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Quasi-distributed sensing network based on coherence multiplexing and spatial division multiplexing for coal mine security monitoring*

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Abstract: A low-cost fiber Bragg grating (FBG) sensing system for coal-mine security monitoring is proposed in this paper. Based on the coherence multiplexing (CM) and spatial division multiplexing (SDM) techniques, this hybrid sensing network can support more than 40 sensors for quasi-distributed detection. It is demonstrated experimentally that the multiplexed sensing signal of each sensor can be clearly distinguished by an optical low-coherence reflectometry (OLCR). Methane concentration is detected with maximum sensitivities of an intensity variation of 10.92% and a concentration variation of 1%, using a well-designed sensor structure. Strain and temperature are also detected by this system, which also exhibits good results in the experiment.

Key words: Fiber Bragg grating, Coherence multiplexing, Spatial division multiplexing, Optical low-coherence reflectometry, Methane concentration

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1 Introduction

Frequent coal-mine accidents cause thousands of deaths each year in China, due to unawareness of abnormal environmental conditions, such as methane concentration, temperature, and the strain beneath coal-mines. If an effective monitoring system is created for multi-parameter detection at multiple locations under the coal-mine in real time, such tragedies can be efficiently avoided (Liu, 2007).

Fiber Bragg gratings (FBGs) are used to design smart and high resolution sensors for a majority of applications due to their efficient properties, such as an electrically passive operation, electromagnetic immunity, high sensitivity, compact size, and especially large multiplexing capability (Kersey *et al.*, 1997; Dennison and Wild, 2008; Gagliardi *et al.*, 2008; Lu *et al.*, 2008; Tsuda *et al.*, 2009). The FBG based Fabry-Perot (FP) sensor is one of these applications; it has very high resolution and sensitivity to the FP cavity length variation, and has attracted a great deal of research interest recently (Han and Wang, 2006; Chin *et al.*, 2007; de Oliveira *et al.*, 2007). On the other hand, several multiplexing techniques have been reported in previous research targeted at building networks for distributed or quasi-distributed sensing applications (Igawa *et al.*, 2008; Men *et al.*, 2008; Crunelle *et al.*, 2009). However, most of these techniques need high-cost light sources and other expensive devices. As an alternative, optical low-coherence reflectometry (OLCR) is one of the coherence multiplexing techniques; it needs just a normal low-cost broadband light source or even white light, and can demultiplex signals from several interferometric sensors (Sorin and Baney, 1995; Chapeleau *et al.*, 2003; Karalekas *et al.*, 2008). Such a

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technique was employed to interrogate sensors based on fiber Bragg grating pairs (FBGPs) in our previous work (Guan *et al.*, 2007; Liu *et al.*, 2008). Here we continually employed an OLCR to interrogate signals from three types of FBGP sensors to measure temperature, strain, and methane concentration at multiple sensing locations. Its multiplexing capacity was quadrupled by adding an optical switch in the system, which shows the potentialities for quasi-distributed coal-mine security monitoring applications.

2 Principle

Fig. 1 shows the schematic diagram of the proposed sensing system. Each sensor is composed of two identical FBGs, where one works as the sensing FBG to measure environmental parameters, and the other is a reference. These two FBGs form an in-fiber Fabry-Perot interferometer (FPI). An optical path difference (OPD) is induced by the FPI since the light is reflected by these two FBGs at different locations, and the value of the OPD is $\Delta L_i=2n_{eff}l_i$, where n_{eff} is the effective refractive index of the fiber core and l_i is the interval between the two FBGs. Thus, according to Guan (2007), the reflected electric fields from the two FBGs of one sensor can be expressed as

$$\begin{cases} E_1(\omega)=\rho_1(\omega)E_0(\omega), \\ E_2(\omega)=\tau_1{}^2(\omega)\rho_2(\omega)\exp(-\mathrm{i}\Delta\varphi_{\mathrm{FPI}})E_0(\omega), \end{cases} \tag{1}$$

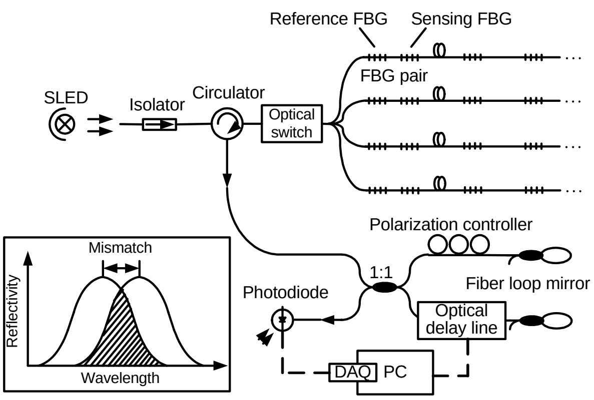

Fig. 1 Schematic diagram of the proposed spatial-division-multiplexing/coherence-multiplexing system for fiber Bragg grating pair (FBGP) sensors
The inset is the correlation of two reflected field from an FBGP. SLED: superluminescent diode; DAQ: data acquisition

