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RESEARCH ARTICLE

Light intensity-referred and temperature-insensitive fiber Bragg grating dynamic pressure sensor

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Abstract Temperature-insensitive fiber Bragg grating (FBG) dynamic pressure sensing based on reflection spectrum bandwidth modulation and differential optical power detection is proposed and experimentally demonstrated. A special double-hole cantilever beam is designed to induce linear strain-gradient distribution along the sensing FBG, resulting in FBG reflection spectrum symmetrical broadening and optical power increase. Based on the theory of optical waveguide and material mechanics, the causation of FBG spectrum broadening under the linear strain-gradient is analyzed, and the corresponding force-to-bandwidth broadening relation and force-to-optical power relation are formulized. FBG spectrum bandwidth and reflection optical power linearly change with applied pressure and both of them are insensitive to spatially uniform temperature variations. For a temperature range from −10°C to 80°C, the measured pressure fluctuates less than 1.8% F.S. (120 kPa) without any temperature compensation. The system acquisition time is up to about 80 Hz for dynamic pressure measurement.

Keywords guided wave and fiber optics, fiber sensing, fiber Bragg grating (FBG), dynamic pressure sensing, bandwidth modulation, optical power detection

1 Introduction

Sensors based on fiber Bragg grating (FBG) have attracted considerable interest for its distinguishing properties [1,2]. Pressure measurement is one of their primary applications. Due to the dual sensitivity of FBG to temperature and pressure, considerable research has been devoted to the development of the discrimination between the effects of these two parameters. Many effective methods based on FBGs have been proposed to measure temperature and pressure simultaneously [3–8]. Discriminating methods based on two separate FBGs include the pressure-shielded reference FBG method [3], hybrid long-period grating (LPG) and FBG [4], dual-wavelength superimposed FBGs method [5,6] and different cladding-diameter FBGs method [7]. Methods using a single FBG for discrimination can be concluded as primary and second orders of diffraction method [8], FBG written in a highly birefringent fiber [9] or double-doped fiber [10,11], FBG attached on different base-plate materials [12] or packaged in different polymers [13]. Accessorial methods are to combine FBGs with other facilities such as a Fabry-Perot interferometer [14], a thermochromic material [15] and a fluorescence decay within short lengths which is about a few centimeters of doped fiber [16]. However, pressure and temperature information in these schemes are still wavelength encoded, which restricts their direct employment in practical applications that often require complex interrogation units. Therefore, a ready-to-acquire fiber grating sensing scheme in which wavelength changes can be directly transformed to optical power variations would be of great value. Designing sensors with better quality and lower cost would encourage further researches in this field.

In this paper, a novel method for dynamic pressure measurement that uses a single FBG based on reflection spectrum bandwidth modulation and optical power detection is proposed and experimentally demonstrated. A double-hole cantilever beam (DHCB) is designed to provide pressure-induced axial strain gradient and temperature-affected uniform strain along the sensing FBG. Spectrum broadening and reflection optical power change with the pressure, but they are immune to spatially uniform temperature variation. This special beam-based sensor permits dynamic pressure measurement and allows a

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cost-effective demodulation process simply by optical power detection.

2 Sensing principle

Figure 1 shows the configuration of the double-hole cantilever beam (DHCB). The DHCB is made of high-elastic steel with a symmetrical structure. The FBG is axially pasted onto the upper surface of the left arc beam in coverage of a calculated linear strain gradient, and pressure is vertically applied at the central position of the beam.

