

# A novel weight measurement method based on birefringence in fiber Bragg gratings

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**Abstract** Unlike the usual wavelength modulation principle of fiber Bragg grating (FBG) sensors, a novel weight sensor based on birefringence in FBG is proposed in this paper. The creation of the birefringence is based on the different stresses of the two orthogonal directions in the fiber core cross-section. If weight is applied on an FBG in the radial direction, two reflection spectra with different polarization states which can be observed by an optical spectrum analyzer will occur. An experimental prototype is set up and the measurement principle is described in this paper. Preliminary experimental results indicate that the proposed measurement method is very suitable for the application of heavy weight measurement in the range of 20 tons, especially for vehicle load monitoring in highway charge-by-weight systems. The sensitivity of weight measurement is estimated to be about 5 kg.

**Keywords** fiber Bragg grating (FBG), birefringence, vehicle weighing, charge-by-weight

## 1 Introduction

Overloading or overweight goods on highways has become a very serious problem for current road management systems and transportation. The charging method based on electronic weight measurement in highway systems is being used in some countries. It is a scientific, rational, and fair method. Among many kinds of weighing instrumentats and sensors, those based on fiber optical sensor technology have shown a lot of merit and have become the most suitable method for weight measurement in highway systems.

Many researches have been conducted to measure the weight of moving vehicles, and weight-in-motion (WIM)

systems can be applied to monitor vehicle loads, regulate overload violations, and plan road-maintenance policies [1,2]. The frequently used device for weight measurement is piezoelectric sensors, which can be installed under the pavement at each lane and detects the axle weight of a passing vehicle by measuring the force applied from tires. The piezoelectric sensor, however, has a high-pass filter characteristic, which means that the output signal may be distorted. To restore the original sensor signal, an inverse function of a high-pass filter with piezoelectric parameters is developed [3].

Fiber optical sensors are small, making them suitable for embedded structures and easy to be built in. They have high sensitivity and a long lifetime. They are not easily interfered by environmental conditions, resistant to elevated temperatures, and resistant to corrosion. Lee proposed a method for weight measurement using macro-bending in fiber optic interferometric sensors [4]. Liu presented the design of a weight sensor based on the polarimetric properties of optical fiber. The sensor probe consists of an optical fiber embedded between two metallic plates with a hole filled with epoxy. Experimental results showed that it was suitable for a measuring range of up to several tons [5]. In this paper, based on the birefringence effect in fiber Bragg grating (FBG) caused by weight in the radial direction, a novel weight sensor principle is proposed, and the preliminary experiments are carried out to prove the feasibility. It can be used in transportation toll systems by measuring weight in highway systems. Compared with other methods for weight measurement, the proposed idea in this paper first uses FBG as a weight sensor and the birefringence effect caused by the load as a measurement principle. A simple signal demodulation method is used.

## 2 Principle of weight measurement

Light from a broadband source (BBS) passes through a power modulation device (PMD), and then the light

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power becomes linearly increasing. According to the mode theory of fiber optics, when force is applied on fiber in the radial direction, the birefringence effect of the light transmitting in fiber will occur and create two additional orthogonal polarization modes. If a weight is applied on an FBG in the radial direction (as shown in Fig. 1), two reflection spectra with different polarization states ( $\lambda_x$  and  $\lambda_y$  as shown in Fig. 1) will occur and can be observed by an optical spectrum analyzer (OSA) at the receiving end. These two reflection spectra will separate from each other due to the weight increment. The respective resonance wavelength of the two reflection spectra can be expressed as

$$\lambda_x = 2\gamma n_x, \quad (1a)$$

$$\lambda_y = 2\gamma n_y, \quad (1b)$$

where  $n_x$ ,  $n_y$  are respectively the effective refractive indexes of the two polarization states;  $\gamma$  is the intrinsic period of the FBG.

