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Analysis of the performance of strain magnification using uniform rectangular cantilever beam with fiber Bragg gratings

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ABSTRACT

A thorough analysis of the performance of different strain magnification structures with fiber Bragg gratings (FBG) is demonstrated in this paper. Four kinds of cantilever beams with different shapes have been designed by using a laser cutting technique. Simulation results show that the strain magnification structures of the different cantilever beams are different. There is a positive and linear correlation between the displacement of the free end of the cantilever beam and the average strain at the pasting position of the FBG. The correlation is used to calculate the displacement sensitivity and analyze the efficacy of the different strain magnification structures. Sensitivity enhancement factors (compared to a reference beam) of 2.67, 2.14 and 2.57 were measured experimentally for the different beam shapes studied, while the theoretical prediction factors were 2.67, 2.24 and 2.55, respectively. There is a reasonable agreement between simulation and experiment, which shows that the efficacy is related to the increasing rate of the average strain over the FBG length. The proposed method can be used to enhance the sensitivity of the FBG sensor and further improve the sensor structure design.

1. Introduction

Over the past decades, FBG have been extensively researched as strain gauge elements and now have become one of the most popular optical fiber sensing technologies. This is the result of their well-known advantages, such as compact size, ready multiplexing capability, corrosion resistance and anti-electromagnetic interference. However, due to the frangibility and stiffness of the optical fiber, the FBG cannot be used as sensor directly. Besides, the practical application of the FBG sensing technology is also subject to low sensitivity and cross-sensitivity. To solve these problems, exploring new structures and principles is the basic development direction.

A cantilever beam is often used to solve these problems because of its simple structure and stable performance. The measurement of displacement, force, acceleration and other quantities in the engineering field can be realized by pasting an FBG onto the surface of the cantilever beam [1–5]. Two FBGs are used simultaneously in a cantilever beam sensor to measure strain with temperature compensation [6]. The central wavelength of the FBG sensor can be easily measured by a commercial demodulator. This method is very simple and works well in temperature compensation, and it can be used for simultaneous measurement of temperature and strain. On the other hand, some techniques such as slow light [7], curved elastic beam [8], hydramantic structure [9] and necked shaped leaf spring beam [10] were applied to cantilever beam FBG sensors, and the properties of these FBG sensors were improved with wider measurement range and higher measurement sensitivity. But they are usually too complex or require more special instruments. In addition, some complicated cantilever beam structures [11–14] with one FBG have been designed to solve the cross-sensitivity problem. In these methods, the FBG is pasted on the non-uniform deformation region of the cantilever beam surface. It will result in a chirped FBG with the bandwidth of the reflectance spectrum proportional to the strain gradient. The variation of the bandwidth is essentially insensitive to a temperature change. Because only one FBG is used, it greatly reduces the cost of the FBG sensor. But the measurement of bandwidth is too dependent on the expensive optical spectrum analyzer, which limits its practical application.

In these solutions, the non-uniform strain distributions are only used to chirped FBGs to solve the cross-sensitivity problem. When a displacement is applied to the free end of the uniform rectangular cantilever beam with a through hole, the strain values near the

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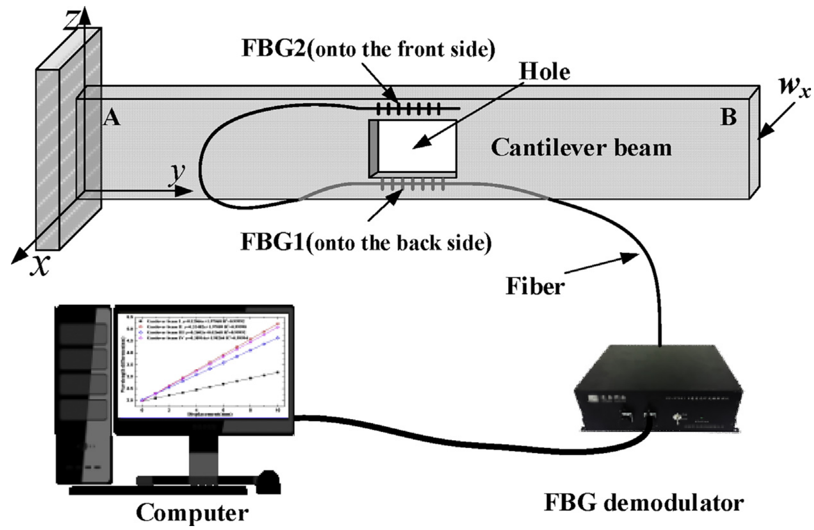

Fig. 1. Schematic diagram of the system for displacement measurement.

area of the through hole will become larger [15]. The sensitivity of the FBG strain sensor can thus be improved by placing the FBG to the strain magnification point. However, usually these non-uniform strain distributions are different. Therefore, it is meaningful to analyze the efficacy of the different strain magnification structures.

