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The pore water pressure sensor based on Sagnac interferometer with polarization-maintaining photonic crystal fiber for the geotechnical engineering

Wei-Qiang Feng [a,b,*], Zheng-Yong Liu [c], Hwa-Yaw Tam [c], Jian-Hua Yin [a,b]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] PolyU Shenzhen Research Institute, Shenzhen, China
[c] Photonics Research Center, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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ABSTRACT

The pore water pressure sensors with the six-hole suspended-core polarization-maintaining photonic crystal fiber (SC-PM-PCF) and commercial polarization-maintaining photonic crystal fiber (PM-PCF) are designed based Sagnac interferometer and calibrated in the laboratory. According to the theoretical analysis and calibration results, the transmission spectrum is very sensitive to the pore water pressure. It is found that the wavelength of the spectrum has a good linear relationship with variances of the surrounding pore water pressure, and the coefficient of wavelength–pressure of the commercial PM-PCF is 304.41 kPa/nm with the length of 35 cm as the sensing element while the coefficient of the SC-PM-PCF is 254.75 kPa/nm with the length of 100 cm. Finally, the two PM-PCF sensors are applied and compared with the conventional Pore water Pressure Transducers (PPTs) in a physical model test. It is found that measurements of the PM-PCF sensors are in good agreement with the results measured by the conventional PPTs.

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1. Introduction

Pore water pressure plays an important role in geotechnical engineering as it is closely related to safety and stability of many geotechnical structures. The electrical sensors such as the electrical strain gauges and vibrating wire strain gauges are widely used in geotechnical testing and projects to measure the pore water pressure [1]. However, drawbacks of electro-magnetic interference, short circuit and lack of durability significantly limit the accuracy of these sensors and affect their applications [2]. In order to overcome these limitations, the fiber optic sensors, which are mainly based on Fiber Bragg Grating (FBG) technology, are commonly used in geotechnical testing [3]. Fiber Bragg Grating sensor for the pore water pressure measurement was presented by attaching the sensor on a porous sintered stainless steel [1]. It is noted that the temperature effect is an important factor in the most FBG sensing, and the accuracy and range of FBG sensors are directly related to the plate stiffness, where FBG sensors are attached. Due to the simple design, less susceptibility to environmental noise and low bending loss, the polarization-maintaining photonic crystal fiber (PM-PCF) has attracted a subsequent research and sensing applications [4–8]. Measurement of pressure and temperature is usually conducted for PM-PCF research [9,10]. It is found that PM-PCF is less temperature dependence than conventional polarization-maintaining fibers (PMFs) and Fiber Bragg Grating (FBG) sensors since it is made of pure silica without any other adopted materials such as GeO_2 to increase the index of refraction [11,12]. The birefringence of PM-PCF can be up to 10^{-2} in practice [13], which is higher than that of conventional PMFs owing to its flexible design.

Given the advantage of the PM-PCF sensors, it is proposed to extend the PM-PCF sensor into geotechnical engineering to measure the pore water pressure. PM-PCF-based pore water pressure sensors are designed, fabricated and calibrated in this paper. The feasibility and performance of measuring the pore water pressures is investigated in a physical model in the laboratory. Classical Pore Pressure Transducers (PPTs) are also adopted for comparison. The details and results are presented and discussed in the following parts.

* Corresponding author at: Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.

E-mail addresses: 11901182r@connect.polyu.hk (W.-Q. Feng), zhengyong.liu@connect.polyu.hk (Z.-Y. Liu), hwayaw.tam@connect.polyu.hk (H.-Y. Tam), jianhua.yin@connect.polyu.hk (J.-H. Yin).

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2. Principle and design of PM-PCF-based pore water pressure sensor

2.1. Principle of the PM-PCF sensor

One main characteristic of PM-PCFs is that there is an array of asymmetrical air holes along the fiber, the birefringence is introduced and shows the capability of direct pressure sensing [14]. In this study, one commercial polarization-maintaining PCF (PM-PCF) and one six-hole suspended core polarization-maintaining PCF (SC-PM-PCF), fabricated in the Hong Kong Polytechnic University, were used. The type of commercial PM-PCF is Blaze Photonics PM-1550-01, and it has two large air holes adjacent to the core. The SC-PM-PCF, specially designed and made by authors, has an elliptical suspended-core supported by six large holes, as shown in Fig. 1(b). The SC-PM-PCF was fabricated using stack-and-draw technique. After drawing into fiber, it has an elliptical core with a major and minor axis of ~8 μm × 4 μm, while the outer diameter is kept at 125 μm. Due to the design of elliptical core, the fiber has high intrinsic birefringence of 4.7×10^{-4}. There are six big holes supporting the suspended-core, and each hole has the dimension of ~22 μm by 27 μm. As for the commercial PM-PCF, it has a core with the size of ~6.6 μm by 4.5 μm in diameter, which gives an intrinsic birefringence of 4.2×10^{-4}. The diameters of small holes and two large holes are 2.2 μm and 4.2 μm. It should be noted that both types of the fibers are made of pure fused silica glass, which has a refractive index of 1.444 at the wavelength of 1550 nm. Owing to the single material used with low thermal effect, the temperature dependence of the fibers can be ignored within small variation range [5,11,12]. Fig. 1 illustrates the schematic setup of the pore water measurement using PM-PCF and SC-PM-PCF sensors. The simulated mode intensity profiles of both fibers are shown in Fig. 1(b).