When the disturbance is applied on the FBG, the Bragg reflection wavelength will change as follows [6]:

$$\begin{aligned} d\lambda_B = & \left[ 2\gamma \left( \frac{\partial n_0}{\partial f} \right) + 2n_0 \left( \frac{\partial \gamma}{\partial f} \right) \right] dP \\ & + \left[ 2\gamma \left( \frac{\partial n_0}{\partial T} \right) + 2n_0 \left( \frac{\partial \gamma}{\partial T} \right) \right] dT, \end{aligned} \quad (2)$$

where  $P$  is the applied disturbance;  $f$  is the line distributed force;  $T$  is the temperature; and  $n_0$  is the effective refractive index of the fiber core. If the temperature is invariant and only the radial force is applied on the fiber, the wavelength shift will be the only function of the effective refractive index. Thus, in the fiber core (as shown in Fig. 2), in the two orthogonal directions, the effective refractive index variation due to the radial stress (or the transverse load) can be expressed as [6]

$$\Delta n_{0,x} = -\frac{n_{0,x}^3}{2E_1} \{ (p_{11} - 2\nu_1 p_{12})\sigma_x + [(1 - \nu_1)p_{12} - \nu_1 p_{11}]\sigma_y \}, \quad (3a)$$

$$\Delta n_{0,y} = -\frac{n_{0,y}^3}{2E_1} \{ (p_{11} - 2\nu_1 p_{12})\sigma_y + [(1 - \nu_1)p_{12} - \nu_1 p_{11}]\sigma_x \}, \quad (3b)$$

where  $n_{0,x}$  and  $n_{0,y}$  are the initial effective refractive

indexes in the two orthogonal directions;  $p_{11}$  and  $p_{12}$  are the elasto-optical coefficients of the fiber;  $E_1$  and  $\nu_1$  are the Young's modulus of elasticity of the fiber and Poisson's ratio of the fiber; and  $\sigma_x$  and  $\sigma_y$  are the stress components in the fiber center. According to Eqs. (2) and (3), there is

$$\Delta\lambda_{B,x} = -\frac{n_{0,x}^3 \gamma}{E_1} \{ (p_{11} - 2\nu_1 p_{12})\sigma_x + [(1 - \nu_1)p_{12} - \nu_1 p_{11}]\sigma_y \}, \quad (4a)$$

$$\Delta\lambda_{B,y} = -\frac{n_{0,y}^3 \gamma}{E_1} \{ (p_{11} - 2\nu_1 p_{12})\sigma_y + [(1 - \nu_1)p_{12} - \nu_1 p_{11}]\sigma_x \}. \quad (4b)$$

When the applied weight is on the fiber, the mechanical deformation and mechanical stress will occur. Thus, the birefringence stress of the quartz single mode fiber generated by the line distributed force,  $f$ , can be expressed as  $\sigma_x = f/(\pi R)$ ,  $\sigma_y = -3f/(\pi R)$  [7,8], where  $f = F/L$ ,  $F$  is the applied force along the fiber length  $L$ ; and  $R$  is the radial of the fiber cladding. Thus, Eq. (4) can be rewritten as

$$\begin{aligned} \Delta\lambda_{B,x} - \Delta\lambda_{B,y} = & \frac{f\gamma}{\pi R E_1} \left\{ n_{0,x}^3 [p_{12}(3 - \nu_1) - p_{11}(1 + 3\nu_1)] \right. \\ & \left. - n_{0,y}^3 [p_{11}(3 + \nu_1) - p_{12}(1 + 5\nu_1)] \right\}. \end{aligned} \quad (5)$$

Thus, based on the nature parameters of the fiber, the difference between the two FBG wavelengths shifts of the two polarization states under the applied transverse load can be obtained.

Because the weight signal is measured by recording the difference between the two FBG wavelengths shifts of the two polarization states, the temperature variation will lead to a same direction shift of the two FBG wavelengths, but not their separation. The temperature effect (cross-sensitivity) will be eliminated.