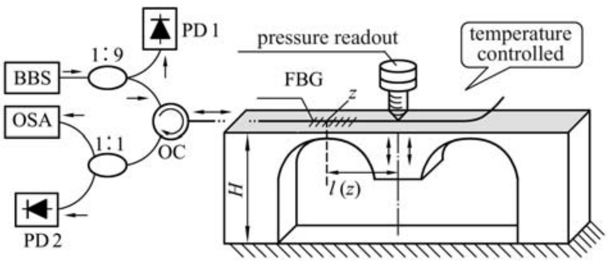

Fig. 1 Schematic diagram of dynamic pressure sensing system

Based on material mechanics [17], the axial strain ε of DHCB at point z can be expressed as

$$\varepsilon(z)=\frac{Hl(z)}{2EI(z)}\cdot F, \tag{1}$$

where H is the height of the beam, $l(z)$ is the horizontal distance between point z and the point where force is applied, E is Young's modulus of the beam material, F is the applied force per square centimeter, and $I(z)$ is inertia moment of the beam at point z, which changes along the fiber axis owing to its relationship with the beam material and its dependence on the cross section area of the beam.

Equation (1) indicates that, when a certain force is applied, the axial strain $\varepsilon(z)$ of the beam will change along the fiber axis, because both $l(z)$ and $I(z)$ are position-dependent. Suppose that the grating length is L, then the total axial strain change $\Delta\varepsilon$ along the grating can be expressed as

$$\Delta\varepsilon=\frac{H}{2E}\int_{Z_0}^{Z_0+L}\frac{l(z)}{I(z)}\mathrm{d}z\cdot F. \tag{2}$$

If an originally uniform FBG is subjected to the axial strain gradient and under a uniformly distributed temperature circumstance, the bandwidth broadening can be described as

$$\Delta\lambda_{\mathrm{BW}}=2n_{\mathrm{eff}}\Lambda(1-p_{\mathrm{e}})\cdot\Delta\varepsilon, \tag{3}$$

where n_{eff} is the effective refractive index of the fiber core, Λ is the grating period, p_{e} is effective photoelastic constant, and $\Delta\varepsilon$ is the strain gradient along the grating.

Substituting Eq. (3) with Eq. (2), the force-to-bandwidth broadening relation can be expressed as

$$\Delta\lambda_{\mathrm{BW}}=n_{\mathrm{eff}}\Lambda\frac{(1-p_{\mathrm{e}})H}{E}\int_{Z_0}^{Z_0+L}\frac{l(z)}{I(z)}\mathrm{d}z\cdot F. \tag{4}$$

With reflection spectrum broadening, the total reflection power of the chirped FBG will also be increased. The power increase ΔP can be formulated as

$$\Delta P=k\alpha^2RP_{\mathrm{BBS}}(\lambda)\cdot\Delta\lambda_{\mathrm{BW}}, \tag{5}$$

where k and α are the optical power tap coupling ratio and the fiber loss leading to FBG, respectively; R and $\Delta\lambda_{\mathrm{BW}}$ are the reflectivity and the bandwidth broadening of the grating, respectively; and $P_{\mathrm{BBS}}(\lambda)$ is the power spectral density of the broadband optical source (BBS).

Substituting Eq. (5) with Eq. (4), the force-to-power increase relation, then, can be expressed as

$$\Delta P=k\alpha^2RP_{\mathrm{BBS}}(\lambda)n_{\mathrm{eff}}\Lambda\frac{(1-p_{\mathrm{e}})H}{E}\times\int_{Z_0}^{Z_0+L}\frac{l(z)}{I(z)}\mathrm{d}z\cdot F. \tag{6}$$

Equations (4) and (6) indicate that the spectrum bandwidth variation and optical power change are dominated only by (and linear with) the applied force, independent of temperature.

Based on rigorous finite element method (FEM), the static stress distribution of DHCB under vertically applied force is described in Fig. 2 and the corresponding strain magnitude profile along the upper surface of DHCB is evaluated, as shown in Fig. 3. The strain profile describes a symmetrical strain distribution. The coverage of FBG is depicted by the double-dashed lines. Within the grating coverage, there exists a large linear strain gradient region from point a to b, with a zero strain point c right above the top of the arc hole. The sensing grating suffers a linear strain conversion, with stretch on the left and compression on the right. Therefore, the reflection spectrum presents a symmetrical broadening with red shift in stretch parts and blue shift in compression parts. Because both ends of the grating partly exceed the linear strain gradient inflexions at point a and b, a sub-peak turns up on both edges of the broadening spectrum. Subsequent experimental results confirm the above analysis, as shown in Fig. 4. When different pressures are applied on the beam, as shown in Fig. 3, a similar strain profile is achieved and the strain value of the affixed grating region are proportionally increased with

