Appl Phys B (2009) 95: 383–387
DOI 10.1007/s00340-008-3350-6

Applied Physics B
Lasers and Optics

Temperature-insensitive strain measurement using a birefringent interferometer based on a polarization-maintaining photonic crystal fiber

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Received: 13 October 2008 / Revised version: 28 November 2008 / Published online: 13 January 2009

Abstract We propose a novel and simple scheme for a temperature-insensitive strain measurement by using a birefringent interferometer configured by a polarization-maintaining photonic crystal fiber (PM-PCF). The wavelength-dependent periodic transmission in a birefringent interferometer can be achieved by using a PM-PCF between two linear polarizers. Since the PM-PCF is composed of a single material, such as silica, the peak wavelength shift with temperature variation can be negligible because of the small amount of the birefringence change of the PM-PCF with temperature change. The measured temperature sensitivity is −0.3 pm/°C. However, the peak wavelength can be changed by strain because the peak wavelength shift is directly proportion to strain change. The strain sensitivity is measured to be 1.3 pm/με in a strain range from 0 to 1600 με. The measurement resolution of the strain is estimated to be 2.1 με. The proposed scheme has advantages of simple structure and low loss without a Sagnac loop, temperature insensitivity, ease installation, and short length of a sensing probe compared with a conventional PMF-based Sagnac loop interferometer.

PACS 42.81.Gs · 42.81.Pa

1 Introduction

Fiber-optic sensor technology has attracted much attention because it can provide the most simple and convenient methods to monitor the external perturbation change, like temperature, strain, and pressure. It has a lot of advantages, such as high sensitivity, electromagnetic immunity, compactness, and ease of fabrication [1, 2]. The most important issue of fiber-optic sensors is to discriminate multiple measurands, such as temperature, strain, bending, etc. A number of fiber grating-based sensors have been investigated and installed for a range of physical sensors because fiber gratings have wavelength selective nature, high sensitivity, and high compatibility [3, 4]. However, various fabrication equipment, such as UV laser, high-precision translation stage, phase mask, etc., is required to induce the photo-induced refractive index change for the fabrication of fiber gratings. The specific sensing technique based on an antiresonant-guiding photonic crystal fiber (PCF) was investigated for a refractometric sensor [5].

Recently simple methods of fiber-optic sensors exploiting versatile polarimetric techniques were proposed for the curvature and temperature measurement [6–8]. A PCF with core asymmetry was applied for measurement of lateral pressure by monitoring the variation of the phase and the group modal birefringence [6]. An absolute temperature sensor based on an unbalanced high-birefringence Sagnac loop with a polarization-maintaining fiber (PMF) was demonstrated [7]. After configuring a fiber loop mirror with a standard 3-dB coupler and a PMF, temperature and strain sensitivities can be discriminated by measuring the peak wavelength shift. Since the conventional PMF has two different materials, such as germanium and silica, different thermal expansion coefficients of two materials change the birefringence of the fiber and the peak wavelength can be shifted as the surrounding temperature increases. D.H. Kim et al has proposed temperature-insensitive Sagnac interferometer with a PCF [8]. Since the PCF consists of a single material like silica and periodic arrangement of air holes,

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the fringe pattern is not changed by the temperature variation. The fiber loop structure, however, has drawbacks of the complicated installation technique, high loss due to the use of a 3-dB coupler, and low efficiency of compatibility with another sensing head.

In this paper, we investigate a novel and simple configuration for a temperature-insensitive strain measurement based on a birefringent interferometer fabricated with a PM-PCF. The wavelength-dependent sinusoidal transmission spectrum can be achieved by using a PM-PCF between two linear polarizers. Since the PM-PCF is composed of a single material, such as silica, the birefringence variation of the PM-PCF with temperature change, which is the sum of the thermal expansion and optic coefficient, becomes small and the peak wavelength shift with temperature variation can be negligible. However, the peak wavelength of the PM-PCF-based birefringent interferometer strongly depends on the strain change because the phase change of the interferometer is directly proportional to the strain change. Therefore, the temperature-insensitive strain sensor can be achieved. The strain sensitivity is measured to be 1.3 pm/με in a strain range from 0 to 1600 με.

