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Simultaneous discrimination of strain and temperature using dual-gratings in one fiber

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ABSTRACT

An alternate solution to measure the stain and temperature simultaneously is proposed. In the acknowledged techniques, the most simple way of measuring stain and temperature simultaneously is to write fiber Bragg gratings (FBGs) in two fibers with different diameters. However, this way has a disadvantage of weak joint and high loss of splicing point which cannot be ignored. We present a new method to overcome this disadvantage by fabricating this dual-gratings sensing structure in one fiber, thus, the strength of this sensor is greatly increased and the transmission loss is nearly zero. This sensor is calibrated in a temperature range from 20 °C to 70 °C and in a strain range from 0 to 900 $\mu\varepsilon$. The temperature sensitivity coefficients of these dual-gratings are completely consistent, and at the same time the strain sensitivity coefficients are flexible which can be adjusted by controlling the diameter of fiber. The reflection peak wavelengths of this sensor have a good linear relationship with strain and temperature and match the theoretical calculation well in our experiments.

1. Introduction

Optical fiber grating sensors [1] have attracted many attentions due to their excellent characteristics for a large range of measurands, like pressure, strain, temperature, refractive index, acceleration and so on. They are widely used in optical sensing over the past decades. Like all the optical fiber sensors, they have many advantages such as small size, lightweight, low cost, immunity to electromagnetic interference, large dynamic bandwidth, and flexibility multiplexing capability. However, there is a one important limitation of fiber grating sensors which is the cross sensitivity of all the measurands. This problem has been investigated by many researchers and many discriminating techniques have been reported. One type is based on FBG in itself, such as two FBGs in different diameter fibers with splicing [2], FBGs written in different kinds of fibers [3], a FBG written in a splicing point between two different fibers [4,5], a superstructure FBG [6], a titled FBG [7], a dual-wavelength grating [8], a reverse index FBG [9], FBG embedded in hybrid composite laminates [10] and a single FBG based on the polarization properties analysis [11]. And the other type is about the FBG combined with another component, like a FBG combined with a long period grating (LPG) [12–14], FBGs combined with taper [15–17], a sampled FBG combined with a LPG [18], a polarization holding fiber loop mirror or inter-modal interferometer (IMI) combined with FBG [19,20], a FBG and multimode fibers [21] and a Lyot fiber filter with a FBG [22] etc.

In all the discriminating techniques which are mentioned above, the most convenient and easy-fabricated technique is "two FBGs in different diameter fibers with splicing" considering about practicality [2]. Usually, this sensor is fabricated by splicing two FBGs written in fibers with different diameters [2]. However, the sensor is unpractical, because of the weak joint and high loss of splicing point between two fibers with different diameters due to the mismatch of numerical aperture (NA). In this paper, we present a new method to fabricate a sensor for simultaneous discrimination of strain and temperature. This sensing structure can be achieved through etching some segment of the fiber cladding and writing fiber Bragg gratings. Thus, the dual-gratings are in one fiber and there is no splicing point, so, the strength of the sensor is greatly increased and the loss is nearly zero in this sensor.

2. Principle of operation

According to coupling-mode theory [1], there is

$$\lambda_B = 2n_{\text{eff}}\Lambda \tag{1}$$

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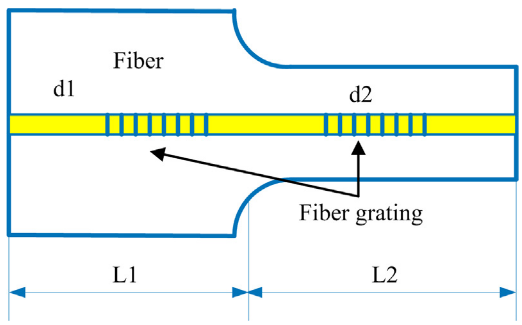


Fig. 1. The geometry of dual-gratings in one fiber.

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the guide mode, Λ is the grating period.

When strain changed, the wavelength shift $\Delta\lambda_{BS}$ of the peak wavelength λ_B is

$$\frac{\Delta\lambda_{BS}}{\lambda_B} = (1-p_e)\Delta\varepsilon = K_S\Delta\varepsilon \tag{2}$$

where $p_e = [p_{12} - (p_{11} + p_{12})\nu]\left(n_{eff}^2/2\right)$ is the effective photoelastic coefficient, p_{11} and p_{12} express photoelastic coefficients, ν is Poisson ratio. Such as a typical fiber, p_{11} = 0.121, p_{12} = 0.270, ν = 0.170, n_{eff} = 1.456 thus p_e = 0.216. $\Delta\varepsilon$ is the axial strain of fiber Bragg grating.

When temperature changed, the wavelength shift $\Delta\lambda_{BT}$ of the peak wavelength λ_B is

$$\frac{\Delta\lambda_{BT}}{\lambda_B} = (\alpha_T + \zeta_T)\Delta T = K_T\Delta T \tag{3}$$

where α_T is the thermo-optic coefficient, ζ_T is the thermal expansion coefficient.