where $E_0(\omega)$ is the field of the input light source, $\rho_1(\omega)$ and $\rho_2(\omega)$ are the reflection coefficients of these two FBGs, $\tau_1(\omega)$ is the transmission coefficient of the reference FBG shown in Fig. 1, and $\Delta\varphi_{\mathrm{FPI}}=\Delta L_i\omega/c$ is the phase difference induced by OPD inside the FPI.

Then the light propagates through the OLCR, which is used to distinguish the multiplexed sensing signals. The OLCR is actually a scanning Michelson interferometer (MI). The OPD between the two arms of the MI can be changed by scanning the tunable optical delay line (TODL) inserted in one arm. Thus, the output field $E_3(\omega)$ can be given by

$$E_3(\omega)=\frac{1}{2}(1+\exp(-\mathrm{i}\Delta\varphi_{\mathrm{MI}}))(E_1(\omega)+E_2(\omega)), \tag{2}$$

where $\Delta\varphi_{\mathrm{MI}}$ is the phase difference induced by the scanning MI. Therefore, the light intensity I detected by the photodiode can be expressed as

$$I\propto\frac{1}{2\pi}\mathrm{Re}\left\{\int_{-\infty}^{+\infty}E_3^*(\omega)E_3(\omega)\mathrm{d}\omega\right\}. \tag{3}$$

If we consider only the alternating part (AC), Eq. (3) can be simplified as

$$I_{\mathrm{AC}}\propto\frac{1}{4\pi}\mathrm{Re}\left\{\int_{-\infty}^{+\infty}E_1(\omega)E_2^*(\omega)\exp[-\mathrm{i}(\Delta\varphi_{\mathrm{FPI}}-\Delta\varphi_{\mathrm{MI}})]\mathrm{d}\omega\right\}. \tag{4}$$

Only when $\Delta\varphi_{\mathrm{FPI}}=\Delta\varphi_{\mathrm{MI}}$, can the interference occur, because of the short coherence length of the light source. Furthermore, the oscillating parts of the interfered light intensity can be rewritten as

$$I_{\mathrm{AC}}\propto\mathrm{Re}\left\{\int_{-\infty}^{+\infty}E_1(\omega)E_2^*(\omega)\mathrm{d}\omega\right\}. \tag{5}$$

We can find that the interfered light intensity is proportional to the correlation of two reflected fields (i.e., the overlapping area of the two reflection spectra). When there is no exoteric variation added to the sensing FBG, the reflection spectra of the two FBGs totally overlap with each other and produce a maximum interfered intensity. If the ambient condition around the sensing FBG changes, the resonance wavelength of the sensing FBG will shift beyond that of the reference one, which is shielded from the environment, causing a mismatch between the central peak wavelengths of the two FBGs' reflection spectra, as shown in the inset of Fig. 1. This leads to a reduction of interfered intensity. From the relationship between the detected interfered intensity from a photodiode and the central wavelength mismatch, it is easy to deduce the variation of the sensing parameter.

FBGPs with different intervals can be multiplexed in series according to the coherence multiplexing (CM) technique. During the scanning of the TODL, only a single FPGP sensor's interference signal can be demultiplexed when the FBGP-induced OPD can be compensated exactly by the MI-induced OPD. The multiplexing capacity depends on the maximum scanning range of the TODL and the minimum interval variation of the two FBGPs. Considering the temperature controlled light source and the well fixed fiber link, we assume that the polarization properties of this system are constant. Therefore, we use a polarization controller to optimize the polarizations for an efficient interference. In addition, the spatial division multiplexing (SDM) technique greatly increases the multiplexing capacity of the whole system. Also, a four-port optical switch introduces a sensor array to the system (Fig. 1). Each chain of sensors can work independently with OLCR to form a fundamental CM system and there is no cross-talk between chains, which is the greatest advantage of the SDM technique.

3 Experimental results and discussions

A broadband superluminescent diode (SLED) with short coherence length was used in the experiment as the light source. In each chain, 10 FPGPs with different intervals were cascaded in line to form a sensing array for the detection of methane concentration. Each FBG had a resonance wavelength located around 1548 nm and a bandwidth of about 0.8 nm. To improve the multiplexing capacity of the system and reduce the crosstalk among the adjacent sensors, the gratings were fabricated with very low reflectivity (~2%).