2 Experimental scheme for the strain measurement technique with temperature-insensitivity

Figure 1 shows the experimental scheme for the proposed temperature-insensitive strain measurement based on the birefringent interferometer fabricated by a PM-PCF. It consists of a broadband light source, two in-line fiber polarizers (O/E Land Inc.), a PM-PCF (Crystal Fiber A/S, PM-1550-01) with length of 13.6 cm. The insertion loss of the polarizer was less than 1 dB. The PM-PCF was spliced to a single mode fiber (SMF) with length of 5 cm by using a fusion splicer (Fitel Inc.). The splicing loss was measured to be ∼2.8 dB because of the mode-field mismatch and the different numerical aperture between the SMF and the PM-PCF. The broadband light source (HP83437A) was connected to the polarization controller (PC), which was implemented to stabilize the polarization state of the input light. The 3-dB bandwidth of the broadband light source was 40 nm at the wavelength of 1550 nm and the total power was −13 dBm. The linear polarizer converted the polarization state of the input light to the linear one. As the converted light propagates in the PM-PCF, the phase retardation can be induced by the birefringence of the PM-PCF. The transmission output was monitored by an optical spectrum analyzer (OSA). The resolution bandwidth (RB) of the OSA used in this experiment was always fixed at a value of 0.1 nm.

3 Operation principle for temperature-insensitive strain measurement based on the birefringent interferometer exploiting a PM-PCF

The proposed technique is basically composed of the PM-PCF between two linear polarizers, which have fast axis of the fiber rotated 45° relative to the polarizer axis [9]. The transmission characteristics of a birefringent interferometer strongly depend on the phase difference between the two axes of the birefringent fiber with wavelength dependence [9]. This can produce the sinusoidal wavelength dependent transmission spectrum in the birefringent interferometer. The wavelength-dependent transmission characteristic ($T(\lambda)$) of the birefringent interferometer can be expressed by [9]

$$T(\lambda) = \cos^2\left(\frac{\pi}{\lambda_o} n_{PM} L_{PM}\right), \quad (1)$$

where λ_o is the operating wavelength. n_{PM} and L_{PM} are the birefringence ($n_{PM} = n_x - n_y$) and the length of the birefringent medium, respectively. The black line in Fig. 2 shows the measured transmission spectrum of the PM-PCF-based birefringent interferometer. The wavelength spacing and the extinction ratio of the birefringent interferometer were measured to be ∼20.5 nm and ∼30 dB, respectively. After measuring the birefringence of the PM-PCF based on the Sagnac Loop, we obtained the birefringence value of 8.6×10^{-4}, which was in a good agreement with previous results [8]. Based on the measured birefringent of the PM-PCF and (1), the theoretical result of the transmission spectrum of the birefringent interferometer was shown in Fig. 2 (red line),

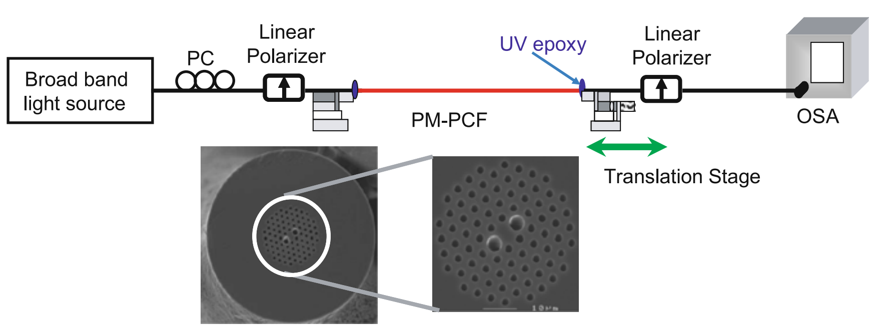

Fig. 1 Experimental setup of the proposed temperature-insensitive strain measurement based on the birefringent interferometer fabricated with a PM-PCF. The scanning electron microscopy image of the cross-section of the PM-PCF was shown in the *inset*