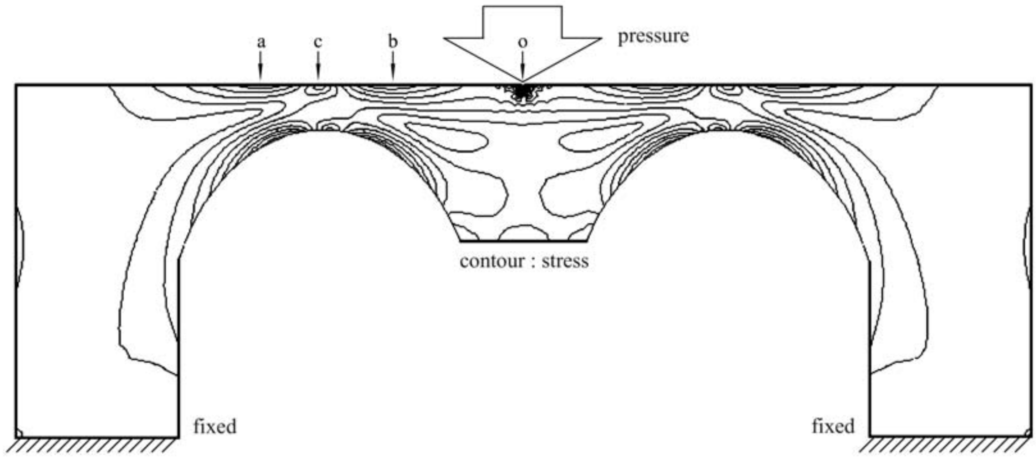

Fig. 2 Stress distribution of DHCB under vertically applied pressure

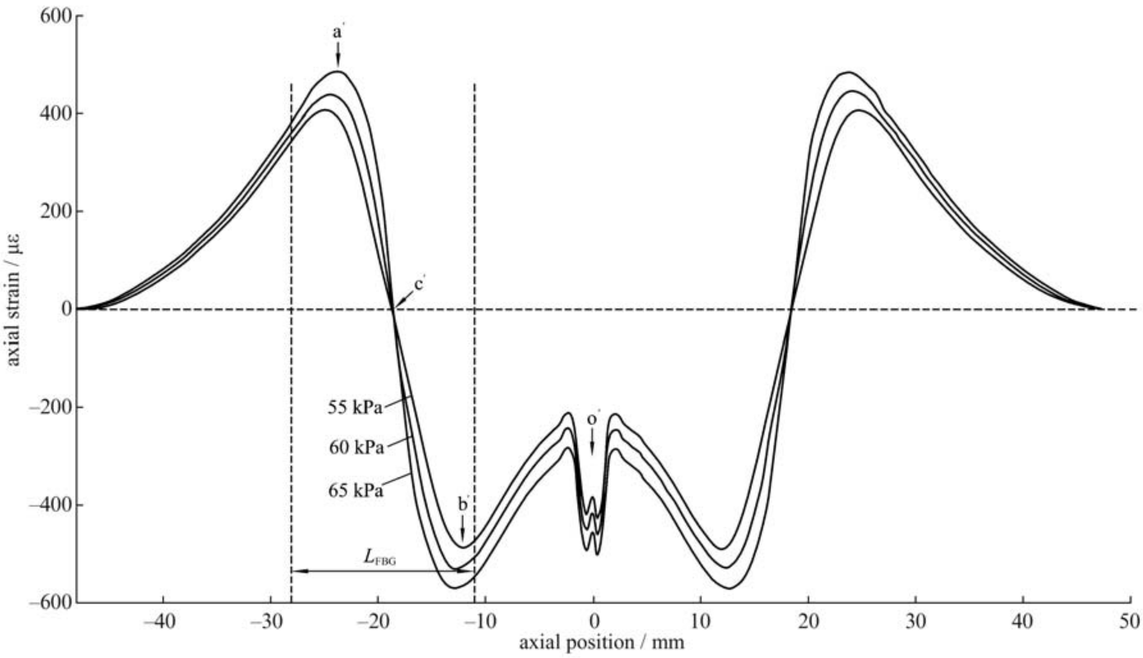

Fig. 3 Strain magnitude distribution along the up surface of arc beam at the pressures of 55, 60 and 65 kPa

