High pressure sensor based on photonic crystal fiber for downhole application

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We demonstrate a polarization-maintaining (PM) photonic crystal fiber (PCF) based Sagnac interferometer for downhole high pressure sensing application. The PM PCF serves as a direct pressure sensing probe. The sensor is transducer free and thus fundamentally enhances its long-term sensing stability. In addition, the PM PCF can be coiled into a small diameter to fulfill the compact size requirement of downhole application. A theoretical study of its loss and birefringence changes with different coiling diameters has been carried out. This bend-insensitive property of the fiber provides ease for sensor design and benefits practical application. The pressure sensitivities of the proposed sensor are 4.21 and 3.24 nm/MPa at ~1320 and ~1550 nm, respectively. High pressure measurement up to 20 MPa was achieved with our experiment. It shows both good linearity in response to applied pressure and good repeatability within the entire measurement range. The proposed pressure sensor exhibits low temperature cross sensitivity and high temperature sustainability. It functions well without any measurable degradation effects on sensitivity or linearity at a temperature as high as 293 °C. These characteristics make it a potentially ideal candidate for downhole pressure sensing. © 2010 Optical Society of America

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1. Introduction

Fiber optic sensors for downhole application have attracted much research interest in both academia and industry [1–5]. Conventional electrical gauges used for in-well parameter measurements have a high failure rate when implemented in a high temperature environment. Fiber optic sensors have an estimated lifetime of 5–10 years, function up to 250 °C [4], are electrically passive, and are suitable for use in explosive and/or corrosive environments. Fiber optic sensors for downhole application are focused mainly on the measurement of temperature, pressure, strain, and flow [5]. Most fiber optic pressure sensors for downhole application are based on conventional fibers. However, because of the ultralow pressure sensitivity of these fibers, elaborate transducers or complicated structures need to be introduced to gain and enhance such functionality. On the other hand, photonic crystal fibers (PCFs) have been less exploited for downhole sensing application. As a new class of optical fiber, PCF guides light by a periodic array of microstructure running down the entire fiber length [6,7]. Owing to the novel structure with flexible design, numerous applications, including sensing applications, have been proposed for PCFs [8–19]. One of the most attractive characteristics provided by PCFs is an

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airhole structure that is sensitive to pressure and thus has the potential for direct pressure sensing. Recently, a polarization-maintaining (PM) PCF was made commercially available. The PM PCF has two large airholes that surround a solid core in one of the orthogonal directions. The PM PCF exhibits high birefringence, low bending loss, and reduced temperature sensitivity [11,12,15]. A PM PCF used as a sensing element for strain, pressure, torsion, and curvature measurements has been reported [13–18]. The multiplexing capability of the PM PCF based sensors with a Sagnac interferometer configuration has also been investigated [20]. Together with our proposed multiplexing techniques, we believe the proposed sensors can be further enhanced in a real application.

We report on the high pressure sensing capability of the PM PCF based Sagnac loop interferometer [16]. Characteristics of the sensor have been investigated with regard to downhole application. High birefringence and bend insensitivity of the PM PCF enabled us to use and to coil a relatively short length of fiber, resulting in a compact sensor that can be used to advantage in space-limited downhole application. The pressure achieved during our experiment reached 20 MPa. The pressure sensitivities of the proposed pressure sensor are 4.21 and 3.24 nm/MPa at ~1320 and ~1550 nm, respectively. The pressure sensor responds to the applied pressure with good linearity and is highly repeatable. It is less sensitive to temperature, owing to the low thermal coefficient of the PM PCF, which is made entirely of pure silica and thus reduces the requirement of temperature compensation when it is used in a harsh environment where temperature fluctuation is inevitable [15]. In addition, its pressure sensing performance has been tested to function well to as high as 293 °C.