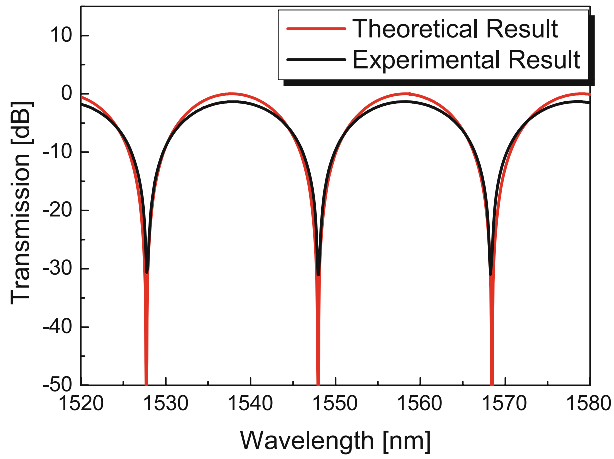

Fig. 2 Theoretical and experimental results of transmission spectra of the PM-PCF-based birefringent interferometer

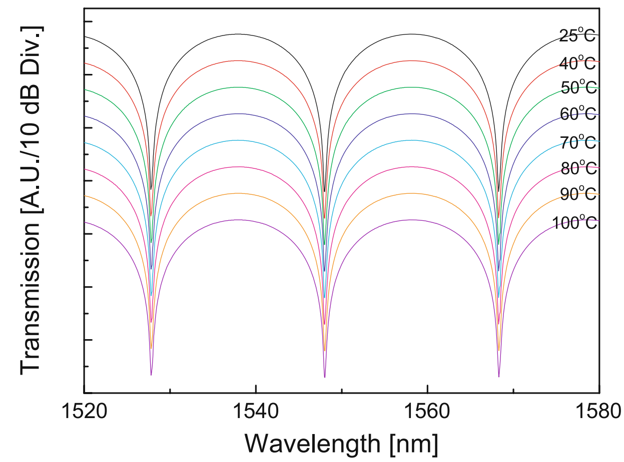

Fig. 3 Experimental results of transmission spectra of the proposed PM-PCF-based birefringent interferometer with the applied temperature change

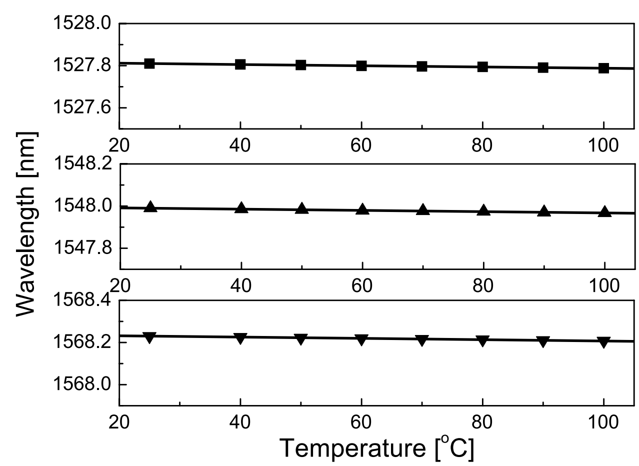

Fig. 4 Experimental results of peak wavelength shift as a function of applied temperature

which was in a good agreement with the experimental result.