A novel method based on a special catalyst for methane concentration sensing was developed by our group (Zhou and Guan, 2007). This avoids the disadvantages of traditional electrical sensors, such as being hard to multiplex, sensitive to electromagnetic interference, and easy to produce electrical flash causing the methane explosion. The catalyst is actually a kind of Pt/Al_2O_3 alloy which can efficiently reduce the oxidation temperature of methane. The catalyst was placed inside a round hole, which can be driven by one single dry battery with 1.5 V contained in this package (Fig. 2). Catalytic reaction of methane occurred at a low temperature without a flame and released heat to raise the temperature around the catalyst. Also, the sensing FBG was efficiently installed to detect the temperature variation.

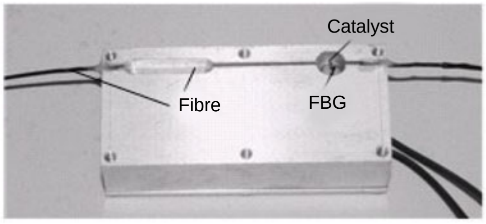

Fig. 2 Photograph of the packaged fiber Bragg grating pair (FBGP) based methane sensor

The packaged sensor was then placed into a well-designed gas cell in which the methane concentration can be adjusted by controlling the ratio of the methane and the air using a high-precision flowmeter. The inset of Fig. 3 shows the detected interferogram, from which the sub-interferograms can be clearly distinguished. When the methane concentration increased, the spectrum of the sensing FBG moved towards a longer wavelength, and the interfered intensity decreased as expected. We measured the methane concentration from 0% up to 6.4% (the threshold of methane to explore is around 5%, so it is meaningless to measure higher concentrations). The interference intensity decreased quickly as the methane concentration increased. When the methane concentration was low, the sensor worked with the minimum sensitivity of an intensity variation of 4.07% and a concentration variation of 1%. In the middle range of the curve (2%–5% of methane concentration), it had an approximately linear relationship between the methane concentration and the interference intensity, where we obtained the maximum sensitivities of an intensity variation of 10.92% and a concentration variation of 1%, at the environmental temperature of 27 °C. Furthermore, we can make the sensor work at the most sensitive range by introducing a pre-mismatch between the resonance wavelengths of two FBGs, although at the cost of the total sensing range.

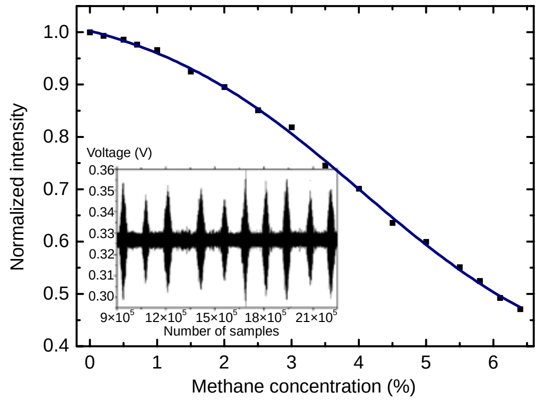

Fig. 3 Relationship between normalized interference intensity and methane concentration
The inset shows the detected interferogram

Strain and temperature are also important parameters in coal-mine security. Therefore, more experiments were undertaken to test the system performance of strain and temperature measurement. The resulting curves (Fig. 4) showed similar shapes to those of methane concentration detection, which perfectly verified the deduced principles discussed above. The maximum sensitivities were calculated as 0.212%/με for strain and 2.034%/°C for temperature, respectively. Since this sensing system contained no expensive devices, it demonstrates a relatively high performance-cost ratio and is actually very suitable for a coal-mine monitoring application.

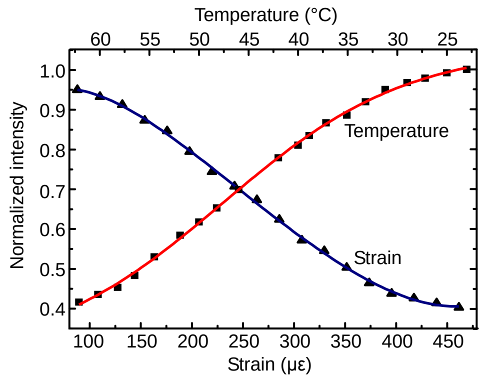

Fig. 4 Relationship between normalized interference intensity and strain/temperature

4 Conclusions

An FBGP based multiplexing system is proposed for quasi-distributed sensing applications. It is experimentally demonstrated that an OLCR can distinguish multiplexed signals from the CM system. The multiplexing capacity of the complete system is successfully quadrupled using a four-port optical switch. In the experiment, methane concentration, strain, and temperature can be easily detected with good results. In addition, the system has a high performance-cost ratio and great potential for coal-mine security monitoring applications since no expensive devices are required.

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