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RESEARCH ON THE EXTRINSIC FABRY-PEROT INTERFERENCE (EFPI) TECHNOLOGY FOR OPTICAL FIBER SENSING TECHNOLOGY OF MINE GAS**

1. Introduction

At underground, the key gas component is methane that is inflammable and explosive. Gas monitoring can avoid preventing and reducing safety accidents in coal mine. Gas concentration monitoring is very important for coal mine safety and personal safety.

For the defects of chemical detection methods, people at home and abroad began to study the optical detection method to replace the traditional chemical detection method. The principle of optical fiber sensing technology of mine gas is spectrum optical fiber gas sensing, which is different from the traditional gas sensor. Particularly, it has advantages of high sensitivity, high speed responsibility, wide dynamic range, explosion-proof, nonflammable, nontoxic and telemetry. Optical fiber has the characteristics such as: small volume, light weight, flexibility, stable chemical property, anti-electric magnetic field interference and electric insulation. It works reliably, especially in hazardous and bad environments. Therefore, the optical fiber sensing mine gas system has attracted considerable attention, in recent years.

This paper adopts the method of Extrinsic Fabry-Perot Interference (EFPI) technology for optical fiber sensing technology of mine gas. The relation between light intensity and concentration of gas is obtained from the analysis of the varying information which is

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interference spectrum returned from EFPI optical fiber sensor, and then the concentration of gas is calculated. Optical fiber sensing technology of mine gas is telemetry, which is characterized with high reliability, high reliability and well stability. And by this method, we can analyze historical data and the distribution of gas concentration under wells to get predict gas disaster and gas burst and make warning.

2. Spectral domain EFPI optical fiber sensing theory

2.1. System block diagram of EFPI optical fiber sensing

On the mechanism of spectral domain interference demodulation, optical spectral analysis equipment is used for light signal detection unit. We can get changes of the optical path difference, according to analyzing cosine form spectrum signal interference modulated by optical spectrum and returned from sensing unit of analysis. System block diagram of EFPI optical fiber sensing is shown in Figure 1.

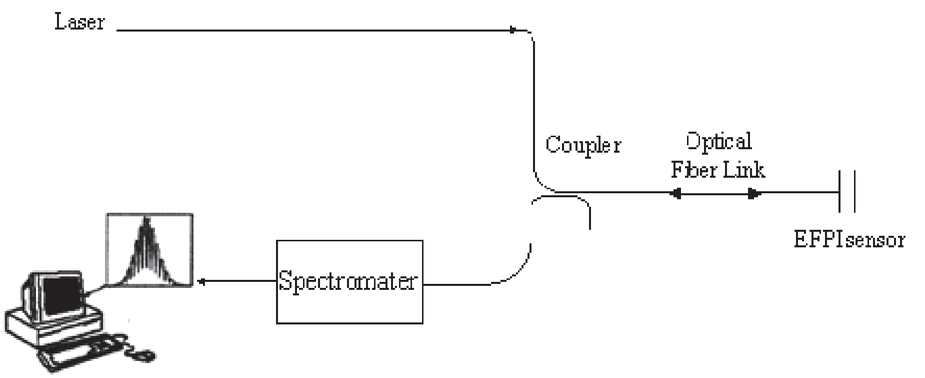

Fig. 1. System block diagram of EFPI optical fiber sensing

2.2. Mechanism of interference demodulation for coal gas in spectral domains based on optical fiber sensing

For the coupling loss, EFPI-type sensor actually has multi-beam interference with energy loss. When laser beams enter the cavity from optical fiber, let r be reflection coefficient and t be transmission coefficient. When laser beams enter optical fiber from the cavity, let r' be reflection coefficient and t' be transmission coefficient. Optical field in $F - P$ cavity can be expressed as E_0e^{iwt}.

And optical fields by multiple reflections are expressed as follow:

$$E_{r1} = E_0 r e^{iwt}$$

$$E_{r2} = E_0 t r' t' L e^{i(wt-2ks)} \tag{1}$$

$$E_{r3} = E_0 t r'^3 t' L^2 e^{i(wt-4ks)}$$

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Among them, $k = \frac{2\pi}{\lambda}$ is the wave number, s is the depth of $F-P$ cavity, w is frequency of light wave. Electric field vector of superimposed reflected light is shown as follow:

$$E_r = E_{r1} + E_{r2} + E_{r3} + \ldots$$

$$= E_0 e^{iwt}\left(r + r'tt'Le^{-2ikl} + r'tt'r'^2 L^2 e^{-4ikls} + \ldots\right) \tag{2}$$

Among them,

$r = -r' = \sqrt{r}$,

$tt' = t(1-r)$.

