Optics & Laser Technology 41 (2009) 431–440

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

# Multi-component force measurement using embedded fiber Bragg grating

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ARTICLE INFO

*Article history:*
Received 17 November 2007
Received in revised form
21 July 2008
Accepted 8 August 2008
Available online 30 September 2008

*Keywords:*
FBG sensor
Multi-component force measurement
Vector force measurement

ABSTRACT

The development of new fiber Bragg grating (FBG)-based multi-component force sensors is described. A two-component and a three-component force sensor have been fabricated and tested. The two-component force sensor measures the normal and the longitudinal shear component of the force. The three-component force sensor measures the normal, the longitudinal shear and the transverse shear component, and thus provides the magnitude as well as the direction of the force in the three-dimensional space. In the two-component sensor, one FBG is embedded rectilinearly and another non-rectilinearly within carbon composite layer. In the three-component force sensor, one FBG is embedded rectilinearly and two mutually perpendicular FBGs non-rectilinearly within the carbon composite layer. This paper presents the basic sensor structure and the proof-of-concept experimental demonstration of the two sensors. Force measurement within the range 0–15 N has been successfully conducted within 10% deviation.



## 1. Introduction

Multi-component force measurement is an important aspect of several engineering applications such as robotic grippers, where information is needed about the normal and the shear forces at the contact surface between the gripper and the object for secure grasping [1]. Another example of multi-component forces is in the foot sole, where the simultaneous measurement of the shear and the pressure components will provide complete information of three-dimensional (3D) stress distribution at discrete points along a diabetic patient's foot, so as to enable the suitable rehabilitative programs to be adopted [2].

Although the concept of multi-component force measurement is very important, very few sensors have been fabricated so far [3–8]. Most of these sensors are prone to electromagnetic interference (EMI), which may lead to inaccuracy in the measurement. Using fiber Bragg gratings (FBG) for multi-component force measurement will make the sensor system immune to EMI. Fernandez et al. [9] reported an FBG strain sensor-based multi-component force sensor, which was based on Maltese cross-shaped transducer for measurement of the three components of the force. Although linear response is obtained, a large number of FBG strain sensors (8 FBG-based strain sensors) are needed and rigorous analysis is required to determine the various components.

Our group has previously developed an FBG-based pressure sensor and recently reported a shear force sensor [10–12]. The two concepts are now utilized together to develop a sensor that measures the normal and the shear force simultaneously. This sensor structure is further modified to measure all the three components of the applied force, namely (i) normal force (and hence, pressure), (ii) longitudinal shear and (iii) transverse shear.

The following sections discuss the basic structure and the test results of the newly developed FBG-based multi-component force sensor. First, a brief discussion on the basics of FBG is presented followed by the pressure sensor, shear force sensor, two-component force sensor and finally, the three-component force sensor.

## 2. FBG as sensing element

An FBG is essentially a wavelength-selective filter. An FBG will reflect light that has a wavelength $\lambda_b$ corresponding to twice its period $\Lambda$, multiplied by the effective refractive index of the fiber $n_{eff}$ that the propagating mode sees [13]

$$\lambda_b = 2\Lambda n_{eff} \qquad (1)$$

Light at other wavelengths will be transmitted without significant attenuation. In other words, the grating operates as a narrow-band wavelength notch filter. Fig. 1 shows the typical

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0030-3992/$ - see front matter 
doi:10.1016/j.optlastec.2008.08.004