2. Principle and Fabrication of the Pressure Sensing Element

A. Experimental Setup

The experimental setup of our proposed high pressure sensor based on PM PCF with a Sagnac loop configuration is illustrated in Fig. 1. The operating principle of the PM PCF based pressure sensor has been reported previously [15], so we summarize only the essential details here. As shown in Fig. 1, the 3 dB coupler splits the input signal equally into two signals with a $\pi/2$ phase difference between them. The two signals counterpropagate through the PM PCF before they interfere again at the coupler. With a broadband light source at the input, the output transmission spectrum is approximately a periodic function of the wavelength. The pressure-induced birefringence change of the PM PCF results in a phase difference between the two signals and then causes a shift of the output interference spectrum. Applied pressure variation can then be determined by measuring the wavelength shift of the interference spectrum. Alternatively, intensity-based detection can also be implemented if we use a laser at the input and a photodetector to measure the output. This could decrease the cost of the system and make it easier to achieve a highly portable system [15]. We used a broadband light source based on a superluminescent light-emitting diode (SLED) that combines two SLEDs centered at 1320 and 1550 nm. The Sagnac loop consists of a 3 dB fiber optic coupler and a piece of PM PCF spliced to the two ports of the coupler on one side. The PM PCF (PM-1550-01, by Blaze Photonics, Bath, UK) has a beat length of <4 mm at 1550 nm. The total loss of the two splicing points was ~4 dB, and the splicing points had good mechanical strength [21]. The length of the PM PCF was 60 cm and coiled circularly to a diameter of 1.8 cm. Thus, it is compact and suitable for use in space-limited downhole applications. The PM PCF here serves as a direct pressure sensing element without the use of a transducer. An optical spectrum analyzer was used to record the sinelike interference output signal from the Sagnac loop in the wavelength domain. The coiled PM PCF was placed inside a pressure chamber. Together with the 3 dB coupler, they were kept stable during the experiment. The high pressure chamber was filled with oil. Its pressure can be adjusted by a high pressure compressor and measured with a pressure gauge, as illustrated in Fig. 1. The pressure chamber is fitted with a feedthrough sealed by glue to extend the fiber outside the chamber for measurement. Although the maximum pressure value of the pressure compressor is 30 MPa, the glued feedthrough failed at such high pressure, and thus the measurement results presented here are all limited to 20 MPa. In addition, the chamber was positioned inside a temperature-controlled furnace. Hence, by using this setup we can adjust both pressure and temperature to verify the performance of our proposed pressure sensor.

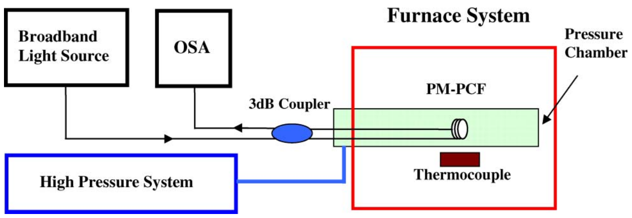
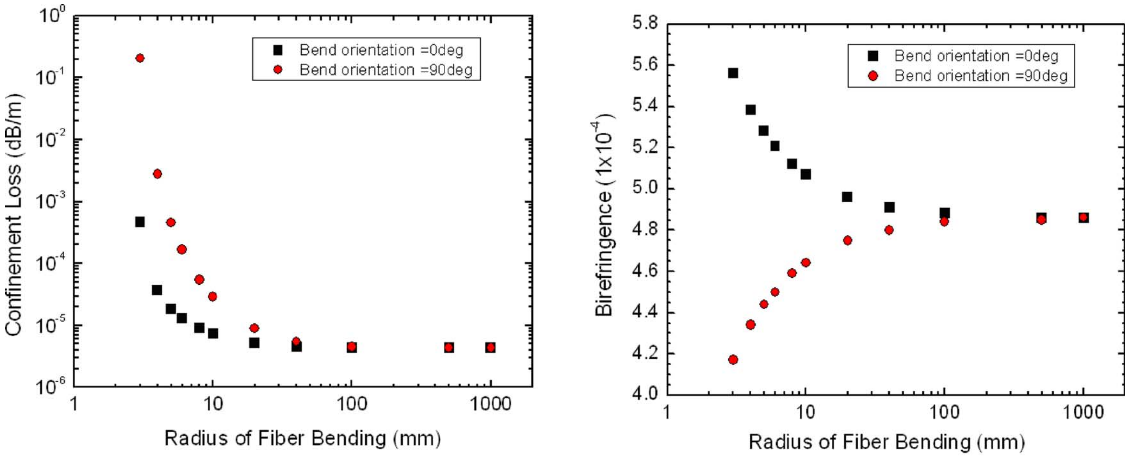


Fig. 1. (Color online) Experimental setup of the PM PCF based Sagnac interferometer for high pressure sensing application.