The reflected light field is expressed as follow:

$$E_r = E_0 e^{iwt} r^{0.5}\left[1 - \frac{(1-r)}{r}\sum_{n=1}^{\infty}(rL)^n\ e^{-i2nks}\right] \tag{3}$$

Conjugate optical field is shown as follow:

$$E^*{}_r = E_0 e^{iwt} r^{0.5}\left[1 - \frac{(1-r)}{r}\sum_{n=1}^{\infty}(rL)^n e^{i2nks}\right] \tag{4}$$

The relationship formula between incident intensity and incident field is shown as follow:

$$I_i = E_0 e^{iwt} \times E_0 e^{-iwt} = E_0{}^2 \tag{5}$$

The reflective light intensity is shown as follow:

$$I_r = E_r \times E^*{}_r$$

$$= I_i r\left[1-\frac{(1-r)}{r}\sum_{n=1}^{\infty}(rL)^n e^{-i2nks}\right]\times\left[1-\frac{(1-r)}{r}\sum_{n=1}^{\infty}(rL)^n e^{i2nks}\right]$$

$$= I_i r\left[1-\frac{(1-r)}{r}\sum_{n=1}^{\infty}(rL)^n\left(e^{-i2nks}+e^{i2nks}\right)+\frac{(1-r)^2}{r^2}\sum_{n=1}^{\infty}(rL)^n e^{-i2nks}\times\sum_{n=1}^{\infty}(rL)^n e^{i2nks}\right]$$

According to conjugate complex number formula, $e^{-2nks}+e^{2nks}=2\cos(2nks)$, the above equation is simplified as follow:

$$I_r = I_i R\left[1-\frac{(1-R)}{R}\sum_{n=1}^{\infty}(RL)^n\times 2\cos(2nks)+\frac{(1-R)^2}{R^2}\sum_{n=1}^{\infty}(RL)^n e^{-i2nks}\times\sum_{n=1}^{\infty}(RL)^n e^{i2nks}\right]$$

$$I_r = I_i \times r \times \frac{1+L^2-2L\cos(2ks)}{1+(rL)^2-2(rL)\cos(2ks)} \tag{6}$$

I_i is the incident intensity, L is the loss coefficient of fiber coupling. The above equation is the theoretical formula of white-light interference demodulation for coal gas in spectral domains based on optical fiber sensing, according to the loss coefficient of fiber coupling from multi-beam interference. Finally the concentration of the gas is figure out, by Beer law and the relations between light intensity and concentration of gas.

3. Spectrum signal de-noising

3.1. Theoretical basis

Before locating spectral peaks, de-noising is necessary. The normalized interference spectrum of wavelength domain is obtained by micro fiber spectrometer.

$$I_n(\lambda) = 2\left[1+\gamma\cos\left(\frac{4\pi G}{\lambda}+\varphi_0\right)\right] \tag{7}$$

The interference spectrum of wavelength domain is the band limited signal which is limited frequency components. Therefore, the signal isn't suitable for FIR Low-Pass Filter to reduce noise. Wavelet Transform is an effective method to realize de-noising of non-band limited signal. We decompose signals into a wavelet basis function by wavelet transform.

A series of wavelet functions superposition is obtained by the time translation and the scale extension. Wavelet is defined as the interior product of different scales and the awaiting analysis $x(t)$, after the displacement of t in the function $\Psi(t)$ of mother wavelet:

$$WT_x(a,\tau) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\psi^2\left(\frac{t-\tau}{a}\right)\mathrm{d}t, \qquad a > 0 \tag{8}$$

The original signal is recovered by the superposition of every wavelet transform coefficient and wavelet function of time translation and scale extension. In order to study the appearance of high frequence better, the adjustable frequency-time window generated by wavelet based on some wavelet basis function becomes narrow automatically, or otherwise. The method based on wavelet multi-resolution analysis, shows the different frequency characteristics, which decomposes signals at different frequencies. Signals are decomposed into two portions of detail including high frequency components and approximation including low frequency components. The approximation is decomposed into two further portions of detail and approximation. The decomposed degree is higher, the frequency is lower. The decomposing of signals, which is used to decompose the mixed signal composed by different frequency, effectively, applies to signal-noise separation.

