when SNR is larger than 10000, the error can be reduced to below 1 ppm.

### 3. Experiment and discussion

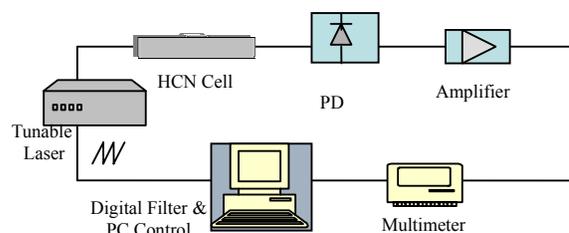


Fig. 4. Experimental schematic diagram.

The experimental configuration is shown in Fig. 4. To obtain the whole NIR absorption spectrum, the input light of a tunable laser source (ANDO-AQ4321D) of 1 mW, which was scanned from 1520 nm to 1580 nm with a step wavelength of 1 pm, was passed to a NIST Standard Reference Material HCN absorption cell (2v, band, 22.5 cm path length, 13.3 kPa pressure, corresponding to concentration of 121000 ppm of HCN gas [9]); After the absorption of HCN molecules, the light from the gas cell was detected by a broadband photodiode (PD) with an amplifier, whose gain was 3.9V/mA; Finally, the spectrum was recorded by a personal computer (PC).

The entire HCN NIR absorption spectrum is shown in Fig. 5. The depth of the R(7) absorption line at 1537.299 nm was about 1.6V, corresponding to the gas concentration of 121000 ppm in the cell by Beer's Law. The amplitude of the noise around the dip of R(7) was found to be  $2 \times 10^{-5}$  V. The SNR was about 80000, corresponding to the minimum detectable gas concentration of  $N_{\min} = 1/\text{SNR} \times 12.1\% = 1.5$  ppm [3]. After the use of the aforementioned FIR filter for the unfiltered R(7) absorption line, the minimum voltage fluctuation around the dip reached to about  $1 \times 10^{-6}$  V, corresponding to the minimum detectable gas concentration up to about 0.1 ppm.

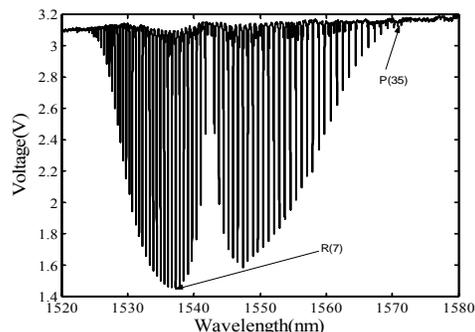


Fig. 5. NIR absorption spectrum of HCN gas.

To show the effect of the FIR filter more prominently, input power from the laser source was reduced to  $10\mu\text{W}$ , and then the SNR became rather smaller. The P(35) absorption line at  $1572.387\text{ nm}$ , the most distinguishably weakest peak in Fig. 5 was used to analyze. The PB and SB frequency of the filter were set to be  $1.5\text{ MHz}$  and  $450\text{ MHz}$  respectively, and the order of the filter  $N$  was set to be 7. The experimental result is shown in Fig. 6. It can be seen that the spectrum after filtering was significantly smoother. The SNR is increased from 8 to 160, with  $13\text{ dB}$  enhanced after the use of the well-designed FIR filter. Moreover, Fig. 7 shows a linear relationship of the unfiltered and filtered SNR of P(35) absorption line with the input power of the light source, which indicates the input power will not affect the capability of the designed filter.

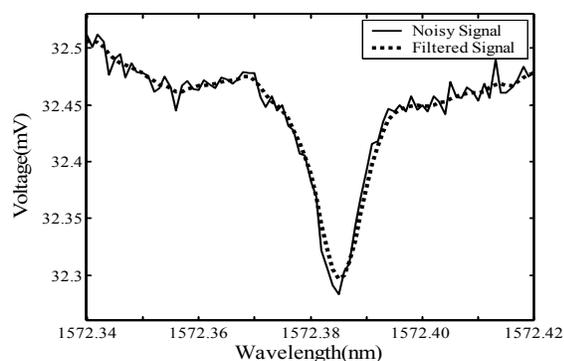


Fig. 6. Spectra of P(35) absorption line.

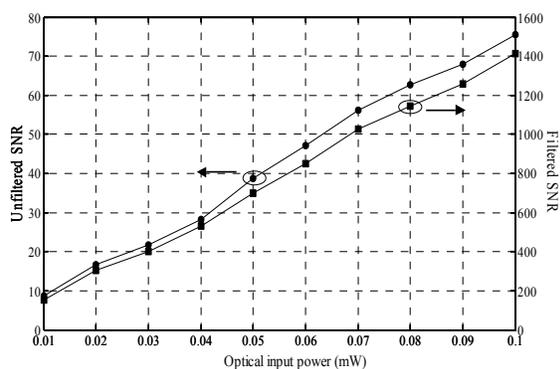


Fig. 7. Signal-to-noise ratio of P(35) absorption line vs. optical input power.

#### 4. Conclusions

A feasible scheme is proposed to improve the sensitivity of the HCN gas sensor by using digital signal processing technique. Both simulation and experimental results have showed that the detection accuracy is enhanced to  $0.1\text{ ppm}$  at the absorption wavelength of  $1537.299\text{ nm}$  while the input power is  $1\text{ mW}$  by using the well designed digital FIR filter. Furthermore, the weakest absorption gas lines can also be detected by using this technique while they cannot be detected by using other methods.

#### References

- [1] Todd B. Sauke, Joseph F. Becker, Modeling, measuring, and minimizing the instrument response function of a tunable diode laser spectrometer, *Journal of Quantitative Spectroscopy & Radiative Transfer* **91**, 453 (2005).
- [2] Gillian Whitenett, George Stewart, Hongbo Yu, Investigation of a tunable mode-locked fiber laser for application to multipoint gas spectroscopy, *Journal of Lightwave Technology* **22**, 3, March 2004.
- [3] Min. Zhang, D. N. Wang, Wei. Jin, Yanibiao. Liao, Wavelength modulation technique for intra-cavity absorption gas sensor, *IEEE Transactions on Instrumentation and Measurement*, **53**, 1, Feb 2004.
- [4] Arthur. Maki, Wolfgang. Quapp, Stefan. Klee, Intensities of hot-band transition: HCN hot bands, *Journal of Molecular Spectroscopy* **171**, 420 (1995).
- [5] George Stewart, A. Mencaglia, W. Philp, Wei. Jin, Interferometric signals in fiber optic methane sensors with wavelength modulation of the DFB laser source, *J. of Lightwave Technology*, **16**, 1, Jan 1998.
- [6] H. B. Yu, W. Jin, Y. B. Liao, et al., A novel fiber-optic intra-cavity sensing network using a mode-locked fiber ring laser, 2002 IEEE.
- [7] C. C. Chan, W. Jin, M. S. Demokan, Enhancement of measurement accuracy in fiber Bragg grating sensors by using digital signal processing, *Optics & Laser Technology* **31**, 299 (1999).
- [8] Emmanuel C. Ifeakor, Barrie W. Jarvis, *Digital Signal Processing: A Practical Approach*, pp. 367-380 (Chapter 7).
- [9] S. L. Gilbert, W. C. Swann, C. M. Wang, Hybrid cyanide absorption reference for  $1530\text{-}1560\text{ nm}$  wavelength calibration-SRM 2519, NIST Special Publication, **137**-260 (1998).

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