

Fully distributed pressure sensing with ultra-high-sensitivity using side-hole fibers

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Abstract: A highly sensitive distributed pressure sensing system (< 20 hPa) based on phase sensitive optical time-domain reflectometry with side air holes fiber is proposed, reaching a sensing range of 1.05 km with a 5 cm spatial resolution. © 2018 The Author(s)

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1. Introduction

Pressure sensing has important applications in obstacles or leakage detection in oil and gas industries, and pressure monitoring of multiple locations is subject to a high demand from today's complex industrial facilities and gas delivery systems [1]. Distributed fiber sensors (DFS) have drawn intense attentions since it is inherently safe and stable owing to the inert nature of the fiber material. Moreover it shows a low-cost per sensing point, which makes it an attractive candidate for applications in these fields. Several distributed pressure sensing (DPS) schemes have been proposed based on Brillouin optical time-domain reflectometry (BOTDA) [2], Brillouin dynamic gratings (BDG) [3] or optical frequency-domain reflectometry (OFDR) [4], limited by either low pressure sensitivity [2], or sophisticated configuration [3] or fundamentally limited sensing distance [4]

Recently, phase-sensitive optical time-domain reflectometry (Φ -OTDR) has attracted a growing interest due to its ultra-high sensitivity [5,6]. Φ -OTDR measures the coherent intensity from Rayleigh backscattering (RS) along the fiber, which originates from fluctuations of the material refractive index induced during the manufacturing process. By scanning the frequency of the interrogating pulses using a highly coherent laser, "noise like" but static reflection spectra (reference spectra) for each sensing point along the fiber are obtained, under the condition that the refractive index keeps constant [7]. A local refractive index change in the fiber, which can be induced by temperature or strain, leads to a proportional phase change, which can be compensated by a frequency shift (FS) of the interrogating pulses. Consequently, the phase change will turn into a FS in the RS spectrum and this FS can be estimated by cross correlating the current spectrum with a reference spectrum. Based on this technique, distributed birefringence (Bi) measurement was demonstrated [8], enabling the discrimination of temperature and strain by combining the distinct temperature and strain sensitivities along orthogonal polarization axes [9]. The interrogation scheme of Φ -OTDR is relatively simple, and there is no fundamental limit on sensing distance, making it potentially a good candidate for high-quality distributed sensing applications, for instance, for DPS.

In this paper, a DPS system is proposed based on Φ -OTDR with frequency scanning using both polarization axes of side air holes fibers (SAHFs). With this dedicatedly designed fiber, the temperature and pressure responses are experimentally investigated. Results demonstrate that the proposed DPS is capable of measuring the local pressure over a ~ 1 km sensing range with 5 cm spatial resolution, leading to $> 20,000$ spatially resolved sensing points. In addition, an ultra-high pressure sensitivity is found in SAHFs, which is ~ 2 GHz/bar for FS along a single Bi axis with a pressure uncertainty of ~ 15 mbar (~ 15 hPa).

2. Experimental setup

The experimental setup is shown in Fig.1 (a). The optical source is a distributed feedback laser (DFB) with a linewidth of 1 MHz followed by two cascaded electro optical modulators (EOMs) and a semiconductor optical amplifier to shape optical pulses with high enough extinction ratio and with a duration down to 500 ps, to obtain a spatial resolution as sharp as 5 cm. The optical pulses are then sent to a polarization switch and controller, so that their polarization state can be precisely aligned with each polarization axis of the fiber under test. This way the frequency shift induced by a temperature change δT or a pressure change δP can be evaluated separately along the two axes. Fast and broad (~ 30 GHz) frequency scans of the interrogating pulses are achieved by direct tuning of the laser current with a frequency scanning step of 64.5 MHz.

