A novel strain and position sensor based on a linearly chirped fiber Bragg grating

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We propose and experimentally demonstrate a position sensor system based on a thermally-induced linearly chirped fiber Bragg grating (LCFBG). Eight NiCr resistance wires are used to heat the LCFBG at eight small points to generate multiple narrowband transmission peaks within the stopband of the transmission-mode LCFBG. By monitoring the wavelength shift of the thermally-induced transmission peaks, strain information can be extracted. This sensor system provides the unique advantages of compact structure, cost-effective, able to demodulate both the strain and position information with only one sensor element.

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1. Introduction

Fiber Bragg gratings (FBGs) have shown their full versatility in the field of sensing. FBGs are capable of measuring a number of different physical parameters simultaneously [1-3], and can be distributed over a large area, due to their many advantages such as mechanical robustness, inherent immunity to electromagnetic noise, compactness, simplicity in fabrication, and unique wavelength-encoded operation. Strain sensing utilizing FBGs has shown a large amount of academic and commercial interest [4-5]. These applications utilize FBGs positioned at strategic points along the measured structure to generate a strain measurement from individual points along an array [6]. Most of the previous works have been conducted through an uncomplicated determination of the strain, pressure or temperature exerted on the FBG by means of a simple measurement of the wavelength shift by the sensing grating element. However, only a few [3-4] have reported the measurement of two or more parameters simultaneously.

In this work, a novel strain and position sensor system based on a thermally-induced LCFBG was proposed and experimentally demonstrated. By monitoring the wavelength shift of the thermally-induced transmission peaks, the axial strain applied to the grating can be extracted. Due to the linear relationship between the heating points and the thermally-induced transmission peaks, the position information of the heating point, where the phase shift was introduced to the grating, can also be demodulated from the monitored transmission spectrum. This FBG sensor system has many advantages including compact structure, cost-effective, able to demodulate both the strain and position information, simultaneously, with only one sensor element.

2. Principle and experimental setup

Heating a small region of an FBG will introduce a perturbation to the spectrum of the grating [7]. The fiber's refractive index in this small region is perturbed when being heated, because the thermal expansion coefficient is much smaller than the thermal-optical coefficient of the fiber. The change in the fiber length can thus be neglected compared with the thermally induced phase shift [8]. When the temperature change is large enough, a transmission peak is generated within the stopband of the LCFBG [9]. For a temperature change of less than 570 K, the heating process is non-destructive, that is, the spectral disturbance (transmission peak) is not due to a permanent change to the property of the grating [7], [9]. When the temperature change is much smaller than 570 K, the perturbation to the grating's spectrum will disappear. Thus if we individually control the thermally-induced multiple perturbations to the LCFBG, a switchable and tunable comb filter can be developed as described in [11-12].

Based on the tunable optical comb filter, a novel strain and position sensor system is developed as shown in Fig 1. A 6-cm long LCFBG is fixed in the middle of a stage made of a heat-insulated material. Two electric connector arrays are on the top and bottom of the stage. Forty 0.3 mm wide V-grooves spaced at 1.25 mm are set across the LCFBG, which is fixed by two fiber holders placed in the middle of the stage. Eight NiCr resistance wires with a diameter of 0.2 mm each are fixed in the V-grooves of the stage to heat the fiber at eight different points. The fiber used for grating fabrication was hydrogen-loaded for over 3 weeks to increase its photosensitivity before inscribing it with a phase mask (2.25 nm/cm chirp rate). The LCFBG has a 28~30 dB deep stopband between 1535.4 nm to 1554 nm. Note that a LCFBG with a deep stopband is very important as the rejection ratios of the thermally induced transmission peaks are preferred to be as large as possible. The heating element consists of eight 0.2 mm-thick 8 cm-long resistance wires with a resistivity of 37.5 Ω/m. Each of the resistance wires is connected with a variable resistor (0-100 KΩ) in order to independently control the electrical power consumed by every resistance wire, which in turn controls the temperature change at each of the heating points, where the fiber was in touch with resistance wires. The current of the power supply used is less than 2 A, and the consumed electrical power is about 8 W.

