Phase birefringence in optical fibers typically fluctuates over their length due to geometrical imperfections induced from the drawing process or during installation. Currently commercially available fibers exhibit remarkably low birefringence, prompting a high standard for characterization methods. In this work, we detail a method that uses chirped-pulse phase-sensitive optical time-domain reflectometry to directly measure position-resolved linear birefringence of single-mode optical fibers. The technique is suitable for fiber characterization over lengths of tens of kilometers, relying on a fast measurement (~1 s) with single-ended access to the fiber. The proposed method is experimentally validated with three different commercial single-mode optical fibers. © 2020 Optical Society of America
mapping each frequency detuning to a specific time section of the pulse, so any locally induced change to the optical path may then be estimated as local time delay in the recovered backscattered power trace. This technique has been successfully used to quantify several parameters, most notably dynamic strain, with remarkable performances [15,16], over long distances with fast sampling rates.

In this work, we propose a technique based on a slight alteration of traditional CP-φOTDR aimed at fiber local birefringence characterization. In particular, the presented method directly recovers the birefringence spatial profile of state-of-the-art single-mode optical fibers with high sensitivity, over long lengths, and in a short measurement time (~1 s).

It has been previously shown that in a backscattering-based estimation process, such as the one employed in this work, any circular birefringence is indistinguishable from a rotation of polarization [17]. Essentially, the round-trip phase difference between any given pair of scatterers \( i, j \), in a linearly birefringent medium, may be expressed as

\[
\Delta \phi_{ij}^{\text{f}} = \frac{4\pi L_{ij}}{\lambda} (\bar{n} \pm B/2)
\]

for linear polarized light along the two axes of linear birefringence (slow, \( \phi_{ij}^{\text{s}} \), corresponding to the choice of “+”), and fast, \( \phi_{ij}^{\text{f}} \), to the choice of “−”), where \( B \) is the birefringence of the medium, \( \bar{n} \) is the average index for unpolarized light, and \( L_{ij} \) is the distance between scatterers. On the other hand, for the case of circular birefringence, when sending either right or left circularly polarized light, we expect the following:

\[
\Delta \phi_{ij}^{\text{c}} = \frac{2\pi L_{ij}}{\lambda} (\bar{n} \pm B_{\text{c}}/2) + \frac{2\pi L_{ij}}{\lambda} (\bar{n} \mp B_{\text{c}}/2)
\]

\[
= \frac{4\pi L_{ij}}{\bar{n}}
\]

where, for circular birefringence \( B_{\text{c}} \), we see the phase difference measured between any two given scatterers is in principle cancelled by virtue of the round trip. Hence, only the linear birefringence component may affect the CP-φOTDR measurement.

In order to now outline our method of estimation of the linear birefringence of the medium, we describe any given homogeneous section of the optical fiber by its two orthogonal eigenstates of polarization \( \hat{v}_1 \) and \( \hat{v}_2 \), such that \( \hat{v}_1 \cdot \hat{v}_2 = 0 \) and the corresponding effective indices. Any polarization \( \hat{s} \) may be decomposed into those eigenstates as \( \hat{s} = (\hat{v}_1^* \cdot \hat{s}) \hat{v}_1 + (\hat{v}_2^* \cdot \hat{s}) \hat{v}_2 \). In general, any state of polarization of light, \( \hat{s} \), rotates unpredictably (albeit deterministically) during propagation within a single-mode fiber. The electric field backscattered at any given fiber section may then be generally described as

\[
e(t) = (\hat{v}_1^* \cdot \hat{s}) e_1(t) \hat{v}_1 + (\hat{v}_2^* \cdot \hat{s}) e_2(t) \hat{v}_2
\]

Hence, the photodetected CP-φOTDR signal equals

\[
q(t) = |\hat{v}_1 \cdot \hat{s}|^2 p(t - \tau) + |\hat{v}_2 \cdot \hat{s}|^2 p(t + \tau)
\]

where \( p(t) \) is the recovered CP-φOTDR power trace for an effective index \( \bar{n} \), and \( \tau \) corresponds to the chirp-induced delay for a \( \Delta n = B/2 \), as given by the system’s sensitivity [14]:

\[
\tau = -\frac{v_0 t_p}{\delta \nu \bar{n}} \left( \frac{B}{2} \right),
\]

with \( v_0 \) being the laser frequency, \( \delta \nu \) the chirp bandwidth, and \( t_p \) the pulse width. It is now convenient to represent polarization by 3D unit Stokes vectors. Let \( \hat{V} \) be the Stokes vector associated with \( \hat{v}_1 \), so \( -\hat{V} \) is the one associated with \( \hat{v}_2 \). Having \( \hat{S} \) be the Stokes vector of \( \hat{s} \), we can write

\[
|\hat{v}_1 \cdot \hat{s}|^2 = \frac{1}{2} (1 \pm \hat{V} \cdot \hat{S}) = \frac{1}{2} (1 \pm \gamma),
\]

where \( \gamma = \hat{V} \cdot \hat{S} \), and \( i = 1, 2 \) (corresponding to the choice of the “+” or “−” case, respectively). For polarization \( \hat{S} \) or its orthogonal state \( -\hat{S} \), the retrieved signals are linear combinations of the signals recovered from the two polarization eigenstates of the fiber:

\[
q_1(t) = \frac{1}{2} [(1 + \gamma) p(t - \tau) + (1 - \gamma) p(t + \tau)],
\]

\[
q_2(t) = \frac{1}{2} [(1 - \gamma) p(t - \tau) + (1 + \gamma) p(t + \tau)].
\]

Cross-correlating the two components leads to

\[
R_{12}(t) = \frac{1}{4} [2(1 - \gamma^2) c(t) + (1 + \gamma)^2 c(t - 2\tau) + (1 - \gamma)^2 c(t + 2\tau)],
\]

where \( c(t) \) is the autocorrelation of \( p(t) \). Notice that whenever light is aligned with the eigenstates of polarization of the fiber (\( \gamma = 1 \)), Eq. (7) simplifies to \( q_1(t) = p(t - \tau) \) and \( q_2(t) = p(t + \tau) \), and Eq. (8) simplifies to \( R_{12}(t) = c(t - 2\tau) \), as expected.