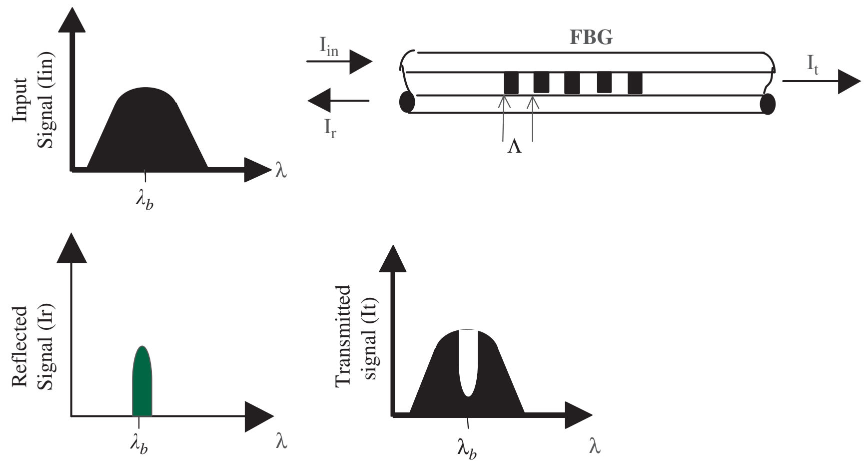


**Fig. 1.** Transmission and reflection spectrum of fiber Bragg grating.

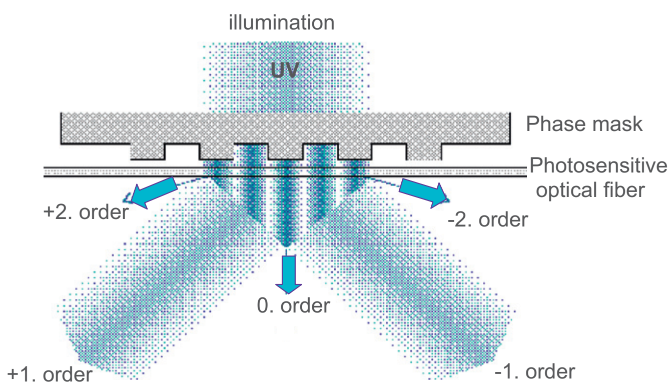


**Fig. 2.** Phase mask photo-imprinting of fiber Bragg grating.

transmission and reflection spectra of light obtained by launching a broad spectrum of light into an optical fiber containing an FBG. FBGs can be formed by exposing a photosensitive optical fiber to a 3D fringe pattern created by interfering two high-energy ultra-violet beams (holographic) [14] or by the transmission pattern from an appropriate diffractive optical element (phase mask) [15]. Irradiation of the silica fiber with the bright portions of the UV pattern, spurred by the presence of defect centers, creates a permanent modulation of refractive index of the core.

The FBG fabrication technique employed in this study involves the use of a +1/−1-order phase mask, as shown in Fig. 2. The UV source is a 248 nm KrF Excimer laser, Lambda Physiks model, COMPex205. The phase mask is optimized to diffract the UV light equally into the $\pm1$ order. Self-interference between these two orders creates an interference pattern into the core of the photosensitive fiber with the grating period at halve the pitch size of the phase mask. Additional zero-order and higher-order noises are highly suppressed by the phase mask.

Eq. (1) shows that the Bragg wavelength depends on the grating periodicity ($\Lambda$) and the effective refractive index ($n_{\mathrm{eff}}$) of the core. Any external perturbations that can change the grating periodicity and/or the refractive index will alter the Bragg wavelength and the shift will be a measure of the applied perturbation. This property of the FBG is used for the development of sensors. The advantages of FBG-based sensors over other fiber optic sensors are primarily due to signal encoding. An FBG measures strain and temperature through a spectral shift of a narrow wavelength band. This wavelength-encoding scheme provides good isolation from noise sources such as intensity fluctuations caused by the light source or bending losses in the lead fiber.

The shift in Bragg wavelength with strain and temperature can be described by [13]:

$$\Delta\lambda_{\mathrm{b}}/\lambda_{\mathrm{b}} = \varepsilon[1 - 0.5\, n_{\mathrm{eff}}^2\{P_{12} - \nu(P_{11} + P_{12})\}] + \xi\Delta T \tag{2}$$

where $\varepsilon$ is the axial strain in the fiber caused by the applied perturbation such as tensile stress/pressure/force/vibration or bending, $\Delta T$ the change in the temperature, $P_{ij}$ the strain optic coefficient ($i,j = 1,2$), $\nu$ the Poisson's ratio and $\xi$ the thermo-optic coefficient. As can be observed from Eq. (2), the reflected Bragg wavelength will be shifted with the variation of the strain and the temperature. This property of FBG is used for the development of sensors [16–19]. The following sections discuss the FBG-based pressure and shear force sensors briefly.

## 3. FBG-based pressure sensor

Pressure can be determined from the normal component of the force and the area it is acting upon. The FBG-based pressure sensor has been fabricated earlier. For the sake of clarity, the sensor structure in described here briefly, interested readers may find the complete information in a related publication [10].

For pressure measurement, the FBG is embedded within the layers of a carbon composite material (CCM). Under bending, the upper layers are under compression and the lower layers under tension. As illustrated in Fig. 3, at a particular layer, there is no strain at all, this layer is known as the neutral layer. Using basic theory of mechanics, it is obtained that when the FBG is embedded at the neutral layer within the CCM, it will not be sensitive to pressure. Whereas, if the FBG is embedded above or below the neutral layer, it will be under compression (when embedded above) or tension (when embedded below) as shown in Fig. 3. Thus, embedding the fiber above or below the neutral layer, the pressure can be transferred as axial strain through compression or tension. This is the concept utilized for fabrication of the pressure sensor. The response of the sensor under the applied pressure is shown in Fig. 4 [10], where Fig. 4(a) shows the response of the sensor when FBG is embedded below the neutral layer and hence is under tension. Thus, the wavelength shift is positive. Fig. 4(b) shows the response of the sensor when the FBG is embedded above the neutral layer and hence is under compression. Thus, the wavelength shift is negative. It is expected that the wavelength shifts should be same for same embedding locations above and below the neutral layers. Same amount of