Fiber Optic Microseismic Monitoring System Used in Underground Coal Mines

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**Abstract.** A fiber optic microseismic monitoring system for underground coal mines is proposed in this paper. The technical details including overall structure, fiber Bragg grating geophone, and interrogation system are introduced. The results show that the system achieves a bandwidth of 1-300 Hz and a dynamic range of 80 dB. An application example of monitoring cross-border mining activities in underground coal mine is presented at the end.

1. Introduction
Microseismic monitoring provides a logistical tool to guide the effort into prevention, rating of seismic hazards and alerts to potential rockmass instabilities in coal mines [1]. In recent years, microseismic monitoring in coal mines has been increasingly taken by using fiber optic geophones. This is based on the advantages of high sensitivity, large dynamic range, electrically passive operation, immunity to electromagnetic interference and other significant advantages [2]. However, the existing mine fiber optic microseismic monitoring systems have narrow frequency band, small dynamic range, and weak expansibility [3], seriously hinder the further development of monitoring system itself.

In this work, a fiber Bragg grating (FBG) geophone based on flexure hinge structure is done to detect the microseismic events, getting a wider frequency bandwidth. A precision edge filter interrogation system based on digital signal processing technology is provided to implement data acquisition (DAQ), seismic interrogation, clock synchronization and data communication, ensuring system large dynamic range and good expansibility. The results and actual application demonstrate that this system is quite suitable for precision microseismic monitoring in underground coal mines.

2. System implementation
As shown in Figure 1, the system mainly consists of FBG geophone, interrogation substations, host station and hardware precision time protocol (PTP) time server. The substations are distributed underground while the host station is located above ground; eliminating the needs for large amounts of the optical fiber cable in shaft and making it possible to layout more seismic sensors.

The FBG geophones detect microseismic signals. The resulting signals are digitalized at the substation. Each substation connects with 8 to 16 sensors. All substations communicate with host station via ethernet ring network, while can connect up to 128 sensors. The seismogram data are ultimately recorded and processed at the host station. The PTP time server synchronizes the host station and the substations with GPS clock.

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Figure 1. Topological diagram of fiber optic microseismic monitoring system.

2.1. FBG geophone

The schematic of the FBG geophone is illustrated in figure 2(a). A mass block is connected to the shell of the geophone through a flexure hinge. One end of a FBG is fixed on the extended beam and the other end is fixed on the shell. When the shell vibrates with the acceleration, the mass block rotates around the hinge relative to the shell under the action of inertial force, so that the strain of the FBG changes with the extension of the beam, leading to the shift of the central wavelength of the FBG.

![Figure 2(a)](image1)

Figure 2. Schematic diagram (a) and photograph (b) of FBG geophone.

The dimension of the flexure hinge is marked in Figure 2(a), including width $b$ (not shown in the figure), minimum thickness $t$, cutting radius $R$. Assuming $t$ is far less than $R$, the rotational stiffness of the hinge can be expressed as [4]:

$$K = \frac{9\pi \sqrt{R}}{2Ebt^{35}}$$

(1)

where $E$ is the elasticity modulus of the material. Thus, the resonant frequency can be defined as:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{kh^2 + K}{[(a^2 + c^2)/12 + d^2]m}}$$

(2)

where $k$ is the elastic coefficient of the fiber, $h$ is the height of the beam, $a$ is the length of the mass block, $e$ is the height of the mass block, and $m$ is the mass of the mass block. Moreover, the accelerometer sensitivity (wavelength shift of FBG per unit acceleration) is given by:

$$S = \frac{(1 - p_e)\lambda_a}{l} \frac{md}{kh + K/h}$$

(3)

where $p_e$ is the elastic-optic coefficient of fiber, $\lambda_a$ is the FBG wavelength of fiber, and $l$ is the length of the fiber. By optimizing the parameters $l$, $h$, $d$, $R$, $t$, $a$, $b$, $c$ and $m$, the geophone is designed to fit for microseismic detection in underground coal mines. The optimized parameters have been shown in Table 1. The resonant frequency is designed to be about 450 Hz, while the accelerometer sensitivity is about 65 pm/g. Figure 2 (b) shows the FBG geophone itself.
### Table 1. The parameters of the FBG geophone

| Parameters | \( l \) (mm) | \( h \) (mm) | \( d \) (mm) | \( R \) (mm) | \( t \) (mm) | \( a \) (mm) | \( b \) (mm) | \( c \) (mm) | \( m \) (g) |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Value      | 16     | 10     | 6      | 3      | 0.5    | 10     | 10     | 10     | 20     |