### 3 Experimental set-up and preliminary measurement results

The experimental set-up is shown in Fig. 3. The applied force is applied on the glass plate by using a specially designed loading unit. As shown in Fig. 3, both the sensor fiber and the supporting fiber are kept between two pieces of glass plates using a supporting fiber which is 20 mm

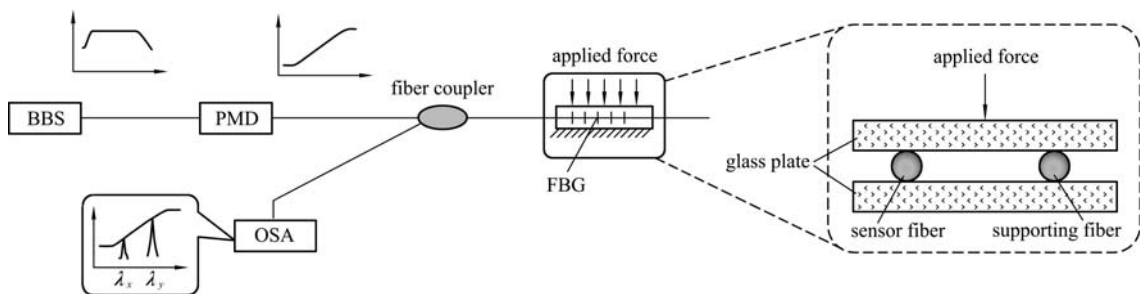
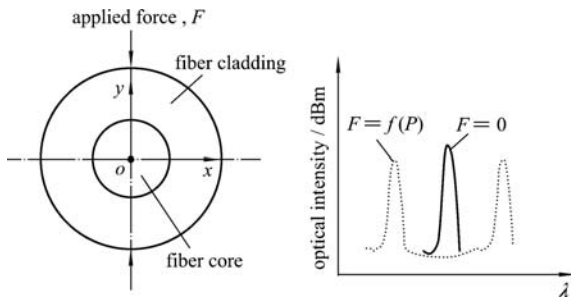


Fig. 1 Principle of weight measurement



**Fig. 2** Cross-section of FBG under a transverse load and reflected spectrum

away from the sensor fiber to keep the applied force uniform. The line distributed force,  $f$ , is perpendicular to the glass plate during the experimental process.

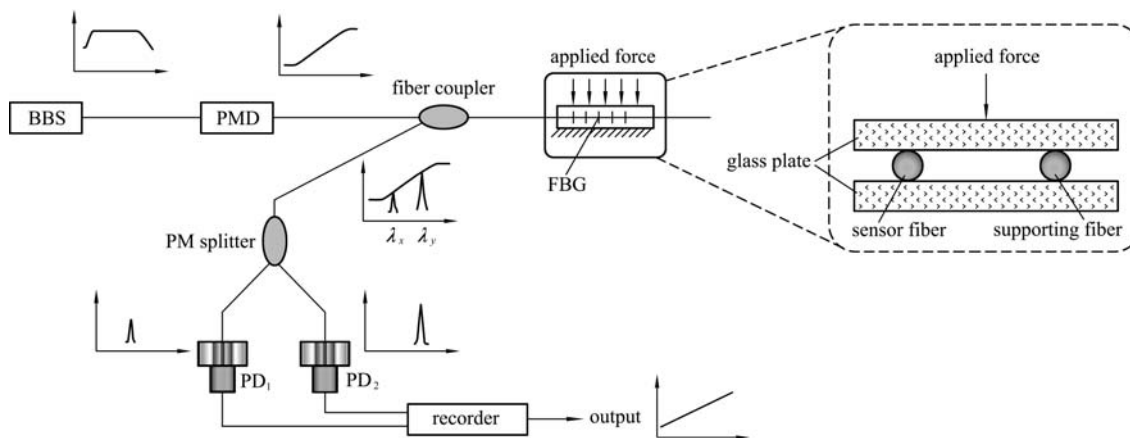
First, the output of the fiber coupler is not connected with the polarization maintaining (PM) splitter, but with an optical spectrum analyzer (as shown in Fig. 1). By the OSA, the reflected spectrum of the FBGs can be observed. If no load is applied on the sensor, there is only a single reflection peak in the reflected FBG spectrum received by OSA, as shown in Fig. 4(a). As the load increases from 0 to 35 kg in this experiment (the actual load can be increased to more than 20 tons), the reflected spectrum becomes wider, but the peak value becomes smaller. At the same time, the peak is separated into two peaks. Furthermore, as the load increases, the reflected peaks move to the longer wavelength direction, following increasing separation between the two separated peaks, as shown in Figs. 4(b) and 4(c). Figure 5 gives the wavelength difference between the two separated peaks. In the experiments, the supporting fiber uses a single-mode fiber with a diameter of 125  $\mu\text{m}$ , which is the same as that of the sensor fiber with an FBG. The center wavelength of the FBG reflected spectrum is 1549.998 nm. The diameter of the glass plate with an adequately smooth surface is 40 mm. The output light wavelength of the broadband light source is from 1525 to 1570 nm, which is sufficient for the measurement range. Research and analyses have