B. Compact Size

One of the most important requirements for downhole sensors is compact size because of the space-limited environment. Our proposed PM PCF based Sagnac interferometric pressure sensor fulfills this requirement. The PM PCF has a low bending loss and can be coiled into a small diameter to the centimeter scale. The PM PCF with a length of 60 cm was coiled to a diameter of 1.8 cm. In our experiment, no obvious changes were observed with regard to loss and birefringence, even when the fiber was coiled to the small diameter of 6 mm [15]. To have a complete understanding of its limitation, we present a



(a) (b)

Fig. 2. (Color online) Numerical results of (a) confinement loss and (b) birefringence of the PM PCF under bending with a 6 mm diameter.

theoretical study of the confinement loss and birefringence change versus the coil diameter. A finite-element method based vectorial optical mode solver (Mode Solutions by Lumerical Solutions, Vancouver, British Columbia, Canada) was used for the simulations. Figure 2 shows the numerical results for the confinement loss and birefringence of the PM PCF with different coiling diameters for two perpendicular orientations. The orientation along the two large holes of the PM PCF is denoted as 0 deg, and the other orientation is denoted as 90 deg. A 6 mm bending diameter was simulated for all the cases, which is close to the physical limitation of the fiber. The confinement loss increases rapidly with the decrease in radius of curvature below an onset value of 10 mm under both bending orientations. However, a low bending loss was found under the extreme bending orientation. A loss of ~0.2 dB was accumulated when a 1 m fiber was coiled 53 times with a radius of 3 mm. In comparison with conventional single mode fiber, its bending loss is quite small. On the other hand, the birefringence begins to increase significantly at a bending radius of 10 mm. The birefringence splits away and indicates a strong effect on different bending orientations. However, only an ~5% change in birefringence was introduced at a 10 mm bending radius. This relatively bend-insensitive characteristic can benefit sensor implementation in real applications.

3. High Pressure Sensing

Figure 3(a) shows the output optical spectrum of the high pressure sensor at the 1550 nm wavelength band. The extinction ratio between the transmission maxima and the transmission minima is ~30 dB around 1550 nm, which is approximately the center wavelength of the light source. The spacing between two adjacent transmission minima is 5.7 nm, denoting a birefringence of 7.0×10^{-4} at 1550 nm. A fiber Bragg grating (FBG) centered at 1544.68 nm is installed together with the PM PCF sensor head to calibrate the applied temperature. When applied pressure increases, the whole spectrum shifts toward longer wavelengths. By measuring the wavelength shift of one of the transmission minima in the wavelength spectrum, the pressure variation can be deter-

