We report a novel polarimetric optical frequency domain reflectometer (P-OFDR) that can simultaneously measure both space-resolved transverse stresses and light back-reflections along an optic fiber with sub-mm spatial resolution. By inducing transversal stresses and optical back-reflections at multiple points along a length of optic fiber, we demonstrate that our system can unambiguously distinguish the stresses from the back-reflections of a fiber with a fiber length longer than 800 m, a spatial resolution of 0.5 mm, a maximum stress level of up to 200 kpsi (1379 Mpa), a minimum stress of about 10 kpsi (69 Mpa), and a stress measurement uncertainty of 10%. We show that our P-OFDR can clearly identify the locations and magnitudes of the stresses inside a fiber coil induced during a fiber winding process. The P-OFDR can be used for fiber health monitoring for critical fiber links, fiber gyro coil characterization, and other distributed fiber sensing applications.

Connectivity is arguably one of the most important aspects of our society today. Fiber optic telecommunication systems make up the backbone of such connectivity, and its reliability is becoming increasingly more important. Therefore, health monitoring for the fiber infrastructure networks for applications, such as stock exchanges, financial institutions, and military installations, are becoming increasingly critical. An ideal fiber health monitoring system is required not only to be able to detect a broken fiber, but also to detect and locate the section of an unhealthy fiber, such as a fiber section with tight bending or with high internal stresses, before it breaks, to allow the service providers to proactively prevent unexpected service failures.

Distributed stress sensing is another area of active research with many important applications [1–4], one of which is to measure the stresses along the fiber in a fiber gyro coil, the most critical component whose quality directly affects the accuracy of the gyro [5,6]. One of the most common coil defects is the stress induced during the coil winding process. In a fiber coil made with polarization maintaining (PM) fiber, the winding stresses at different locations can introduce polarization crosstalks at these locations along the fiber, which can be detected by a distributed polarization crosstalk analyzer [7]. However, a fiber coil made with non-polarization maintaining single-mode (SM) fiber is commonly used for the depolarized fiber optic gyro [8]. In such SM fiber coils, the microbending can induce large stress on the fiber, especially at crossover locations where the fiber transitions from one layer to another. We speculate that such bending, together with the action of potting adhesive, can introduce large polarization dependent loss (PDL) and polarization mode dispersion (PMD) in the fiber coil, which may degrade the performance of the SM fiber coils.

Current commercially available optical time-domain reflectometer (OTDR) can monitor, detect, and locate a section of broken fiber or a fiber section with significant fiber losses caused by severe fiber bending [9]. However, in such situations, the network failure has already occurred and the damage is already done. Although a Brillouin OTDR is able to detect potential optical cable fault due to excessive strain, such a technique may give fault alarms because it cannot distinguish the temperature effect from that of the strain [10,11]. Polarization sensitive OTDRs were reported for measuring the distributed polarization mode dispersion (PMD) in telecommunication fiber links [12,13]. However, the spatial resolution of the proposed method were not sufficient for detecting the extremely high stress-induced birefringence for the applications intended in this Letter, limited by the pulse width and the speed of the electronics. In 2004, Froggatt et al. used a technique of cross-correlating a current measured optical frequency domain reflectometry (OFDR) signal with a reference OFDR trace to obtain the space-resolved strain changes along the optical fiber [14]. However, such a method also suffers from the deficiency that it cannot distinguish the strain from the temperature. In addition, no absolute strain or stress information can be obtained because such a measurement is only relative to the reference. The polarimetric OFDRs reported in [15–18] are capable of detecting distributed PMD and different birefringences along the fiber; however, they required the fiber under test.
(FUT) to be stable to avoid polarization fluctuation during the measurement, which is not practical for field applications. Therefore, there is a need for a fiber stress and bend monitoring system to unambigously detect and locate unhealthy fiber sections with excessive stress caused by tight bends or transverse pressure so as to prevent unexpected failures or breakage in fiber optic networks. Similarly, there is also a need to use a length of fiber to measure the space-resolved stresses with absolute values (not relative) along the fiber for distributed sensing applications.

In this Letter, we report a novel polarimetric optical frequency domain reflectometer (P-OFDR) for space-resolved transverse stress or bend measurements along an optic fiber, which does not require the FUT to be physically stable. The method is based on measuring the local birefringence induced by transverse stress via the photoelastic effect in the fiber. By inducing stresses via fiber bending at multiple points along the optical fiber, we demonstrate that our system can simultaneously obtain both the distributed stress and the reflection curves as a function of distance along the fiber, unambiguously distinguishing the stresses from the optical back-reflections. Our preliminary experiments show that our prototype system has a spatial resolution of 0.5 mm, a measurable distance of over 800 m, a maximum stress level of up to 200 kpsi (1 kpsi = 6.9 MPa), a minimum stress (or sensitivity) of about 10 kpsi, and a stress measurement uncertainty around 10%. Note that unlike the cross-correlation method in [14], in our system, the temperature does not affect the stress or birefringence measurement, unless the temperature change induces a real stress on the fiber via other effects, such as the thermal expansion of a bobbin beneath the fiber or the thermal crimping of adhesives around the fiber. Therefore, our reported technique can also be implemented for the distributed fiber sensing applications for detecting the value of stress along the fiber, although it cannot differentiate whether the stress is applied or thermally induced. As an example for the distributed sensing applications, we show that our prototype can clearly identify transversal stress points in a fiber coil induced during the winding process when the fiber transitioning from one layer to the other. The reported method is not sensitive to the state of polarization (SOP) variations from fiber cable movement so that potentially it is well suitable for the field fiber network health monitoring and fiber sensing applications.