From (1) the phase change ($\Delta\phi$) with the variation of external perturbation can be given by

$$\Delta\phi = \frac{2\pi}{\lambda_o}(\Delta n_{\mathrm{PM}} \cdot L_{\mathrm{PM}} + \Delta L_{\mathrm{PM}} \cdot n_{\mathrm{PM}}), \tag{2}$$

where $\Delta n_{\mathrm{PM}} (= \Delta n_x - \Delta n_y)$ and ΔL_{PM} are the birefringence and the length variation of the PM-PCF, respectively, as the external perturbation changes. The total value of the phase change with the external temperature change is small because of the small variation of Δn and ΔL [8]. Therefore, the temperature sensitivity of the peak wavelength of the birefringent interferometer based on the PM-PCF can be ignored. From (2) the strain-induced phase change of the PM-PCF-based birefringent interferometer can be expressed by [7, 8]

$$\Delta\phi = \phi_0\left(\frac{\Delta L_{\mathrm{PM}}}{L_{\mathrm{PM}}} + \frac{\Delta n_{\mathrm{PM}}}{n_{\mathrm{PM}}}\right) = \phi_0\varepsilon(1+\rho_E), \tag{3}$$

where ε $(= \Delta L_{\mathrm{PM}}/L_{\mathrm{PM}})$ is the strain and ρ_E is the modified coefficient for the strain-induced birefringence change corresponding to the photoelastic constant of the birefringence [8]. From (3) it is clearly evident that the peak wavelength of the birefringent interferometer is shifted to longer wavelength as the strain increases, because the peak wavelength change is directly proportional to the applied strain. Therefore, the temperature-insensitive strain measurement can be readily realized once the PM-PCF-based birefringent interferometer is exploited.

4 Experimental results for measurement of temperature and strain sensitivities

We measured the temperature sensitivity of the proposed sensing head by placing it into a temperature-heating oven. Note that the temperature-heating oven used in this experiment has a limited temperature tuning range between 30 and 100°C. We measured the peak wavelength shift while changing the oven temperature in the range from 30 to 100°C. Figure 3 shows the output optical spectra of the PM-PCF-based birefringent interferometer when temperature increased. Linear shift of three center wavelengths with temperature change was clearly observed to be very small. Figure 4 shows the peak wavelength shift as a function of the applied temperature. After fitting the measured data with a linear function, the temperature sensitivity in terms of the wavelength variation was estimated to be −0.3 pm/°C, which was ~3000 times lower than the previously reported

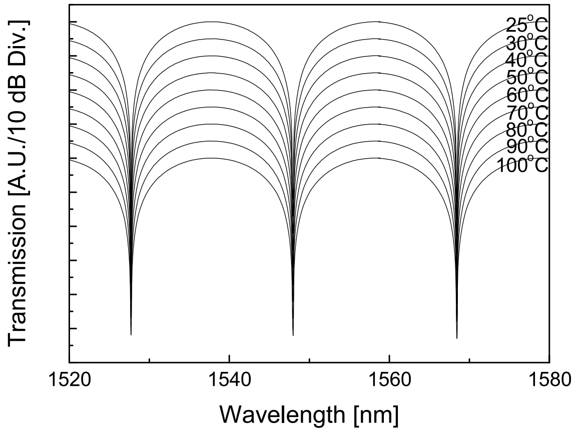

Fig. 5 Theoretical results of transmission spectra of the proposed PM-PCF-based birefringent interferometer with the applied temperature change

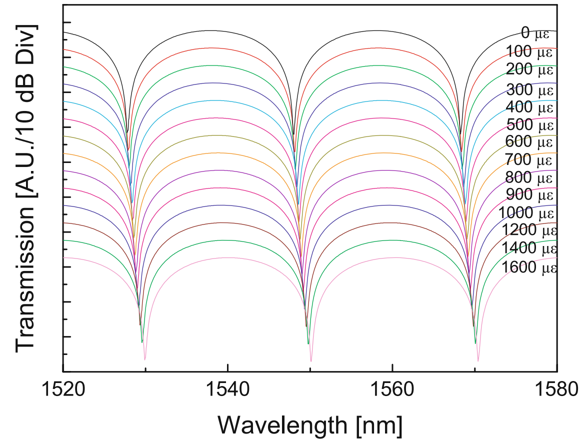

Fig. 6 Experimental results of transmission spectra with the applied strain change