As shown in Fig. 1, two propagating lights which are split by the 3 dB SMF coupler interfere again at the coupler in the loop, the corresponding spectrum is mainly affected by the relative phase difference of the two beams after propagating the commercial PM-PCF or SC-PM-PCF sensor, which is sensitive to the surrounding pressure. The loop transmission spectrum is a function of the wavelength, expressed as [3]:

$$T = \frac{[1 - \cos(\delta)]}{2} \tag{1}$$

where δ is the total phase shift of the Sagnac loop and it includes the intrinsic birefringence phase shift (δ_0) and pressure-induced birefringence phase shift (δ_p) over the length L of the PM-PCF. The total phase shift can be described as:

$$\delta = \delta_0 + \delta_p = \frac{2\pi L}{\lambda_0}(B_0 + k_p \Delta P) \tag{2}$$

where B_0 is the intrinsic birefringence of the PM-PCF, k_p is the coefficient of birefringence-pressure and applied pressure, ΔP is the change of the surrounding pressure, L is the length of the PM-PCF sensor and λ_0 is the original wavelength.

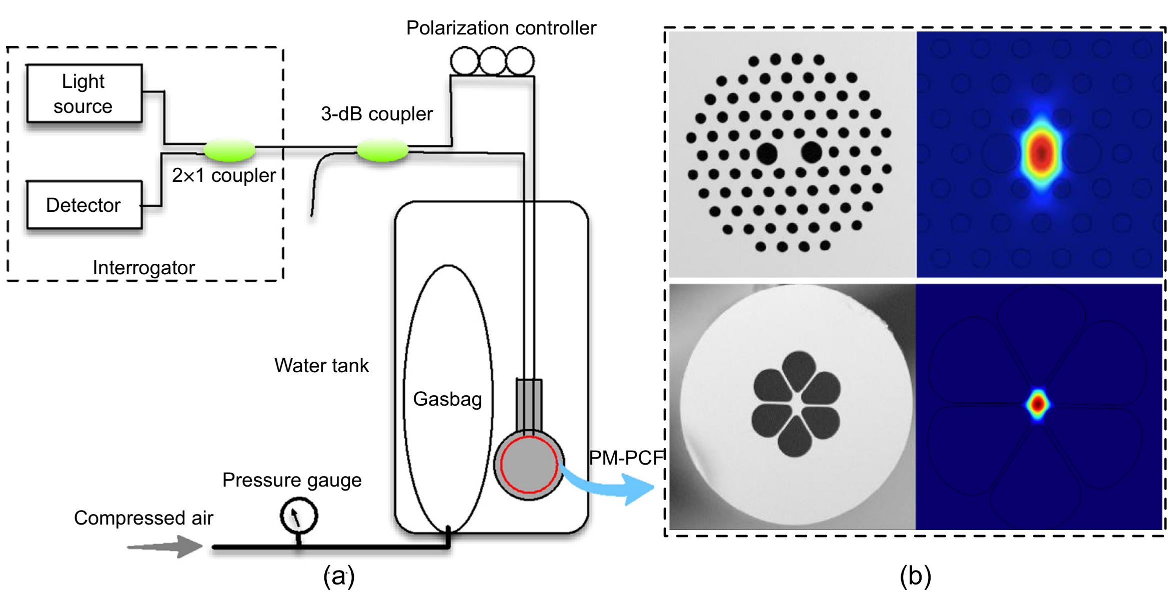
When applying the pressure around the PM-PCF sensor, the pressure-induced birefringence phase shift (δ_p) changes with the pressure and equals to 2π if the transmission minimum moves to the adjacent one. Therefore, the total wavelength shift caused by pressure-induced birefringence is:

$$\Delta\lambda = \frac{\delta_p}{2\pi} \cdot \frac{\lambda_0^2}{B_0 L} \tag{3}$$

Submit $\delta_p = (2\pi L \cdot k_p \Delta P)/\lambda_0$ to Eq. (3), the relationship between wavelength shift and applied pressure can be obtained:

$$\Delta P = \left(\frac{B_0}{\lambda_0 k_p}\right)\Delta\lambda \tag{4}$$

This equation indicates that the applied pressure is linear to the spectral shift since the parameters of B_0, λ_0, k_p are constant. Hence, it is a practical method to determine the surrounding pore water pressure on the optical fiber when the spectral shift of PM-PCF sensor is measured.



(a) Working principle of the pore water pressure sensor with PM-PCF based Sagnac interferometer
(b) The SEM micrograph of the cross-section of commercial PM-PCF, SC-PM-PCF and their corresponding optical mode profiles.

Fig. 1. Schematic diagram of the pore water pressure sensors with PM-PCF-based Sagnac interferometer.

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