In the sections below, we describe the hardware configuration and the theory behind our P-OFDR for measuring the space-resolved transverse stress along an optical fiber with the advantages of single-end operation, high spatial resolution, high stress range, and insensitivity to temperature and SOP variations in comparison to other measurement techniques [10–15]. Figure 1 shows the setup for our P-OFDR measurement system, where a tunable laser with a linewidth around 100 kHz is continuously tuned up to 4 nm around 1550 nm. A small fraction of light (~5%) from coupler 1 is split and then sent to a Faraday rotation mirror (PRM) based Michelson interferometer with a relative time delay of 10 µs for generating clock signals at each “zero-crossing” position of the optical interference fringe signals. The generated real-time clock signals were then used for the P-OFDR raw data sampling. The light was then further split by a 90/10 coupler (coupler 3), in which 10% of the light was used as a local oscillator light to coherently probe Rayleigh back scattering (RBS) light, and 90% of the light was then sent to the fiber under test (FUT) via a circulator. The SOP before entering and after exiting the FUT is randomly varied by an all-fiber polarization controller to uniformly cover the Poincaré sphere. The Rayleigh backscattered light from different locations of the fiber is brought to interfere with the portion of light directly from the tunable laser via a polarization diversity interferometer (the dotted-line box in Fig. 1). The interference signals of the two polarization components are analyzed after detection by PD2 and PD3, and the local birefringence information is then calculated. The transverse stress related to the birefringence is then obtained using the signal analysis procedures described below.

The optical fibers with non-perfect circular symmetry or with bend, twist, or other transverse stress often exhibit local birefringence. Under assumption of no polarization-dependent loss (PDL), the light passing through a section of optical fiber with birefringence will experience a variation of SOP. When a polarized light is propagating in a birefringence fiber, the evolution of the light polarization state can be described using the well-known equation of motion of the Stokes vector, \( \vec{S}(z, \omega) \), which can be expressed as [17,19]

\[
\frac{\Delta \vec{S}(z)}{\Delta z} = \vec{W}_\omega(z) \times \vec{S}(z),
\]

(1)

where \( z \) is the distance of light propagated within the fiber, \( \omega \) is the optical frequency, \( \vec{W}_\omega(z) \) is the local round-trip birefringence vector. If the evolution of light’s SOP can be analyzed along the fiber length, then the local birefringence can be deduced. In particular, we found that the \( \vec{W}_\omega(z) \) can be determined from a mean-square value of differences of local transmission between two closely spaced fiber sections, similar to [13] in which the local birefringence was obtained by analyzing the SOP evolution between two closely spaced frequencies of light. Assuming the local birefringence \( \vec{W}(z) = \vec{W}_\omega(z)/2 \) and following the same procedure as in [13], except substituting the changes in optical frequency \( \omega \) in [13] with \( \Delta z \), we obtain

\[
\vec{W}(z) = \frac{1}{2\Delta z} \cdot \sqrt{15(\Delta T^2(z))_{1/O.SOP}},
\]
where $\Delta T(z) = T(z + \Delta z/2) - T(z - \Delta z/2)$ is the normalized light power difference between two positions at $z + \Delta z/2$ and $z - \Delta z/2$, and $T(z) = P_i(z)/[P_i(z) + P_3(z)]$ is the normalized light power at the location $z$, where $P_i(z)$ is the light power of one polarization component from PBS1 at $z$ measured with one of the detectors PD$_i$ ($i = 2, 3$). In Eq. (2), $\langle \Delta T^2(z) \rangle_{1/0,i,SOP}$ stands for averaging over random input and output SOP variations. The fiber transverse stress as a function of the distance can be extracted from measured distributed fiber birefringence [20,21].

A key aspect of our P-OFDR approach is that the back-reflected light from the FUT at the two neighboring locations is subsequently detected, and their SOPs are analyzed for many random and uniformly distributed input and output SOPs that are uncorrelated with respect to each other. It is worthy to note that because the input SOPs incident into and the output SOPs exited from FUT are random and without specific requirement, the system is independent of the SOP variations from fiber cable movement and, therefore, is well suited for field applications, where the SOP along the fiber is constantly changing [13].

