Measurement 62 (2015) 137–141

Contents lists available at ScienceDirect

Measurement

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

Fiber laser sensor for simultaneously axial strain and transverse load detection

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ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form 12 November 2014
Accepted 19 November 2014
Available online 26 November 2014

Keywords:
Fiber optics sensors
Distributed Bragg reflector fiber laser
Strain sensor
Axial strain
Transverse load

ABSTRACT

We demonstrate a distributed Bragg reflector (DBR) fiber laser sensor for simultaneous measurements of axial strain and transverse load, this sensor might be applied in structure health monitoring. In this scheme, transverse load introduces an additional birefringence and consequently a linear beat note frequency change of the orthogonally polarized lasing modes, while the axial strain can be simply deduced from the wavelength shift of the laser. The sensor's sensitivity is measured to be 1.33 kHz/mg and 1.266 pm/με for lateral load and axial strain respectively.

1. Introduction

With its miniature size, simple wavelength multiplexing, electro-static discharge and electromagnetic interference immunity, fiber Bragg grating sensors have been drawing significant research interests over the past decades. One kind of active FBG sensors, i.e. distributed Bragg reflector (DBR) fiber laser, has a high signal-to-noise ratio (SNR) [1] and a narrow linewidth due to its laser nature. It also benefits from much simpler and cost-effective electrical frequency domain demodulation comparing with FBG's wavelength decoding approach. It thus has been investigated for various sensing applications for different physical measurands, e.g., bending sensors [2], ultrasonic hydrophone [3,4], lateral force sensors [5,6] and accelerometers [7].

The frequency changes of the beat frequency are however greatly reduced by two or more orders of magnitude to less than few kHz/με when it comes to the detection of axial strain [8–11]. Theoretically speaking, for the ideal optical fiber structure which is symmetric and not bended, there will be no change of birefringence introduced by axial strain. It would be hard to get the sensor's axial deformation for the DBR sensor in the frequency domain, even more difficult to know it together with lateral strain loaded. Nevertheless, simultaneously measuring axial and lateral strain is important in stress analysis and applications as bridge and building health monitoring.

To address this, we propose a highly sensitive sensor configuration which can detect the axial strain and lateral load at the same time. Since the axial strain applied is inherently encoded in the lasing wavelength of the sensor. By monitoring the DBR's wavelength together with its beat

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http://dx.doi.org/10.1016/j.measurement.2014.11.017
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frequency, it is possible to simultaneously measure the axial strain and lateral load on the probe. In this manuscript, the sensor's performance and its dependence on temperature and pump current are studied and discussed, and this sensor's the resolution for transverse load is 77 μg, while the axial strain resolution is about 4.73 με.

2. Fiber laser sensor system and its theory

The DBR fiber laser's resonant cavity is formed by a pair of FBGs with matched wavelength, one low reflective (LR) FBG and one high reflective (HR) FBG, which are ultraviolet (UV) light single-side inscribed into a small segment of Er-doped fiber. The HR one is 25 mm long with a reflectivity of ∼35 dB while the LR is 15 mm with reflectivity of about 20 dB. A 400 μm cladding is recoated with FUJIKURA's FSR-02 (coating material: Angstrombond DSM950-200) after the laser's fabrication to protect the bare fiber. The recoated fiber laser structure is shown in Fig. 1.

Fig. 2 demonstrates the configuration of the experimental system. The DBR laser is pumped by a 980 nm pump laser, the output light passes a 980/1550 WDM coupler, an isolator and then to a polarization controller (PC) followed by an inline polarizer. A portion of the light is then split to an optical spectrum analyzer (OSA, Yokogawa's 6317C) to monitor the wavelength which depicts the axial strain, while the other branch illuminates a photo detector (PD, WTD's PTHS992-003). This detector acts as an envelope detector which transferred the beat signal in the optical frequency into an electronic signal at an original frequency ν_0 of 503 MHz. Then this broadband signal which carries the lateral strain information is received with the electronic spectrum analyzer (ESA, HP's 8590A). The transverse strain is applied right on the laser cavity, but not on the FBGs to prevent influence on lasing wavelength. The inset illustrates how the transverse load is applied, a dummy fiber is used to share and balance the weight. Two pulleys are employed to applied axial strain through a hanging plate, and the lower wheel keeps the laser on the table.

