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Technical Note

Monitoring of coal mine roadway roof separation based on fiber Bragg grating displacement sensors

Zhen-Gang Zhao*, Yong-Jun Zhang, Chuan Li, Zhou Wan, Ying-Na Li, Kuan Wang, Jun-fei Xu

College of Information Engineering and Automation, Kunming University of Science and Technology, Kunming City 650500, China

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1. Introduction

The roof separation layer is the biggest hidden danger in coal mine roadway. Major roof falls can cause fatality, injury and significant economic loss [1,2]. Thus the separation layer behavior should be investigated in time during mining, especially in the process of blasting excavation. Numerous studies have been done in the past to investigate roof behavior related to coal mining activities [3]. Tan et al. presented a new approach for predicting bedding separation of roof strata in underground coalmines by analyzing the ratio between current and average vertical bedding separation [4]. As the methane concentration might be much higher in underground coal mine [5], sensors with electronic signals are not suitable to monitor the roof separation. As optical fiber sensors have all-optical characteristics both in signal detection and transmission process, those sensors are very suitable for working in the coal mine environment [6–8].

In the optical fiber structural sensing field, fiber Bragg grating makes excellent optical displacement sensors with high sensitivity [9–11]. Based on the fiber Bragg grating sensing technology, a novel method to safely monitor the separation layer displacement in coal mine roadway is proposed. Analyzing the roof separation by fiber Bragg grating (FBG) displacement sensors, the displacement variation in the blasting process is researched and the influence of blasting on roof separation layer displacement is discussed.

2. Operation principle of a FBG displacement sensor

An FBG is essentially a wavelength-selective filter, which consists of a short segment of single mode optical fiber with a photo-induced periodically modulated index of refraction in the core of the fiber, as shown in Fig. 1.

The Bragg wavelength λ_B depends both on the physical characteristics of the fiber and geometrical characteristics of the grating:

$$\lambda_B = 2 n_e \Lambda \qquad (1)$$

where n_e is the effective refractive index of the grating in the fiber core and Λ is the grating period [12,13]. Both n_e and Λ are dependent on strain and temperature, which enables the FBG to be used for sensing parameters such as temperature, strain and displacement.

A cantilever beam is the key translation component in a differential fiber Bragg grating displacement sensor, as shown in Fig. 2. This cantilever beam is a triangle cantilever beam of constant bending rigidity, where the thick end is fixed on the support; the thin end is vertically jointed to the gage rod. The fiber

* Corresponding author.
E-mail address: zhaozhenganghit@126.com (Z.-G. Zhao).

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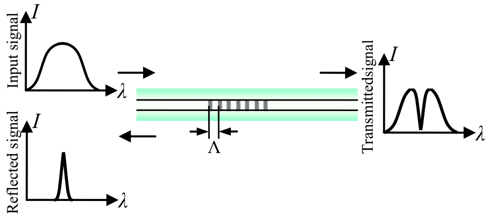

Fig. 1. Transmission and reflection spectrum of FBG.

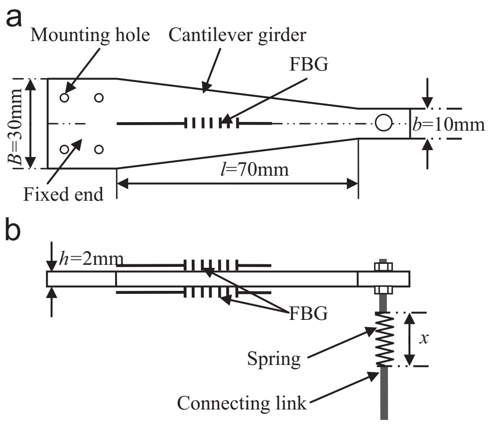

Fig. 2. The schematic diagram of differential FBG displacement sensor, (a) plan view, (b) cross section view.

Bragg gratings are mounted on the top and bottom surfaces of cantilever.

In Fig. 2, the cantilever beam is made from stainless steel of length $l=30.0$ mm, thickness $h=3.0$ mm, width of thick end B, width of thin end b, and obliquity of cantilever beam of constant bending rigidity a. Two Bragg gratings are mounted on the top and bottom surfaces of the beam.