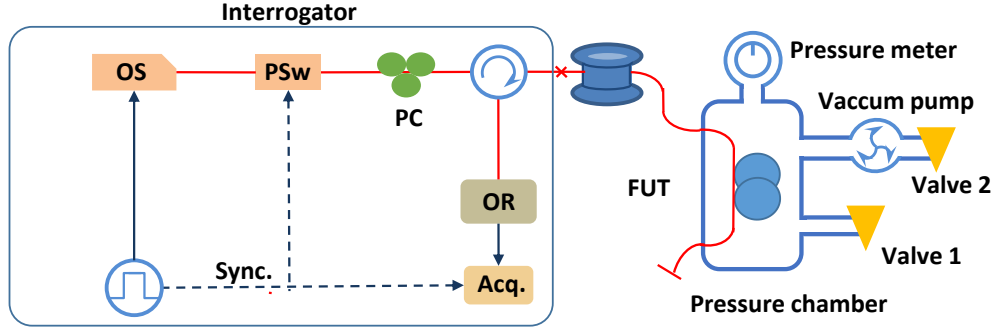


Fig. 1. experimental setup based on frequency-scanning Φ -OTDR with high spatial resolution and the side holes fibers for pressure sensing (OS: optical source; PSw: polarization switch; PC: polarization controller; OR: optical receiver; Acq: acquisition module; FUT: fiber under test; Sync: synchronizer).

The fibers under test are two SAHFs specially designed for pressure sensing [10] and their SEM images are shown in Fig 2. The structure of the fibers resembles the PANDA fiber, except that two air channels take the place of the stress-applying rods in the cladding. Owing to the absence of the stress-applying rods, which is usually made of a different material showing a relatively large thermal expansion coefficient, the Bi of SAHF is much more sensitive to pressure but much less sensitive to temperature when compared to a PANDA fiber. Here we tested two SAHFs with different values of Bi because of their different diameters of the air holes. The fiber with larger air holes (shown in Fig. 2 (a)) has a Bi of $\sim 10^{-5}$ in term of refractive index and is designated as Fiber H, while the other one with a Bi of $\sim 10^{-6}$ is designated as Fiber L, shown in Fig. 2 (b). The length of Fiber H is ~ 10 m while Fiber L is 1.05 km, respectively. Compared to other microstructured fibers tested for pressure sensing, e.g., photonic crystal fibers, the simple structure of SAHF makes it easy to manufacture and splice, and, most importantly for distributed fiber sensing, the fiber loss keeps acceptable for kilometer range sensing. The measured losses are only ~ 5 dB/km for Fiber H and ~ 3 dB/km for Fiber L.

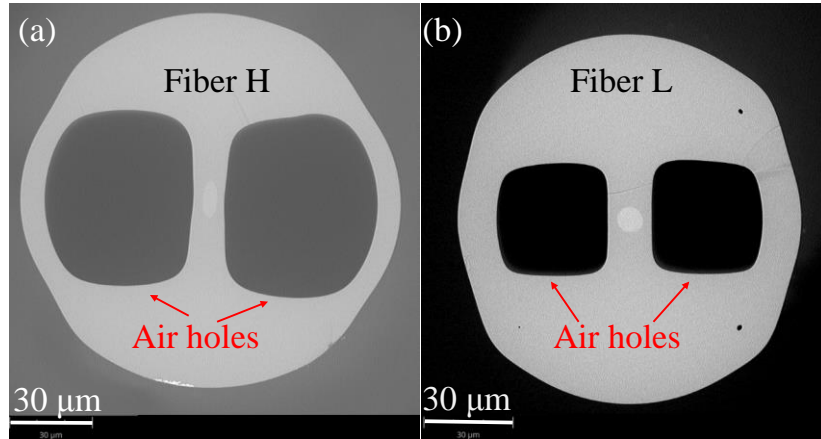


Fig. 2 SEM images showing the air stressing components disposition of the SAHF (a) Fiber H ($\text{Bi}=10^{-5}$) and (b) Fiber L ($\text{Bi}=10^{-6}$)

3. Results and discussions

First, the temperature responses of both fibers are evaluated by placing the fiber into a water bath at preset δT . Fig. 3 shows that the temperature sensitivity of both Bi axes are similar. The calculated temperature sensitivities for the Fiber L are 1.329 GHz/K and 1.325 GHz/K for the fast and slow axis, respectively, resulting in a sensitivity of 4 MHz/K for the Bi change response by subtracting the responses of the two axes. Similarly, the temperature sensitivities are slightly more distinct between the two axes of the high-bi fiber H, which are 1.121 GHz/K and 1.116 GHz/K for fast and slow axes, respectively, leading to 5 MHz/K temperature sensitivity. Through this characterization, it can be claimed that the Bi of SAHFs is fairly insensitive to temperature.