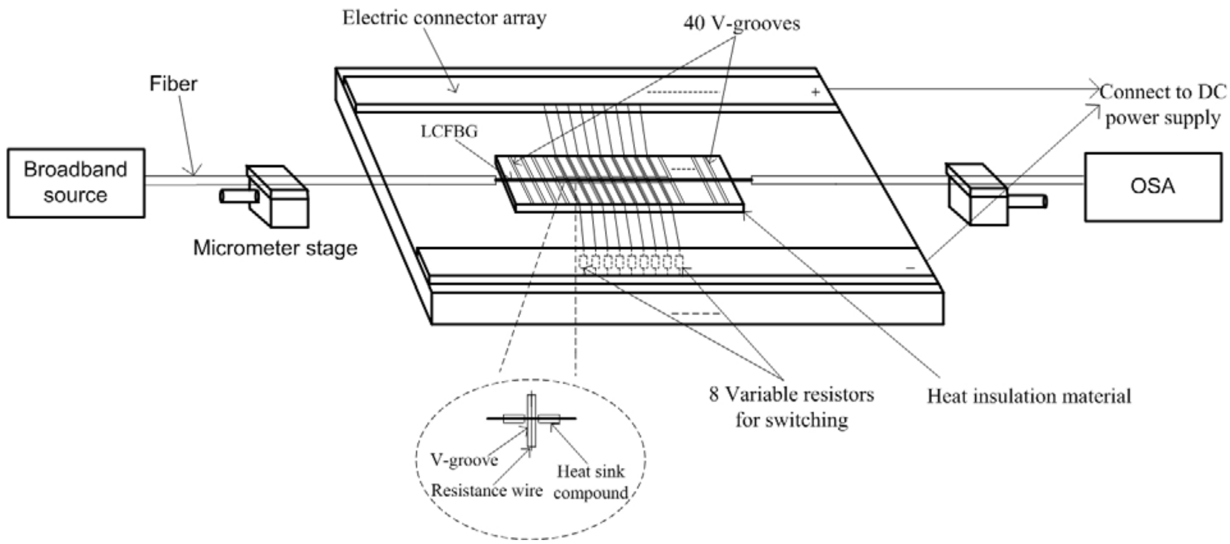

Fig. 1. Schematic diagram of the proposed strain and position sensor system based on the thermally tunable comb filter using a linearly chirped fiber Bragg grating (LCFBG) with multiple heated resistance wires. OSA is optical spectrum analyzer.

When heating all the resistance wires, eight transmission peaks with a wavelength separation of 1.6 nm and 3.2 nm were obtained within the stopband of the LCFBG as shown on Fig. 2. All the thermally induced transmission peaks have a rejection ratio of over 25 dB. The power flatness of the transmission peaks is within 1 dB, which can be controlled by the electric power applied to the resistance wires. Each of the transmission peaks can be switched on and off through appropriately tuning of a particular variable resistor connected to the resistance wire. And the center wavelength of each transmission peak can be tuned by changing the position of the resistance wires on the V-groove because the center wavelength of the transmission peak varies linearly with the position of the heating point [11]. In our experiment, the V-grooves on the stage are spaced at 1.25 mm, which corresponds to a minimal of ~0.4 nm shift of the center wavelength of the transmission peak.

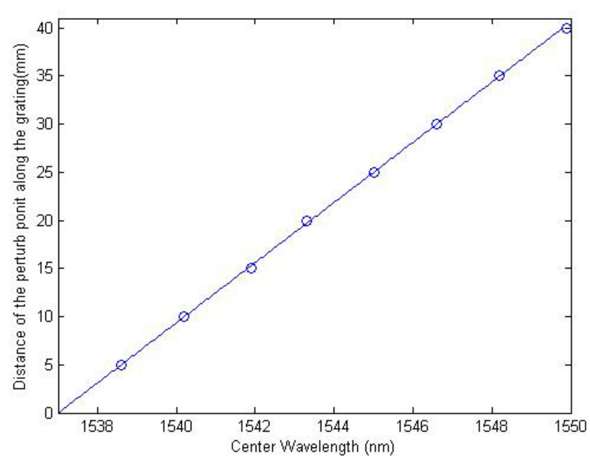

Fig. 2. A relationship between the center wavelength of the thermally-induced transmission peak and the corresponding perturbed position of the grating.