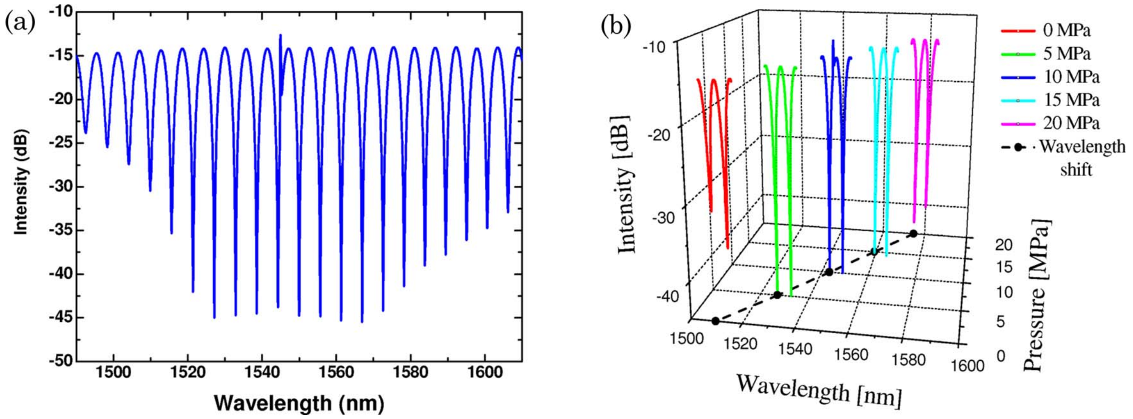


Fig. 3. (Color online) (a) Output optical spectrum of the PM PCF based Sagnac interferometric pressure sensor; the peak shows the reference FBG. (b) Output optical spectra of the pressure sensor under applied pressure from 0 to 20 MPa at room temperature. One of the transmission minima shifts from 1509.8 to 1574.8 nm, and the peak in the third spectrum indicates the reference FBG.

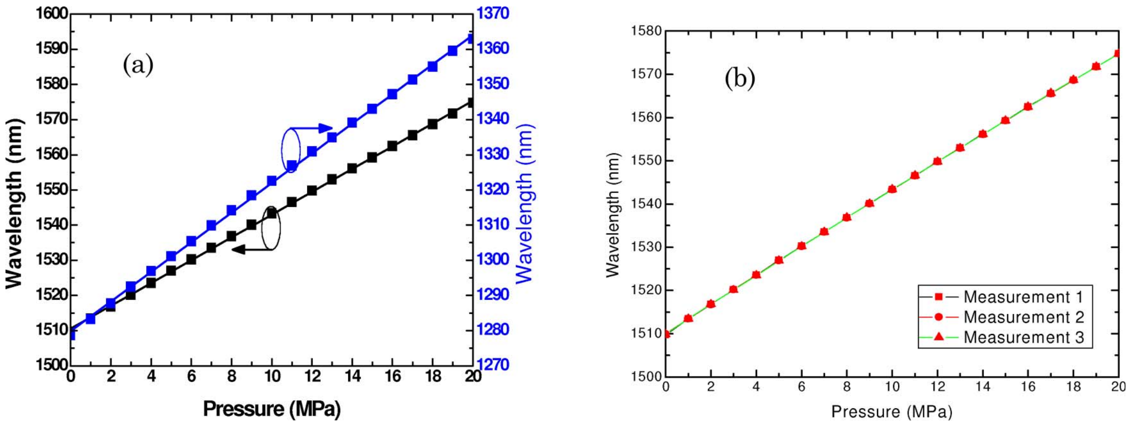


Fig. 4. (Color online) Wavelength shift of the transmission minimum (a) at approximately 1320 and 1550 nm under applied pressure from 0 to 20 MPa and (b) under applied pressure from 0 to 20 MPa; good repeatability is demonstrated.

mined, as illustrated in Fig. 3(b). Initially, one of the transmission minima is at 1509.8 nm. It shifts toward a longer wavelength by 65 nm when the applied pressure increases from 0 to 20 MPa. According to the measured experimental data, the pressure sensitivity can be calculated to be 3.24 nm/MPa by applying linear curve fitting. The pressure response of the sensor is highly linear with a good R^2 value of 0.9997. If a wavelength meter with 10 pm resolution is used, it leads to a pressure resolution of 3 kPa. For comparison, we also performed the experiment with a light source at the 1320 nm wavelength band. The corresponding pressure sensitivity is 4.21 nm/MPa with an R^2 value of 0.9995, as shown in Fig. 4(a). These results agree well with our previous theoretical prediction that the amount of the wavelength shift is approximately proportional to applied pressure at a small wavelength range [15]. For a larger wavelength range, the pressure sensitivity is different because of its corresponding birefringence and the birefringence-pressure coefficient changes at particular wavelengths. Because of the limitation set by the glue we used to seal the fiber feedthrough, the highest applied pressure achieved was 20 MPa. However, there was no obvious evidence showing any physical limitation by the PM PCF itself, thus, higher pressure sensing is possible with this sensor.

The repeatability of the sensor is one of the important issues. To test the repeatability of our proposed sensor, we performed three separate measurements from 0 to 20 MPa. From the experimental results we observed that the proposed sensor is highly repeatable, as illustrated in Fig. 4(b). The calculated average standard deviation for wavelength shift variations is only 0.024 nm, which corresponds to a small pressure variation of 7.55 kPa. This small variation is negligible for high pressure sensing such as downhole application.