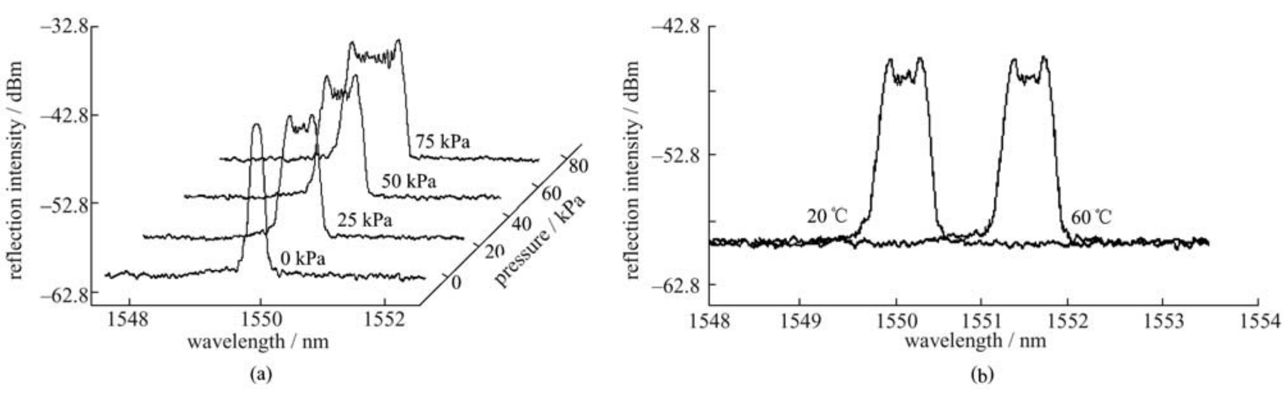

Fig. 4 Reflection spectra of FBG versus (a) pressure at fixed temperature of 20°C; (b) temperature at fixed pressure of 50 kPa

the pressure, which further proves the above mechanical analysis.

Considering the effect of spatially uniform temperature, because the thermal expansion coefficient is related only to the material uniform over the whole cantilever beam, the value is maintained at about 23.6 μm/(m·k) regardless of the position. Axial strains of different parts of the FBG are equal when the temperature changes. Therefore, temperature changes only result in the spectrum shift and do not affect the spectrum bandwidth, as shown in Fig. 4.

3 Experimental results and discussion

Figure 1 shows the proposed sensing device. The sensing FBG used in the experiment is 16 mm long with a central wavelength of 1549.8 nm and a full width at half maximum (FWHM) line-width of 0.2 nm. The FBG spectrum is monitored by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm and its optical power is detected by p-i-n photodiode (PD2). PD1 is used to compensate for the measurement dither error caused by the output BBS fluctuation.

Measurements are performed for pressure up to 120 kPa, as the temperature changes from 10°C to 80°C. The FBG's responses to pressure and temperature are depicted in Fig. 5. Because of the photo-elastic and thermo-optic effects, the wavelength shift is temperature-dependent, as shown in Fig. 5(a). However, this wavelength shift will not affect the total reflection optical power, as shown in Fig. 5(b). As a result of the strain gradient increase along the grating, the spectrum bandwidth broadening and optical power increase linearly vary with the pressure change, insensitive of temperature variations, as shown in Fig. 5(d). Here, in order to cover the whole broadened spectrum, the bandwidth threshold is set to 6 dB. The central wavelength is fixed because of the symmetrical spectrum broadening, as shown in Fig. 5(c).

