Application of distributed optical fiber temperature sensing system based on Raman scattering in coal mine safety monitoring

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***Abstract*—The principle and design of the distributed optical fiber temperature sensing system based on Raman scattering is presented in this paper. The spatial resolution is enhanced by reducing the pulse width of the light source and high speed progressive average etc. The distributed optical fiber sensor not only has the characteristics of resistance to electromagnetic interfere, against fire and so on, but also it can sense the change of temperature along the optical fiber by the form of continuous distance. Because of its ascendency and the augmented performance, This paper also introduces the example used in coal mine goaf temperature monitoring and data analysis.**

Keywords-Distributed optical fiber temperature sensing system; Raman scattering; Stokes and anti-Stokes; Optic time domain reflectometry（OTDR）; Coal mine goaf

I. INTRODUCTION

The imformation technology represented as fiber communication and sensing are strongly developed in this years, which immensely accelerates the progress of human society. Especially, the distributed optical fiber sensor shows practical value in various industry. It is not only transport media but also sensing media. Compared with other sensor, fiber is a new sensor with its individual advantage, such as immunity to flammability, explosion, high voltage and electromagnetism, otherwise, The system is designed for the application of a large-scale multi-point measurement of temperature by measuring the signal of the Raman scattering. Therefore, it can be used in the coal mine safety monitoring. Coal mine goaf fire is one of the great calamity in our country. the environment of coal mine goaf is complex, mine mechanical and electrical equipment fire, gas explosion accident is the direct cause of temperature. Therefore, distributed optical fiber as a new type of sensor in its various advantages, for the coal mine production safety to provide advanced and reliable, economic and practical early fire forecasting and warning system.

II. PRINCIPLE OF THE SYSTEM

A. Raman scattering

A laser pulse is launched into the sensing element, as it propagates along the fiber, as the fiber in the presence of the refractive index of the microscopic inhomogeneity, it can generate Rayleigh scattering, Brillouin scattering and Raman scattering. Raman scattering occurs into the Stokes and anti-Stokes bands, as follows Fig.1. The anti-Stokes is sensitive to the change of temperature along the fiber, and the power is under the influence of the temperature[1].

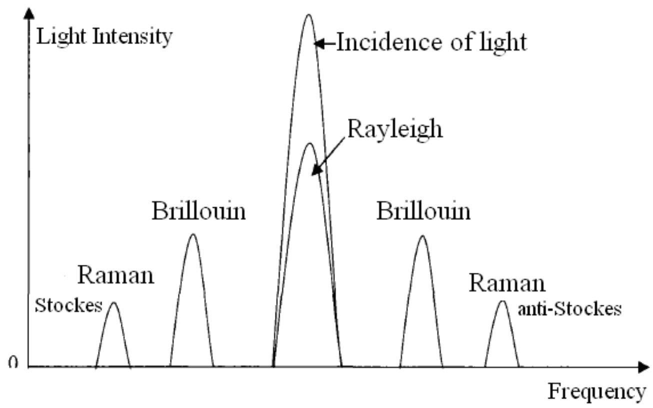

Figure 1. Optical fiber dispersion spectrum

The scattering intensity reacts to the level of the environmental temperature. In Fig.1, Raman scattering photons can be distinguished as Stokes scattering center wavelength and anti-Stokes scattering center wavelength[2]. Therefore, the frequency v_s of Stokes scattering photons is given by

$$v_s = v_0 - \Delta v \quad (1)$$

The frequency v_a of anti-Stokes scattering photons is expressed as

$$v_a = v_0 + \Delta v \quad (2)$$

$R_s(T)$ and $R_a(T)$ are the coefficients that are related with the population on the low or high energy level of the fiber and are related with the local temperature. There are

$$R_s(T) = [1 - \exp(-h\Delta v / kT)]^{-1} \quad (3)$$

$$R_a(T) = [\exp(h\Delta v / kT) - 1]^{-1} \quad (4)$$

Doctoral Fund of Shandong Academy of Sciences where h is the Planck constant; k is the Boltzmann constant[3];

If $T=T_0$, using (3) and (4), we can get

$$\frac{1}{T}=\frac{1}{T_0}-\frac{k}{h\Delta v}[\ln\frac{N_a(T)N_s(T_0)}{N_a(T_0)N_s(T)}] \tag{5}$$

Where *N* is the number of the photons at the injection point of the fiber; T_0 , h , k , $N_a(T)/N_s(T)$ and $N_s(T_0)/N_a(T_0)$ are all known, We can use the high sensitivity of anti-Stokes signal and the temperature sensitivity of the lower Stokes signal as the ratio of temperature information, in order to suppress the intensity of the light source, optical fiber optical injection conditions, and the geometry and structure changes of the optical fiber. So the temperature *T* can be calculated[4].