#### 2.2. Interrogation system

Figure 3 illustrates the interrogation system, which is based on the edge filter approach [5]. The DFB-LD is powered by a constant current source (CCS). The emitted light passes through a circulator and arrives at the FBG geophone. The reflected light passes through the circulator, and is converted into a sensing current (\( I_s \)) by PD2. A built-in BF-PD converts the monitoring light to a reference current (\( I_r \)). They are amplified by two trans-impedance amplifiers (TIA1 and TIA2) to the proportional voltages (\( V_s \) and \( V_r \)), and enter a simultaneous sampling Δ-Σ ADCs. The acquired samples are stored in the FPGA and enter the DSC to perform the division operation. The output signal can be expressed as:

\[
V_0 = k (R + \beta \Delta \lambda)
\]

where \( k \) is the scale factor, \( R \) is the reflectivity of the FBG when the wavelength of DFB-LD is in the half reflectivity spectrum of the FBG, \( \beta \) is the edge slope of the FBG reflectivity spectrum.

![Figure 3. Schematic diagram of interrogation system.](image)

This resulting signal passes through a finite impulse response (FIR) filter, thus obtaining the AC and the DC components of the microseismic signal. The temperature of the DFB-LD is controlled by a PID algorithm running in DSC through a TEC controller, thus regulating the wavelength of the LD to a proper position. This system communicates and synchronizes with host station via IEEE-1588 Ethernet. The PTP supported in DSC allows submicroseconds time synchronization [6].

#### 3. Results

The complete system has been calibrated by using Brüel & Kjær vibration exciter type 4808. Figure 4 (a) and (b) show the frequency response (@ 0.5 ms\(^{-2}\)) and linearity (@ 30 Hz), respectively. It can be seen that the system has a -3dB frequency response of 1 to 300 Hz and has a good linearity over a range of 10\(^{-3}\) to 10 ms\(^{-2}\). The dynamic reaches up to 80 dB.

![Figure 4. Frequency response (a) and linearity (b) of the system.](image)

#### 4. Application in coal mine

A fiber optic microseismic monitoring system was established in Ningtiaota coal mine in Shanxi Province for monitoring cross-border mining activities, which not only damages coal resources, but also may cause rock outburst, methane explosion, etc. Twenty FBG geophones were installed along the tunnel near border. Figure 5 (a) shows the microseismic signals obtained from six of these FBG
geophones. And the spectrum analysis (figure 5 (b)) shows that the frequency range of the microseismic signals is mainly between 5 Hz and 100 Hz.

![Figure 5](image Url)

**Figure 5.** The microseismic signals (a) and their spectrums got by the system

Figure 6 shows the distribution plan of the microseismic events during March 23 to May 11, 2017. It can be seen that microseismic events induced by cross-border mining were monitored inside the border, while issuing a warning. After April 16, 2017, cross-border mining activities were monitored outside the border, and the coal mine safety was secured.

![Figure 6](image Url)

**Figure 6.** Microseismic events distribution induced by cross-border mining

5. Conclusions

A fiber optic microseismic monitoring system for underground coal mines has been developed and characterized. The proposal of this paper is to use a FBG geophone based on flexure hinge structure to detect the microseismic events, getting a wider frequency bandwidth. A precision edge filter interrogation system is provided to implement seismic interrogation, clock synchronization and data communication, not only improving the dynamic range, but also allowing to layout more sensors. This can effectively increase the location accuracy of seismic events. The test results and actual application show that the FBG microseismic system has great potential for mining safety monitoring.

Acknowledgment

This work was partly supported by the National Key Research and Development Plan (No. 2016YFC0801405) and the Natural Science Foundation of Shandong Province (No. ZR2016QZ006).

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