The combined interrogation system based on FBG and a distributed Brillouin network, operating at different wavelengths, can demodulate two independent temperatures and strains. The Bragg grating resonance λ_B is the center wavelength of back-reflected light from a Bragg grating. The Bragg wavelength shift $\Delta\lambda_B$ due to strain and temperature changes is given by:

$$\Delta\lambda_B=\lambda_B(1-p_e)\varepsilon'+\lambda_B(\alpha+\xi)\Delta T=S_\varepsilon\varepsilon'+S_T\Delta T \tag{2}$$

where ε' is the strain change, ΔT is the temperature variation, $p_e\approx 0.22\ \mu\varepsilon^{-1}$ is the effective strain-optic constant for the fiber; $\alpha\approx 0.55\times 10^{-6}\ ^\circ\mathrm{C}^{-1}$ is the thermal expansion coefficient; and $\xi\approx 6.12\times 10^{-6}\ ^\circ\mathrm{C}^{-1}$ is the thermo-optic coefficient. Moreover, the strain and thermal coefficients of relative Bragg wavelength shifts are $0.78\times 10^{-6}\ \mu\varepsilon^{-1}$ and $6.67\times 10^{-6}\ ^\circ\mathrm{C}^{-1}$. At 1550 nm, the strain and thermal sensitive coefficients are $S_\varepsilon\approx 1.21$ pm/με and $S_T\approx 10.3$ pm/°C for silica-based fiber Bragg grating.

In this scheme, the Bragg gratings mounted on the top and bottom surfaces of the cantilever separately experience strains of ε' and $-\varepsilon'$, and are located in the same temperature field T. By using the differential method, the strain ε' and the temperature variation ΔT can be expressed as the function of the Bragg wavelength shifts:

$$\varepsilon'=\frac{\Delta\lambda_B(\varepsilon,\Delta T)-\Delta\lambda_B(-\varepsilon,\Delta T)}{2S_\varepsilon}$$
$$\Delta T=\frac{\Delta\lambda_B(\varepsilon,\Delta T)+\Delta\lambda_B(-\varepsilon,\Delta T)}{2S_T} \tag{3}$$

As the displacement of connecting link occurs, the displacement of the mounting hole d' is converted into the deflection of the cantilever, as shown in Fig. 3. Provided the camber of cantilever is small, i.e., then d' is small, the relation between the pull F on the cantilever and elongation Δx can be formulated as

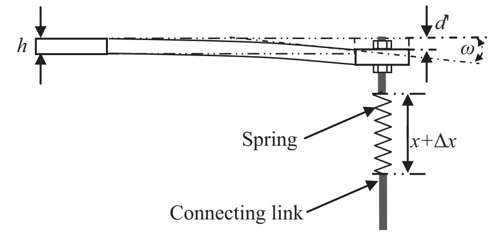

Fig. 3. The schematic diagram of differential fiber Bragg grating strain sensor.

$$F=k\Delta x \tag{4}$$

where k is the elastic coefficient of the spring in the sensor. The bending deflection ω of the cantilever under pull can be expressed as

$$\omega=\frac{Fl^3}{3EI} \tag{5}$$

where E is the modulus of elasticity, I is the area moment of inertia. As the section of cantilever is rectangular, the area moment of inertia is expressed by

$$I=\frac{1}{12}bh^3 \tag{6}$$

where, b and h are the width and thickness of the cantilever, respectively. Plugging Eqs. (6) and (4) into Eq. (5), the deflection of the cantilever can be expressed as a function of the spring elongation Δx:

$$\omega=\frac{4kl^3}{Ebh^3}\Delta x \tag{7}$$

As the relation between the strain ε' and deflection ω on the cantilever can be formulated as:

$$\varepsilon'=\frac{h}{l}\omega \tag{8}$$

The strain of the cantilever can be expressed by

$$\varepsilon'=\frac{4kl^2}{Ebh^2}\Delta x \tag{9}$$

Thus, the strain changes in proportion to the spring elongation Δx.

3. Layout of the FBG displacement sensors in Zhu Xian-zhuang coal mine

Fig. 4 shows the monitoring system of coal mine roadway separation layer. An amplified spontaneous emission (ASE) broadband light source (with an optical spectrum from 1525 to 1565 nm) and a FBG interrogation analyzer with the resolution of 1 pm were used to measure the spectral response of FBG. The incident and reflected light beams share the same physical path by passing a single-mode 1:1 fiber coupler. Two FBGs were applied in this experiment to realize temperature compensation. The difference between central wavelengths of the two FBGs was taken as the effective signal related to separation layer displacement [14].

The roadway roof has a layered structure. When the difference in stiffness between upper layer and lower layer is great, i.e., when the upper is hard rock and the lower is soft rock, roof separation will occur between the layers, as shown in Fig. 5 [4]. When the roof separation occurs, the spring fixed on the cantilever beam will be pulled by the steel cable through a connecting link. Thus the deflection of the cantilever beam will change, which make the