B. Optic time domain reflectometry

A narrow laser pulse is injected into the fiber and propagates along the fiber. The backscattering light along the fiber rebounds to the injection point of the fiber. If the time at which the laser pulse is injected is set to be the time origin[5], there is

$$L=V\times t/2=ct/2n \tag{6}$$

where *L* is the distance between the scattering point and the injection point of the fiber, *t* is the time at which it returns to the injection point, c is the speed of light in the vacuum and n is the refractive index of the optical fiber. Therefore, it can get the information at different positions by measuring the echoes at different times[6].

III. DESIGN OF THE SYSTEM

Distributed optical fiber temperature sensoring system host comprises the following modules[7], see Fig.2.

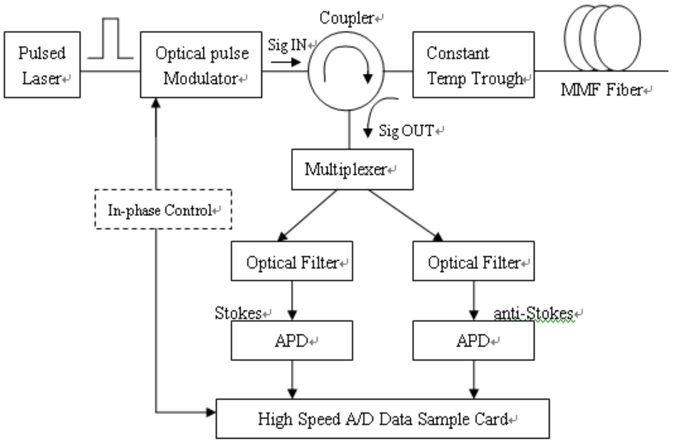

Figure 2. System light path connection

- Laser module: High pulse semiconductor laser and laser drive circuit.
- Thermostatic apparatus: Used to solve the temperature sensor calibration, provide the reference temperature.
- Wave Division Multiplexer(WDM): The bidirectional optical fiber couplers and wavelength division multiplexing.
- Photoelectric receiver, amplifier module: The avalanche photodiode (APD) and high gain, low noise main amplifier.

Under the control of a synchronous control unit triggering a pulse, optical transmitter generates a large current pulse, the pulse driving a semiconductor laser to produce high power and narrow pulse, the light pulses output from the laser through optical coupler into the sensing optical fiber. Laser pulse in the sensing fiber can occur in scattered, the Raman backscattering light with temperature information will back to the optical coupler, optical coupler will not only transmits light pulses directly coupled into the optical fiber, but also it can coupled the Raman scattering light to the Wave Division Multiplexer (WDM) with the different wavelength[8]. WDM is composed of two different wavelength light filter, they are filtered out Stokes light and anti-Stokes light, two light signal passes through the receiver when the photoelectric conversion and amplification, and then by the data acquisition unit for high speed data sampling, conversion to digital data, again after a further signal processing (Improving noise ratio of the signal), to obtain the temperature distribution, which will display on a computer and provide alarm information.

IV. IMPROVE THE PERFORMANCE OF THE SYSTEM

Some measures to improve the performance of the system:

A. Using narrow pulse fiber laser to improve spatial resolution

Spatial resolution *R* is determined by the following factors: Detecting light pulse width, fiber dispersion, response time of the photoelectric conversion device, amplifying circuit band width and A / D conversion rate[9].

As the following equation:

$$R=\sqrt{R_{pulse}^2+R_{A/D}^2+R_{amp}^2} \tag{7}$$

The assumption of measurement system for detecting optical pulses into a rectangle, ignoring the optical pulse in optical fiber chromatic dispersion in, think photoelectric detector and amplifier frequency band is wide enough (including conversion rate is fast enough), t_w is the optical pulse width, V_g as the speed of light in optical fiber, within all the points of the backscatter signal will arrive in measuring terminal overlap each other, so the pump light corresponding to the spatial resolution R_{pulse} is

$$R_{pulse}=\frac{t_wV_g}{2} \tag{8}$$

Optical pulse width is determined by spatial resolution calculation, as Fig.3.

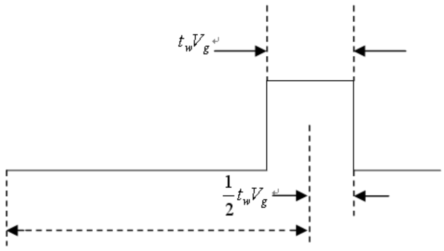

Figure 3. Relationship between pulse width and space-resolution

In this system, A / D conversion rate $R_{A/D}$ and amplifying circuit band width R_{amp} is immobility. In order to improve the spatial resolution, The system spatial resolution requirements to 1m, by the calculation results, using high-speed A / D acquisition card, which A / D conversion rate can reach 150MHz. Amplifier band width 350MHz. So we should reducing the pulse width of the light source. The width of the light source can not exceed 10ns.

B. Hardware accumulative average and wavelet transform to improve the noise ratio and speed of response

The measurement accuracy of the whole system has relationship with the de-noising level to anti-Stokes and Stokes scattering. So the weak signal measurement is must be used in this system. Therefore , Using accumulative average and wavelet transform to achieve the joint scattering signal de-noising processing, and improving signal noise ratio and speed of response of the distributed optical fiber temperature sensing system. The process of accumulative average is in Fig.4.