result based on a conventional PMF [7]. The result was in a good agreement with the previous result [10]. The estimated root mean square error (RMSE) was measured to be ∼2.5 pm. The negative temperature sensitivity of the peak wavelength shift in the proposed sensing head is caused by the negative temperature dependence of the birefringence of the PM-PCF [8]. Based on theoretical analysis of the temperature dependence of the birefringent of the PM-PCF reported in [8] the temperature dependence of the PM-PCF-based birefringent interferometer was calculated. Since the core and the cladding regions of the PM-PCF are composed of a single material, such as silica with low thermo-optic and thermal expansion properties, the temperature dependence of the birefringence of the PM-PCF is small [8]. The estimated temperature sensitivity of the peak wavelength was −0.4 pm/°C. As seen from Fig. 5, the peak wavelength shift was small, which was in a good agreement with the experimental results. The small difference between theoretical and experimental results was caused by the measurement of the peak wavelength shift, the wavelength spacing, and the applied temperature by low quality of the heating oven.

We measured the strain sensitivity while applying tensile strain to the PM-PCF-based birefringent interferometer at room temperature (25°C). Figure 6 shows the transmission spectra of the PM-PCF-based birefringent interferometer with the applied strain change. The peak wavelength linearly increased when the applied strain increased. Significant output peak power variation of the sensing signal was not observed. The measured data for the wavelength shift of three peaks as a function of applied strain are summarized in Fig. 7. After fitting the measured data with a linear function, we found the strain sensitivity to be 1.3 pm/με in a range from 0 to 1600 με. The measurement resolution of the strain was estimated to be 2.1 με, which results from the measurement of the peak wavelength shift, an UV curable epoxy, and the applied strain by the movement of the translation stage.

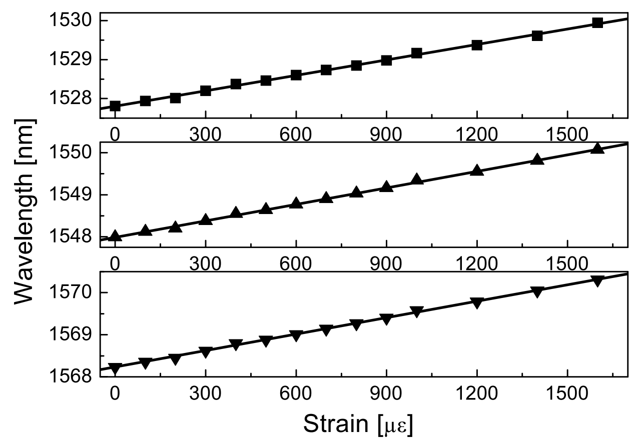

Fig. 7 Experimental results of peak wavelength shift as a function of applied strain

5 Conclusions

In conclusion, we investigated a simple and practical scheme for the temperature-insensitive strain measurement based on the birefringent interferometer. By implementing the polarization-maintaining photonic crystal fiber (PM-PCF) placed in the middle of two linear polarizers, the experimental configuration was significantly simplified without 3-dB couplers. A periodic transmission characteristic with high extinction ratio of ∼30 dB based on the wavelength-dependent retardation of the PM-PCF was achieved. The temperature sensitivity of the peak wavelength of the proposed sensing probe was effectively suppressed by the silica-based PM-PCF. However, when the strain was applied to the proposed sensing head, the peak wavelength shifted to longer wavelength because the variation of the peak wavelength was solely as a function of the applied strain. The measured strain sensitivity of the proposed sensing probe was measured to be ∼1.3 pm/με in a strain range from 0 to

1600 με. We believe that the input light source and the interrogation technique of sensing signals should be improved to fabricate a cost-effective sensing system. The experimental results are very useful in design of robust temperature-insensitive strain sensors for structural health monitoring.

Acknowledgements This work was supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2008-313-C00351).

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