been carried out to explain why the reflected peaks move in the longer wavelength direction as the transverse load increases. When the transverse load is applied on the FBG, a certain extent axial extension will also occur, which leads to the axial strain and the wavelength movement. The two separated peaks move farther away from each other because as the transverse load increases, the additional birefringence effect in FBG core becomes more intense.

A PM splitter and two optical power detectors are used instead of OSA (as shown in Fig. 3) to detect the reflected spectrum signal from the FBG sensor. As the applied load increases, variations of the two orthogonal polarized optical powers created by the birefringence effect will be recorded by two optical power detectors as shown in Figs. 6(a) and 6(b), and their difference can be also received as shown in Fig. 6(c).

From Figs. 6(a) and 6(b), we can see that as the applied load increases, the two orthogonal polarized optical powers ( $B$ ) increase simultaneously. The difference of the optical powers ( $D$ ) is shown in Fig. 6(c). Thus, the separation of the reflection peak of the two orthogonal polarized light can be hardly identified because of the axial strain, which leads to the wavelength shift in the longer direction and enshrouds the birefringence effect. It is fortunate that the effects of axial strain on the two orthogonal polarized lights are the same, i.e., the two signals of wavelength shifts by the axial strain are common-mode signals, which can be removed by differential computing method. The difference of the optical powers, shown in Fig. 6(c), indicates that as the transverse load increases, the two orthogonal polarized light peaks caused by the birefringence effect will separate. The two separated peaks become farther away from each other as the transverse load increases. In the preliminary experiments, the load measurement resolution of 5 kg was obtained.

It is well known that there is a severe problem in the general FBG sensors, i.e., the cross-sensitivity of the strain and temperature. A significant number of methods and