3.2. Experimental data

On the wavelet de-noising of spectrum signal, firstly, we should choose a wavelet basis function to determine the degree N of wavelet decomposition, and then decompose signals n times. Useful interference signals are in low-frequency part, and noise-signals are in high-frequency part. We decompose wavelet to get each coefficient of high-frequency, and then determine a threshold by a certain statistical method. The coefficient of high-frequency that is less than threshold is set zero or decreased. Reconstruction the Nth coefficient of low-frequency part and anther coefficient of high-frequency part in threshold obtains de-noised signals.

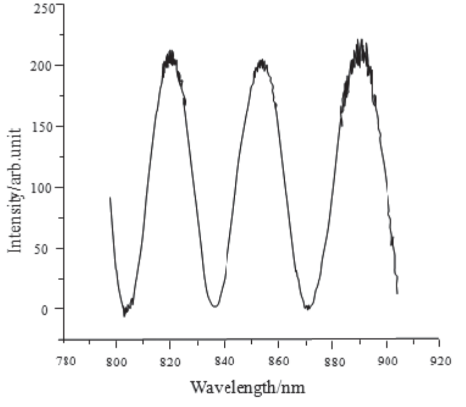

Fig. 2. Normalized spectrum before wavelet denoise

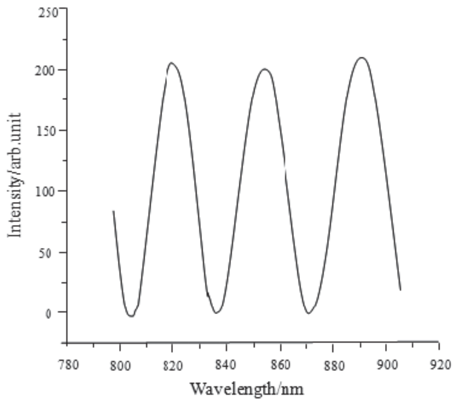

Fig. 3. Normalized spectrum after wavelet denoise

Figure 2 shows the normalized spectrums before wavelet de-noise. Figure 3 shows the normalized spectrums after wavelet de-noise. Compared with the normalized spectrums after the wavelet de-noise, the normalized spectrums before wavelet de-noise are smoother. And it's lossless.

4. Spectrum peak of spectrum signal precise positioning

Micro fiber spectroscopic system in a CCD detector array is the continuous spectrum signal in space discrete sampling, sampling may omit the real spectral peak positions, and polynomial fitting can be used to determine the exact location of the spectrum peak.

Have been obtained the smooth normalized spectrum signals by wavelet de-noise, firstly, by means of a simple comparison, the maxima point of interference spectrum is used as the cursory estimate value of spectrum peak positions in the effective range of the spectrum. By the numbers near the cursory estimate value of spectrum peak positions, the quadratic polynomial curve $I(\lambda) = a_1 + a_2\lambda + a_3\lambda^2$ is fitted by the least squares method. The extreme point of the fit multinomial curve is the exact position of spectrum peak. As Figure 4, it shows the process.

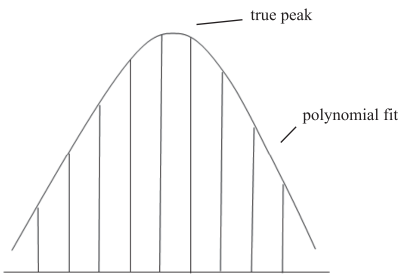

Fig. 4. Polynomial fit method for peak locating in the spectrum

5. Conclusions

In optical fiber sensing technology of mine gas, spectrum de-noising and exact positioning are realized separately by the wavelet transform and the polynomial fit. The measurement technology based on optical fiber sensing technology of mine gas is one of the most wonderful technologies. And it has the strongest anti-interference capability. A new measurement technology of mine gas is proposed in the research, which is applied to a new and practical optical fiber gas sensor and alarm system. The system is up to the requirement of the gas monitoring and alarm system, which is on line, real-time, rapid. The situation that the mortality of million-ton coal-mines in China is much higher than the international standard is improved. A feasible alarm system will be established.

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