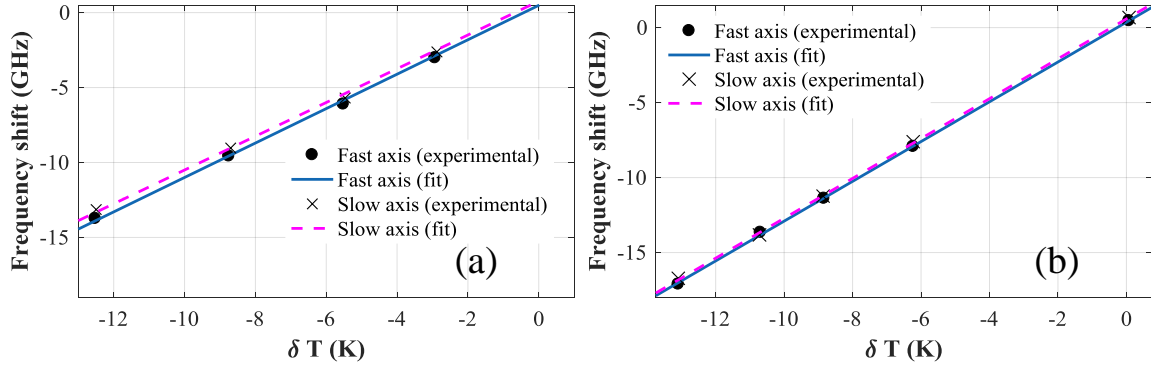


Fig. 3 Frequency shift response with temperature change δT of (a) Fiber H and (b) Fiber L

Then segments of the SAHFs are placed into a pressure chamber to evaluate the pressure sensing performance of the system. Reference spectra are taken under atmospheric pressure (~ 1 bar) and then we use the vacuum pump to reduce the chamber pressure from ~ 1 bar to ~ 0.1 bar. In the meantime, a precision thermal resistor is placed in the chamber to monitor the temperature change in the chamber induced by the pressure change, which can be compensated using the measured temperature sensitivities of the SAHFs.

The distributed FS responses of each axis for both fibers are shown in Fig. 4(a) and Fig. 5(a), respectively. Clear FSs can be seen in the traces (the shaded part in the figure) with a maximum pressure change δP of ~ -0.9 bar. The periodical pattern shown in Fig. 4(a) and Fig. 5(a) may result from some extra strain variations due to the fiber layout in the chamber. The averaged FS responses of the fiber section subject to the pressure changes for both axes are shown in Fig. 4(b) and Fig. 5(b) for Fiber H and Fiber L, respectively. By performing a linear fitting on the response of each axis versus the applied δP , the estimated pressure sensitivities of each Bi axis are obtained in Fig. 4(b) and Fig. 5(b) for both fibers, respectively. As shown in the inset of Fig. 5(a), the standard deviation of the measurements is ~ 0.03 GHz, which corresponds to a pressure uncertainty of ~ 15 mbar (~ 15 hPa).

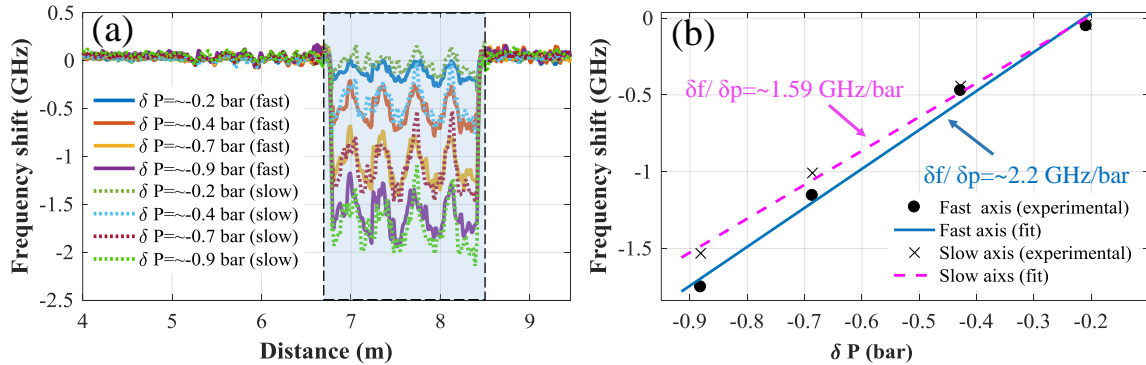


Fig. 4 (a) Distributed responses of fast and slow axes from 0 to ~ 2 GHz along the Fiber H for several pressure changes δP . The shaded area indicates the depressurized fiber section. (b) Averaged frequency shift versus δP for both axes.