**Fig. 3** Preliminary experiment setup of an FBG interrogation system

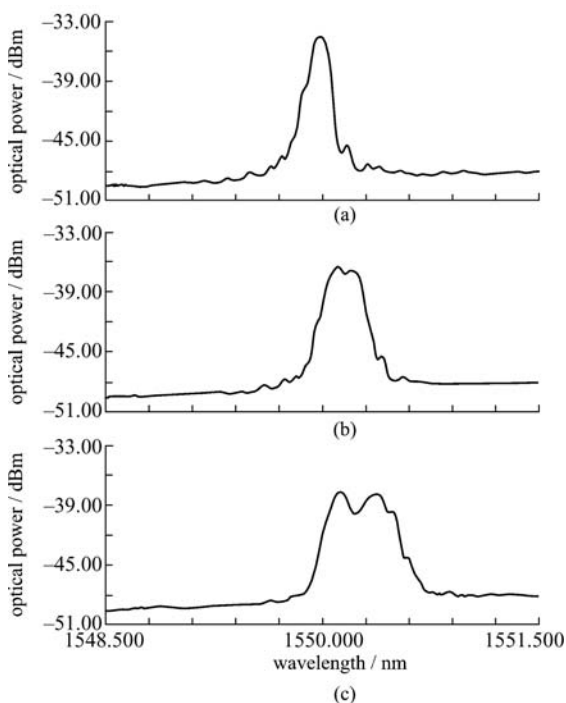


Fig. 4 Reflected spectra of FBG under transverse load

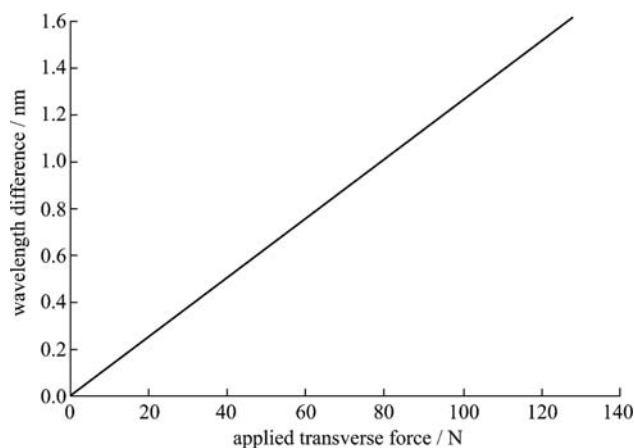


Fig. 5 Wavelength difference with applied transverse force

technologies have been proposed to distinguish between these two measures. In the experimental set-up proposed in this study, the temperature influence on the measurement results can be ignored because of the differential computing method mentioned above.

### 4 Conclusions

A weight sensor based on the birefringence effect of fiber Bragg gratings when applying a transverse load was proposed in this paper. A simple reflected spectrum signal demodulation system and preliminary experimental set-up were developed. The merits of this principle and system

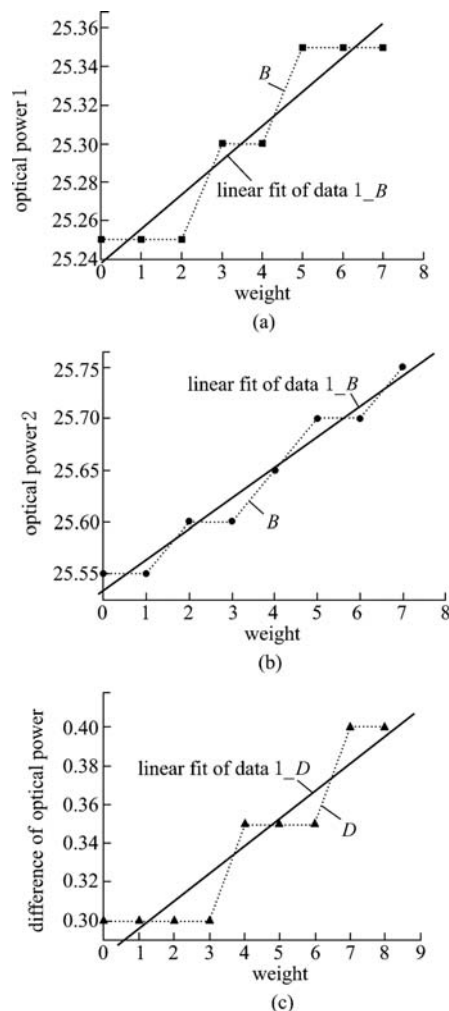


Fig. 6 Optical power of two polarized reflected spectra and their differential values versus transverse load

set-up include fast speed and high sensitivity. Moreover, the signal demodulation system is simple, and the temperature influence on measurement results can be removed automatically. From the experimental results, we can observe a linear characteristic between the weight and the output if the sensor can be observed. A weight measurement resolution of 5 kg can be obtained, which is accurate enough for vehicle load measurement.

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