Two 1-D stages with micrometer were used to apply the axial strain to the LCFBG, when only one resistance wire was heated, which corresponds to the only generated transmission peak at ~1545 nm. And the fiber's two ends were stripped and fixed on the stages. The wavelength shift of the generated transmission peak ≥λ is given by [13]

$$\Delta\lambda = \lambda_B\left(1-\rho_e\right)\varepsilon_z \quad (1)$$

where $\lambda_B = 2n_{eff}\Lambda$ is the Bragg wavelength (in this case, the center wavelength of the generated transmission peak), ρ_e is the effective strain-optic constant, and ε_z is the applied longitudinal strain. The strain, which occurred at any point along the grating, was measured by monitoring the wavelength shift of the generated transmission peak on the transmission spectrum of the grating.

3. Experimental results and discussion

The output spectrum was monitored by an optical spectrum analyzer (OSA) and a broadband amplified spontaneous emission (ASE) light source was used to monitor the output spectrum. Due to the inherent nature of the LCFBG, each generated transmission peaks correspond to a unique position of the grating. The center wavelength of the thermally-induced transmission peaks can be utilized to decode the position information of the heating points since the linear relationship between the perturbed points and the center wavelength of the generated transmission peaks. Fig. 2 shows the linear response of the heating point, where the grating was perturbed, and the center wavelength of the thermally-induced transmission peak when only one resistance wire was heated at one time. Thus, by monitoring the generated transmission peaks, we can demodulate the position information of the perturbed point of LCFBG, which enable us to extract the position of the perturb point where the grating's temperature changes at that point. The slope of the line shown in Fig. 2 is about 0.32 nm/mm. From Fig. 2, we can see that the experimental date (shown as circles) agrees very well with the simulation (show as the line).

The strain measurement was also performed with the proposed method. When the LCFBG was stretched with the two micrometer stage securing two ends of the grating, the generated transmission peaks were observed to shift in wavelength linearly with the applied strain, as shown in Fig. 3. The experimental results (shown as "Δ") and the simulation result according to Eq. (1) (where $\rho_e = 0.22$, for silica fiber, $n_{eff} = 1.446$ and the period of the phase mask, $\Lambda_p = 1067$ nm), agree well with each other. The strain sensitivity is found to be 1.2 pm/με.

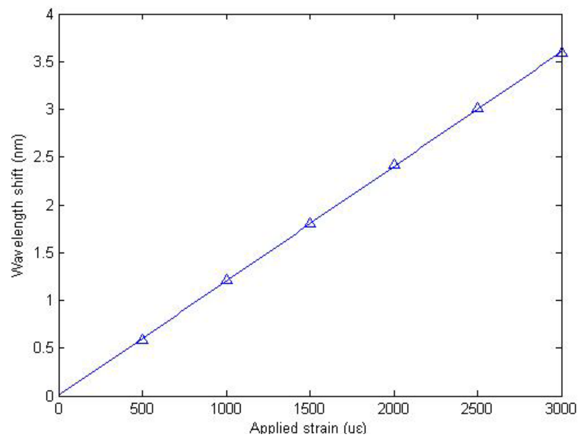

Fig. 3. Linear relationship between the measured wavelength shift of one transmission peak's center wavelength and the applied strain.

With the proposed scheme, we can measure the applied axial strain and obtain the position information of the perturb point along the grating using only one sensor system. By using a travel stage [9], the perturb point can be at any position along the grating. The only flaw of the proposed method is that the strain measurement range will limit the nearest perturb points that could be demodulated at the same time.

4. Conclusions

We proposed and experimentally demonstrated a novel strain and position sensor system based on a thermally-induced LCFBG. By monitoring the transmission spectrum of the LCFBG, the position of the perturb point and the applied strain can be demodulated from the proposed sensor system. The strain resolution is found to be 1.2 pm/με. The proposed method has many advantages such as compact structure, cost-effective, able to demodulate both the strain and position information with only one sensor element.

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