Fig. 1 is the geometry of dual-gratings in one fiber. For a given strain,

$$\frac{\Delta\varepsilon_1}{\Delta\varepsilon_2} = \frac{A_2}{A_1} = \frac{d_2^2}{d_1^2} \tag{4}$$

In Eq. (4), d_2 and d_1 are the two different diameters of one fiber.

It is possible to derive the relationship between the strain applied to the whole structure and the wavelength shifts of the dual-gratings as [2],

$$\begin{pmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{pmatrix} = \begin{bmatrix}\dfrac{K_S(L_1+L_2)}{L_1\left(1+\left(d_1^2L_2/d_2^2L_1\right)\right)} & K_{T1}\\ \dfrac{K_S(L_1+L_2)}{L_2\left(1+\left(d_2^2L_1/d_1^2L_2\right)\right)} & K_{T2}\end{bmatrix}\begin{pmatrix}\Delta\varepsilon\\ \Delta T\end{pmatrix} = \begin{bmatrix}K_{S1} & K_{T1}\\ K_{S2} & K_{T2}\end{bmatrix}\begin{pmatrix}\Delta\varepsilon\\ \Delta T\end{pmatrix} \tag{5}$$

where L_1 and L_2 are also shown in Fig. 1. Due to the different responses of dual-gratings, it is possible to use a simple matrix method in order to discriminate strain and temperature.

In our experiments, due to the dual-gratings written in one fiber, we can approximately conclude that,

$$K_{T1} = K_{T2} = K_T \tag{6}$$

But the strain sensitivity coefficients are different because of the different diameters. It is clear that this sensing structure offers an excellent performance in the simultaneous discrimination of strain and temperature.

In our experiments, L_1 = 20 cm, L_2 = 5 cm, d_1 = 125 µm, d_2 = 57 µm, take this parameters into Eq. (5), we can obtain that the strain sensitivity coefficient of 57 µm diameter is 4.8 times of 125 µm diameter'.

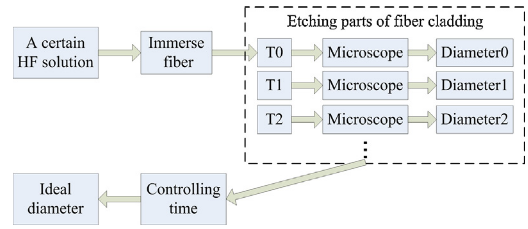


Fig. 2. The flow chart of the controlling of etching process.

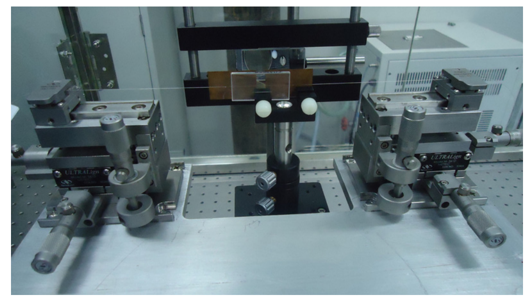


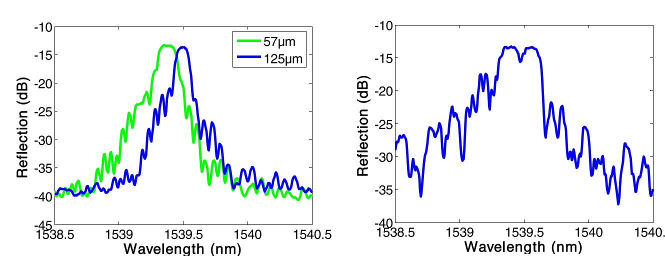
Fig. 3. The picture of fiber grating writing setup.

3. Fabrication

This sensing structure proposed in this experiment was fabricated using photosensitive fiber. And some part of the fiber was etched by hydrofluoric (HF) acid. The cladding of fiber, which was immersed in the HF acid solution, was partly removed. The expected diameter can be obtained by controlling the etching rate and time in the etching process. The detailed process is shown in Fig. 2: The concentration of HF acid solution is the main factor of etching speed. The higher concentration leads to the faster etching speed. For a certain concentration of HF acid solution, the etching speed increases with the decreased of fiber diameter in the whole etching process. Thus, we accurately measured the diameter using a microscope after etching every certain time. Then we can obtain the ideal diameter through the controlling of etching time.

The FBGs were written in different position of the photosensitive fiber by UV exposure through a phase mask using an excimer laser operating at 248 nm as shown in Fig. 3. In this process, we added a rectangle window, which was laid in the front of the phase mask to increase the side-mode suppressive ratio and accurately fix the position of fiber grating.

First, we wrote fiber gratings in the fiber of different diameters using the same writing parameters, respectively. The reflection spectra of these two gratings were measured utilizing a commercial fiber grating demodulator SM125 with a resolution of 1pm from MOI, which was shown in Fig. 4(a). It is clear that these two reflecting peak wavelengths are different due to the differences in effective refractive index caused by the discrepancy in diameter.



(a) (b)

Fig. 4. The reflection spectra of (a) two gratings; (b) this sensor.