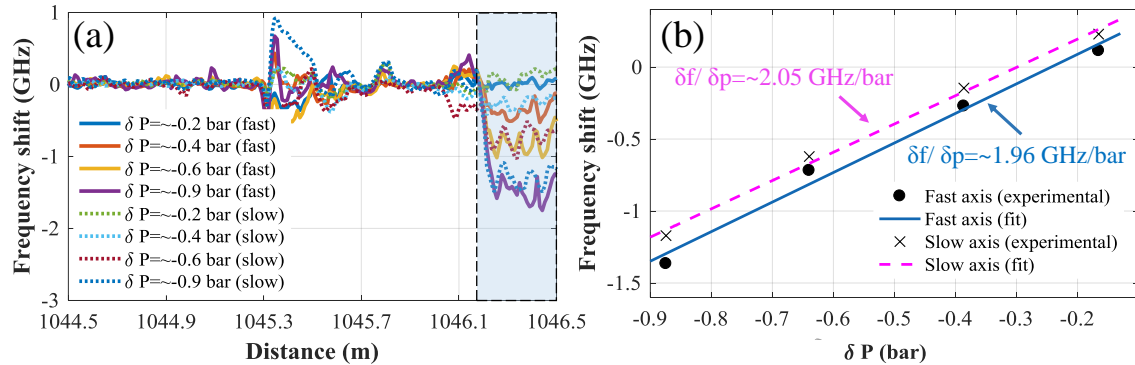


Fig. 5 (a) Distributed responses of fast and slow axes from 0 to ~ 1.5 GHz along the last 2 meters of Fiber L for several pressure changes δP . The shaded area indicates the depressurized fiber section. (b) averaged frequency shift versus δP for both axes

From the results we can see that, for each axis of both fibers, the FS response shows a high pressure sensitivity of around 2 GHz/bar, which agrees with the value reported in [10] and is about 6 times higher than that of a standard single-mode fiber (SMF) according to [11]. It shows that by utilizing SAHFs, the FS of the Rayleigh scattering induced by a δP of 1 bar is similar to the FS caused by a δT of 2 K. Hence for applications where high accuracy is desired, pressure sensing can be achieved through the FS response from a single axis, for which the pressure sensitivity is extremely high. In this case, the effect of temperature has to be compensated by an independent measurement of temperature using a distinct pressure-insensitive fiber (e.g. SMF).

On the other hand, by subtracting the FS responses between the slow and fast axes of the same fiber, which corresponds to the Bi change, the Bi sensitivities are calculated to be 0.61 GHz/bar for Fiber H and 0.19 GHz/bar for Fiber L according to Fig. 4(b) and Fig. 5(b), which is one order of magnitude smaller than the sensitivity of the single axis response. Therefore, if the sensitivity requirement is not so strict, the pressure sensing can be achieved by measuring the Bi change of the fiber, which is very poorly sensitive to temperature as demonstrated in Fig.2. It should be noted that, even with the FS due to the Bi change, which is not as sensitive as the FS from a single axis, the pressure sensitivity is still much larger than the reported distributed pressure sensors based on BOTDA, which is ~ 0.06 MHz/bar [3]. In addition, compared to the DPS based on optical frequency-domain reflectometry [4], the sensing range of the proposed scheme is 150 times larger (1.05 km) than the OFDR-based DPS (7 m) and the spatial resolution here is only 5 times smaller, which results in 30x more spatially resolved points along the sensing fiber.

4. Conclusions

In this paper, a distributed fiber sensor based on a frequency-scanning Φ -OTDR using direct-modulation and a side air holes fiber is proposed. The temperature and pressure response from each birefringence axis are characterized using the system. It has been proved that a kilometer-long 5 cm spatial resolution DPS covering 21,000 resolved points can be realized with a pressure sensitivity of ~ 2 GHz/bar for a single axis Bi response and 0.2 GHz/bar for the Bi response, which makes a pressure accuracy as low as 10 hPa (10 mbar) realistic in a close future.

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