The response time is the key quality metric of this device, especially when the sensor is applied in a rapidly changing or unstable environment. The dynamic pressure measurements of DHCB have been performed. A down-oriented pressure with half-triangle waveform was dynamically applied on the sensing point. The frequency of that waveform was increased until only two points per cycle of the applied pressure can be recorded. This

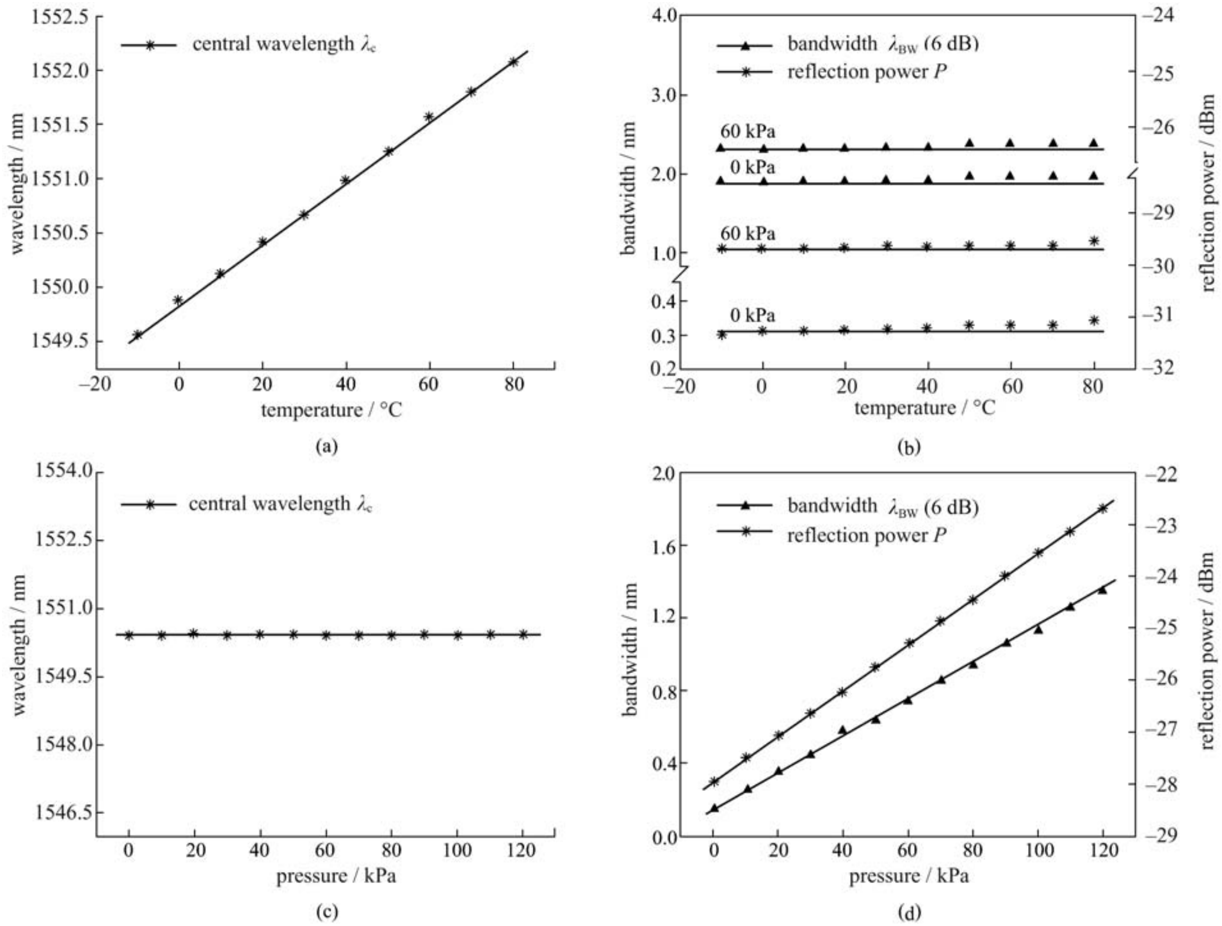

Fig. 5 Characteristics of FBG reflection spectra to temperature and pressure

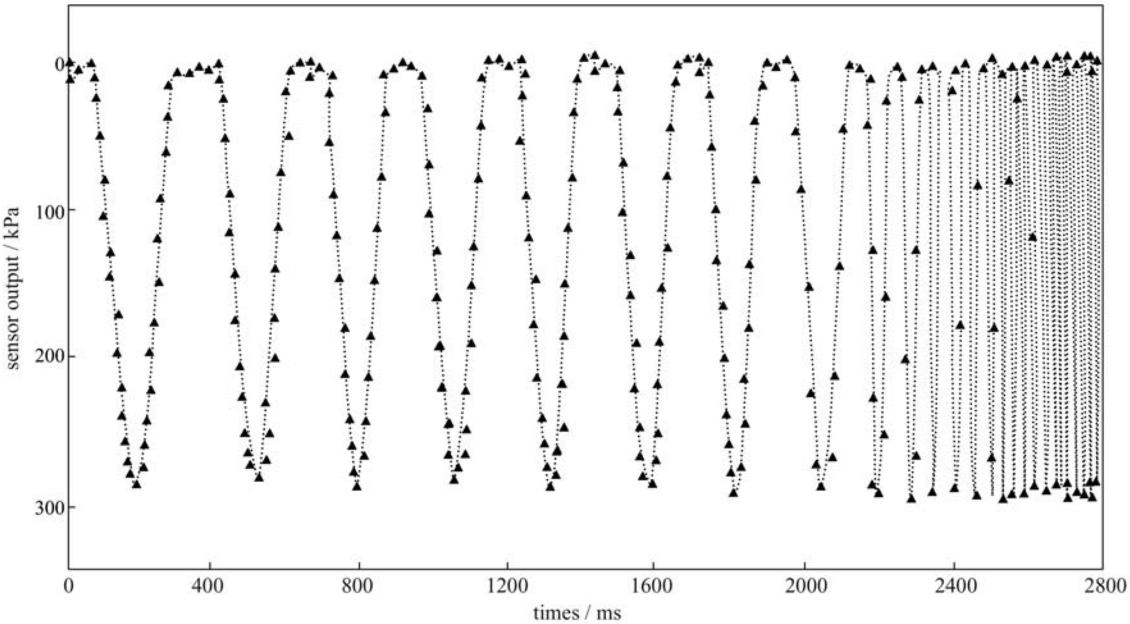

Fig. 6 Output of the sensor under a pressure applied with decreasing period

procedure permits estimating the sensor acquisition time. Figure 6 shows the obtained results, which turns out a system acquisition time of about 12 ms (80 Hz). The restricted aspects include: the reproducible velocity of the cantilever beam when pressure is applied on and off, which is factually determined by the structure-material of the beam and the value of applied pressure; the bonding quality of the grating and the selected grating position; the response time of the detector.

The high-elastic steel-made DHCB shows a good reproducibility and the reflection spectrum is highly stable in dynamic measurement. The pressure sensitivity and measurement range can be flexibly adjusted by changing the arc beam thickness and the beam's material. Precisely pasting the FBG at the largest linear strain gradient region is essentially important to the sensor quality. Because of the thermo-intenerated property of the beam material, the PD2 detected power becomes slightly higher as temperature increases, especially in a higher temperature environment. Further research for performance improvement of the sensor is under way, including selecting beam material with more stable and uniform thermal-mechanical features, precise position where the grating is pasted, improving the bonding quality, and optimizing the beam structure parameters.

4 Conclusions

The feasibility of the DHCB-based FBG dynamic pressure sensor has been investigated. Compared with traditional wavelength shift monitoring techniques, the PD-based optical power detection provides a simple and economical signal demodulation scheme, and it is immune to wavelength shifts induced by temperature fluctuations as well. Short acquisition time and intrinsic temperature immunity facilitates the use of this sensor in various potential applications.

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