An example of the measured reflection trace for an FUT length up to 860 m is shown in Fig. 2, where the OFDR back-reflection curve was extracted from the sum of two squared light intensities measured by two detectors (PD2 and PD3), and its reflectivity was calibrated by an internal reference reflector (not shown in Fig. 1).

To demonstrate the measurement principle described in the sections above, we made an experimental test by using bending-induced transverse stresses along a FUT made with a bending insensitive SM fiber (Corning ClearCurve ZB) where eight bending loops at eight different FUT locations were designed. The bending radius is different at different positions, and they are typically between 5 to 15 mm. In addition to the eight bends, there are also six FC/APC connectors and a fiber splice. The results are illustrated in Fig. 3. In our experiment, the polarization controller randomly adjusted its launched SOP, and the receiver analyzed the received signal corresponding to different polarization controller settings randomly distributed on the Poincaré sphere. The tunable laser is scanned in a range of 4 nm with a scanning speed of 10 nm/s. The results, as shown in the upper and lower plots of Fig. 3, were acquired simultaneously by the same data sampling of the raw data, but with different signal processing algorithms, where the reflection trace in the upper plot was computed by the sum of the squared measured results from two photodetectors (PD2 and PD3 in Fig. 1), and the fiber birefringence trace $W(z)$ was extracted using Eq. (2) with an average of over 200 inputs and analyzed SOPs. The displayed stress value was obtained by a calibration procedure with a calibration weight. The measurement and computation take about 5 min to complete.

As we can see, in the reflection trace (the upper plot of Fig. 3), there are seven light back-reflections associated with six connectors (L1, 2, and 4–7) and a fiber splice (L3). Of particular interest is the stress measurement as shown on the lower plot of Fig. 3 with features associated with fiber bendings, connectors, and splice. With the cross-reference of reflection trace, eight fiber-bending-induced stresses features S1–8 that can be unambiguously distinguished from those of light back-reflections. It is worth noting that the induced transverse stress is higher for smaller bend radii than for larger bend radii, consistent with the bending-induced birefringence calculations [20]. All eight bending-induced fiber birefringence events are seen cleanly with a signal-to-noise ratio over 2. The spatial resolution of our system for the stress measurement is of 0.5 mm, determined by the wavelength scanning range of the laser. The measurement uncertainty from multiple measurements is $\sim 10\%$ when 200 randomly distributed SOPs were used, and it can be reduced by averaging more SOPs, but with longer measurement time. The relative stress levels of all eight fiber loops are consistent with [20].

As an example for distributed stress sensing, we use our P-OFDR to identify stress locations and magnitudes along the optical fiber inside a fiber coil, as mentioned in the introduction. The information obtained can be used for improving the winding process and minimizing such stresses for making better fiber coils, such as a crossover free coil. To demonstrate its capabilities, our prototype system is used to measure a fiber coil with a diameter of 80 mm and clearly identifies periodic stress peaks, as shown in Fig. 4. The periodicity of 23 peaks is the same as the length of each layer of the coil, which is consistent with the expectation that stresses are induced at fiber crossover.

**Fig. 2.** Measured OFDR reflection trace with back-reflections for a FUT with a length up to 860 m.

**Fig. 3.** P-OFDR signal from a length of fiber with six connectors and one splice for introducing reflections and eight fiber loops with different diameters for inducing different amount of stresses. Upper curve, measured reflections L1–7; lower curve, measured fiber-bending-induced stress S1–8.
Distributed stress measurement of a 250 m fiber coil connected with a loose fiber about 130 m in length. Upper, light enters the fiber from the coil side B; Lower, light enters the fiber from the spool side A. The fiber used is the bend insensitive fiber Corning ClearCurve ZBL single-mode optical fiber, and the tension for winding the coil is about 10 g.

Fig. 4. Distributed stress measurement of a 250 m fiber coil connected with a loose fiber about 130 m in length. Upper, light enters the fiber from the coil side B; Lower, light enters the fiber from the spool side A. The fiber used is the bend insensitive fiber Corning ClearCurve ZBL single-mode optical fiber, and the tension for winding the coil is about 10 g.

Further demonstrate that our system is sufficiently sensitive to identify stress points in a fiber coil induced during the winding process when the fiber transitioning from one layer to the other, and can be used for fiber gyro coil inspection applications. Finally, our P-OFDR system is robust against SOP variations caused by fiber cable movement and is well suited for the field measurement of stresses in the fiber and, therefore, is ideal for the fiber infrastructure health monitoring and for distributed fiber optical sensing applications. Note that unlike the reports in [16–18], we aim at detecting the high birefringence induced by large stresses, which may cause the premature failures of optical fibers, especially the bending insensitive fibers with negligible bending losses. Portion of this Letter were presented at OFC2016 [23].

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