In this paper, FBG displacement sensors based on a uniform rectangular cantilever beam with sensitivity enhancement are proposed. The performance of these FBG displacement sensors is studied for different uniform rectangular cantilever beam shapes by using the finite element analysis (FEA) method. The central wavelength difference of the two FBGs pasted on the two sides of the cantilever beam is used for displacement measurements. The simulation and experimental results show that the displacement sensitivity is increased by more than two times. The efficacies of the different strain magnification structures are different, and the efficacy is related to the increasing rate of the average strain over the FBG length.

2. Measurement principle

The displacement can be measured by pasting FBGs on the surface of the uniform rectangular cantilever beam. However, the shift of the central wavelength of the FBG is sensitive to both the temperature and strain. In one cantilever beam sensor, two FBGs can be used to compensate temperature effectively [6,8]. When a displacement is applied to the free end of the uniform rectangular cantilever beam with a through hole, the strain values near the area of the through hole will become larger [15]. This results in a sensitivity enhancement of FBG sensors based on a uniform rectangular cantilever beam. The schematic diagram of the displacement measurement system is shown in Fig. 1.

The light from the FBG demodulator passes through the single mode fiber to the two FBGs. The FBG was apodized and the apodization profile was a Gaussian profile [16]. The reflectivity of the FBG is greater than 80%. The light with a certain wavelength is reflected back by the FBG to reach the FBG demodulator. The central wavelength of the FBG is measured by the FBG demodulator (GC-97001C) based on the dynamic scanning of the narrow-band semiconductor laser. The central wavelength data obtained by the FBG demodulator is displayed and recorded by the computer.

The uniform rectangular cantilever beam and two FBGs are used to design the FBG displacement sensor. The end denoted “A” of the cantilever beam in Fig. 1 is the fixed end and the end “B” is the free end. Two FBGs are pasted onto the opposite sides of the cantilever beam, with FBG1 at the back and bottom of the cantilever beam and FGB2 at the front and top of the cantilever beam. The epoxy resin adhesive (ergo7200) with a Young’s modulus of 2.5 GPa is used to paste the FBGs. The distance from the FBG1 to the end “B” is the same as the distance from the FBG2 to the end “B”. The axial direction of the FBG is parallel to the y axis. To improve the measurement sensitivity of the sensor, a laser cutting technique is used to cut a through hole at the pasting position of the FBG. The changes of the strain distributions brought by the through hole is analyzed in the simulation.

The application of the displacement w_x acts along the x axis at the end “B”, which results in the deformations on the surface of the cantilever beam. Due to the cantilever beam fabrication and the location of the application of the displacement, the behavior of the strain changes along the FBG1 axis are similar to those along the FBG2 axis. The difference is that FBG1 is stretched, whereas FBG2 is compressed. The shifts of the central wavelengths of the two FBGs will be in opposite directions, thus the displacement can be measured by the central wavelength difference of the two FBGs.

The central wavelength shift of the FBG can be expressed as

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = K_{T1}T_1 + K_{\varepsilon 1}\varepsilon_1 \tag{1}$$

$$\frac{\Delta\lambda_{B2}}{\lambda_{B2}} = K_{T2}T_2 + K_{\varepsilon 2}\varepsilon_2 \tag{2}$$

where$K_T = \alpha_F + \xi$, $K_\varepsilon = 1 - p_\varepsilon$, λ_B is the central wavelength of the FBG, $\Delta\lambda_B$is the drift value of the central wavelength of the FBG, α_F is the thermal expansion coefficient, ξ is the thermo-optic coefficient of the FBG, p_ε is the effective photo elastic coefficient of the silica fiber, T is the temperature and ε is the strain. In the equation, the FBG1 and FBG2 are distinguished with the subscript 1 and 2, respectively.

In addition, because the two FBGs are placed at symmetrical positions of the cantilever beam, the strain values of FBG1 and FBG2 are opposite, thus$\varepsilon_1 = -\varepsilon_2 = \varepsilon$ and$T_1 = T_2 = T$. The materials and manufacturing method of the two FBGs are the same, so$K_{\varepsilon 1} = K_{\varepsilon 2} = K_\varepsilon$and$K_{T1} = K_{T2}$. The central wavelength shifts of the two FBGs can be expressed as

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} - \frac{\Delta\lambda_{B2}}{\lambda_{B2}} = 2K_\varepsilon\varepsilon \tag{3}$$

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} + \frac{\Delta\lambda_{B2}}{\lambda_{B2}} = 2K_T T \tag{4}$$