4. Performance in a High Temperature Environment

The high temperature sustainability of fiber optic sensors is an important prerequisite for downhole application. In practice, when designing a sensor system, the variation of an ambient temperature on the sensor response is always a critical issue. The effect of ambient temperature fluctuations on the sensor performance was investigated. The temperature of the furnace was measured with a thermocouple and calibrated by a FBG installed inside the pressure chamber. The pressure sensitivity of the FBG was also

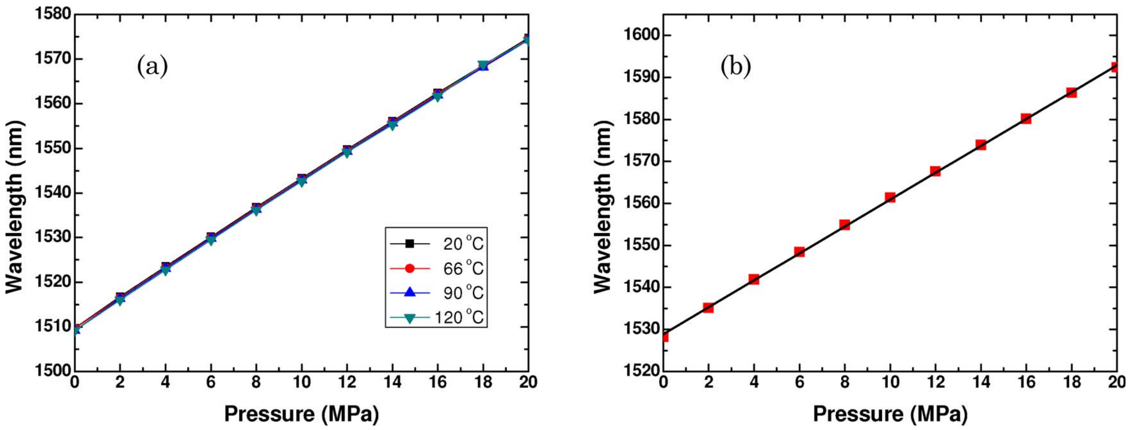


Fig. 5. (Color online) Wavelength shift of the transmission minimum under applied pressure from 0 to 20 MPa at temperatures of (a) 20 °C, 66 °C, 90 °C, and 120 °C and (b) 293 °C.

taken into account in the measurements. We tested the pressure sensor at temperatures of 20 °C, 66 °C, 90 °C, and 120 °C. Figure 5(a) illustrates the measured wavelength shift of the transmission minimum for different temperatures. There is no significant effect on the pressure sensing performance with a 100 °C temperature variation. The corresponding average pressure shift is only −0.19 MPa. The pressure sensor has a low temperature cross sensitivity that agrees with that reported in previous publications [11–15]. Furthermore, the sensor can sustain a temperature as high as 293 °C, as shown in Fig. 5(b); there is no observable degradation in sensor performance. The pressure sensor maintains a linear response with the same pressure sensitivity at a temperature as high as 293 °C, which is well above the typical high temperature of 250 °C for downhole pressure sensing application.

5. Conclusion

The potential of a high pressure sensor for downhole application by use of a PM PCF based Sagnac interferometer has been demonstrated experimentally. The pressure sensor performance has been investigated under high pressure and at a high temperature, both of which are the two main considerations for in-well application. The pressure sensitivity is 3.24 nm/MPa at ∼1550 nm under applied pressure from 0 to 20 MPa. The sensor has a good linear response to applied pressure, is highly repeatable, and functions well without any degradation at a temperature as high as 293 °C. The high pressure sensitivity and the temperature insensitivity as well as the high temperature sustainability of the PM PCF distinguish the proposed high pressure sensor from other fiber optic pressure sensors for downhole applications. The sensor has a direct sensing PM PCF head that is simple to design, compact in size, and easy to manufacture, all of which make it an ideal candidate for high pressure sensing in real applications.

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