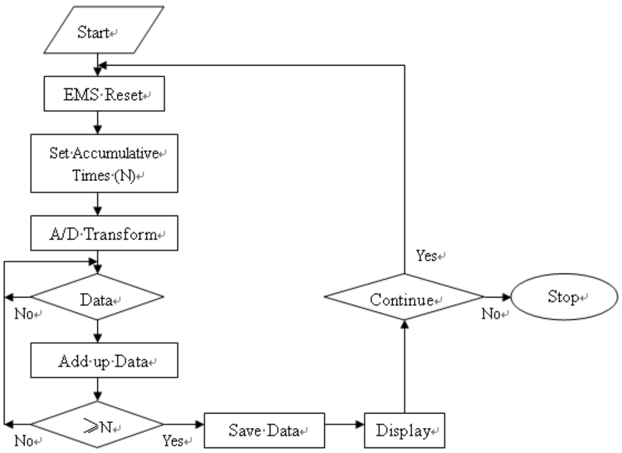

Figure 4. The process of accumulative average

According to the characteristics of distributed temperature measurement signal, mostly useful signal is in the low-frequency part of the noise while the vast majority of noise is random noise, which distributed throughout the frequency range. In order to reduce system noise on the measurement of the impact of the resolution, we can increase the number of signal accumulation times to improve the measurement resolution, which can cause the system to lengthen the measurement cycle, and affect the actual application. Therefore, We select wavelet transform analysis method for the signal de-noising before cumulating, the wavelet transform can be broken down the different frequencies of mixed-signal into different sub-frequency signals, noise can be effectively applied to the separation, and this separation of noise and the filter has its significance. It can ensure that reducing temperature measurement cycle to improve the noise ratio and system speed of response under the premise of spatial resolution.

V. APPLICATION IN COAL MINE MONITORING

The distributed optical fiber temperature sensing system has incomparable advantages than the traditional monitoring system whether in the sensing or in the system performance. In China's coal industry, The coal mine safety of production and security of person is an important event, and the spontaneous of coal mine is the target of safety monitoring object in coal mining area, so the coal mine goaf temperature is an important monitoring objectives. As the coal mine goaf is a bad environment, the use of high mechanical properties of the fiber as a temperature sensor along with the mined area laying, construction is convenient and simple, So the coal mine goaf can be given a continuous temperature signal transmission through optical fiber to the control room, The sensing system can provide a good monitoring program which have long distance temperature monitoring for the coal mine goaf area.

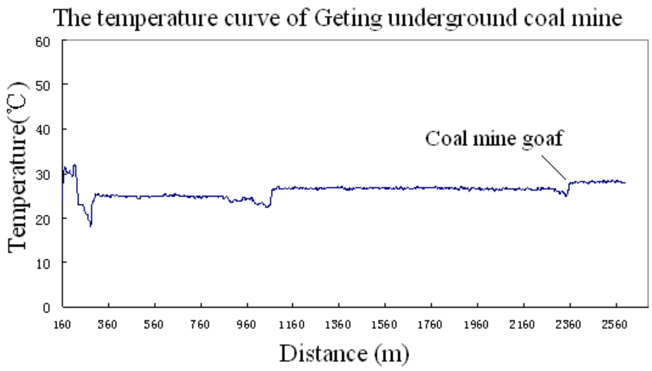

Figure 5. The temperature curve of Geting coal mine

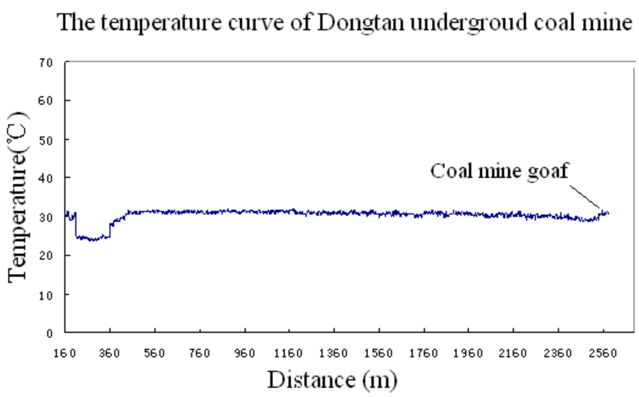

Figure 6. The temperature curve of Dongtan coal mine

VI. CONCLUSION

Distributed optical fiber temperature sensing system based on Raman scattering as emerging sensing monitoring technology in recent years has attracted more and more attention to the safety monitoring field. This paper introduces the system 's basic principle and the system structure, using high-performance hardware and efficient algorithms to improve the spatial resolution, the noise ratio and temperature response time. In the engineering applications, the sensing fiber optic cable laid to coal mine goaf, and applied the real-time monitoring in coal mine goaf temperature and positioning, so that we can get the real-time coal mine goaf temperature condition, this system with its own unique advantages in the coal mine safety monitoring applications, the system plays an significant role for coal mine safety production.

ACKNOWLEDGMENT

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