2.1. Beat frequency dependence on the transverse load

When illuminated with a pump laser, there are two perpendicular polarized light outputs resulting from the fiber birefringence, the two lights eventually form a beat note at the polarizer. The note's original frequency $\Delta\nu_{b0}$ detected by the PD is

$$\Delta\nu_{b0} = \frac{B_0}{n_0}\nu_0 = \frac{cB_0}{\lambda_0 n_0}, \tag{1}$$

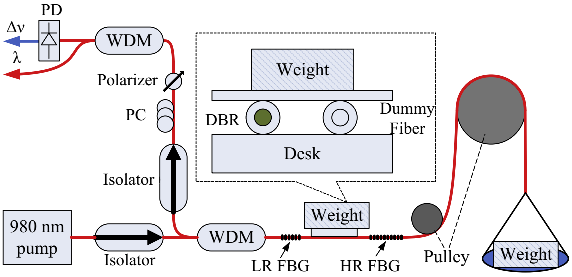

Fig. 2. Experimental configuration of the DBR strain sensor. WDM: wavelength division multiplexer, PC: polarization controller, LR: low reflection, HR: high reflection, FBG: fiber Bragg grating, PD: photo detector.

where c represents the light speed, λ_0 and ν_0 are the average wavelength and average frequency of the two polarization modes respectively, n_0 is the average reflective index of the x and y axes, the original birefringence B_0 is the reflective index differences between axes.

When a fiber is under stress, its effective index is changed due to the photo-elastic effect [12,13]. The effective index changes for x-axis and y-axis can be respectively expressed as

$$\Delta n_{0x} = -\frac{n_0^3}{2E_f}\{(p_{11} - 2\nu_p p_{12})\sigma_x + [(1-\nu_p)p_{12} - \nu_p p_{11}] \times (\sigma_y + \sigma_z)\}, \tag{2}$$

$$\Delta n_{0y} = -\frac{n_0^3}{2E_f}\{(p_{11} - 2\nu_p p_{12})\sigma_y + [(1-\nu_p)p_{12} - \nu_p p_{11}] \times (\sigma_x + \sigma_z)\}, \tag{3}$$

where σ_x, σ_y and σ_z are the stress components in the directions of x, y, and z. p_{11} and p_{12} stand for the photo-elastic coefficients of silica, E_f and ν_p represent the modulus of elasticity and Poisson's ratio for the fiber. The stress induced birefringence can be found out as

$$\Delta B_0 = \Delta n_{0x} - \Delta n_{0y} = -\frac{n_0^3}{2E_f}(\sigma_x - \sigma_y)(1+\nu_p)(p_{11} - p_{12}), \tag{4}$$

Eq. (4) well explains why the induced birefringence is not affected by the axial strain. When a transverse load is applied on the DBR cavity along the slow axis direction (y direction), the induced beat frequency change $\delta(\Delta\nu_{b0})$ can be deduced from [5]

$$\delta(\Delta\nu_{b0}) = \frac{1}{L}\frac{c}{n_0\lambda_0}B_0, \tag{5}$$

as

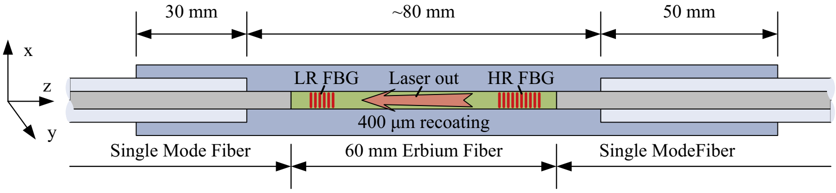

Fig. 1. The fiber laser structure. LR: low reflective, HR: high reflective, FBG: fiber Bragg grating.