A common estimator of time delay employed in CP-φOTDR is the generalized cross-correlation (GCC) algorithm [15], i.e., finding the lag at which there is a maximum of cross correlation,

\[
\delta = \text{argmax}\{R_{12}(t)\}.
\]

To calculate the result of this estimator when applied to Eq. (8), we describe the peak of the correlation function \( c(t) \) as a Gaussian peak; so let \( c(t) = \exp[-t^2/(2w^2)] \). The position \( \delta \) of the cross-correlation peak is determined by setting \( dR_{12}/dt = 0 \). Note that the maximum peak shift is obtained when the signal polarization is aligned with one of the two eigenstates, in which case, the peak shift is exactly \( \pm 2\tau \); therefore, in general, \( |\delta| \leq 2\tau \). Using this constraint, the peak position is well approximated by

\[
\delta \approx 2\gamma \tau,
\]

where the approximation holds as long as \( w^2 \gg \tau^2 \). From a practical point of view, this means that Eq. (10) has a fairly good validity as long as the birefringence-induced delay \( \tau \) is smaller than the width \( w \) of the correlation peak. This width is inversely proportional to the chirp bandwidth \( w \approx 1/\delta \nu \); so by Eq. (5), we see that the condition \( \tau < w \) is equivalent to \( B < 2\bar{n}/(v_0 t_p) \). For a pulse of a few meters, this corresponds to a limit of the measurable birefringence on the order of \( 10^{-6} \), confirming the method can be applied to standard telecommunication fibers.

The process to obtain a local estimation of birefringence consists of sending light with the pairs of polarization states
local basis vector \( \hat{y} \) yields the projection of contribution to the measured delay, as stated in Eq. (2). For the demonstration, three single-mode G.652D fiber spools from different manufacturers (of lengths 1, 4, and 10 km) are used. The polarization synthesizer is programmed to cycle through the six orthogonal polarization states \([(1,0,0); (0,1,0); (0,0,1); (-1,0,0); (0,-1,0); (0,0,-1)]\), holding each state for 100 ms in the two shorter fibers (1.8 s measurement) and 150 ms for the 10 km fiber (0.9 s measurement), due to memory constraints of the acquisition device. The time series acquired for any interrogated position of the fiber consists of a noisy, piecewise-constant function. Each constant time section is then averaged to estimate the effective index shift for that given position in the fiber. The value of \( \delta \) at position \( z \) is then measured as the total index change between orthogonal pairs. An example of the measurement procedure is depicted in Fig. 2.

The self-consistency of the method is then tested by comparing the birefringence spatial profiles, as obtained from each end of the same fiber. Figure 3 shows the obtained results for the 10 km fiber. Spatial resolution of 25 m.
temperature gradient of the room over the course of each acquisition, the correlation coefficient between both is notably high, despite the explicitly low amount of birefringence of the fibers under test. These results are summarized in Table 1 (see column “Corr. Coeff.”), along with the mean birefringence of each fiber [mean(B)] and the standard deviation of the difference between measurements from both extremes of the fiber (as depicted in Figs. 3 and 4), σ12.

The technique displays the ability to measure levels of birefringence intrinsic to the manufacturing process in state-of-the-art single-mode fibers. Moreover, the noticeable decrease in the average birefringence level on the longer fibers (∼20% in the 10 km fiber and ∼10% in the 4 km fiber) is consistent with the effect of spooling. Actually, lower values of z in Figs. 3 and 4 correspond to the inner layers of the spool, where the bending radius is smaller, and hence the bending-induced birefringence [1] is higher. As the measurement proceeds to the outer layers, this deterministic contribution to birefringence decreases in intensity. The measured variation of average birefringence agrees with a radius variation of some millimeters.

To conclude, we propose a method to quickly retrieve spatially resolved measurements of remarkably low linear birefringence in long optical fiber links, with single-ended access to the fiber.

Though this work is restricted to fiber lengths up to 10 km, this limit is imposed by the acquisition hardware memory and not from the technique itself. We expect the actual limits to match the current state of the art for a CP-ϕOTDR (on the order of several tens of kilometers [19]).

The spatial resolution may also be tuned for the application, up to the limit imposed by half the pulse width (5 m, in our experiments). Whenever the birefringence vector undergoes fast spatial changes (e.g., with spun fibers), the measurement at any given position consists of the magnitude of the effective linear birefringence over the measured spatial resolution [20].

All experimental measurements consisted of a fast acquisition of a single cycle of the six polarization states (totaling 1 to 2 s), so we expect that performance could be further improved by averaging several consecutive cycles, in applications where speed is not a major concern. Note that, since the underlying model assumes small time delays of the optical power trace, further work and analysis are required to assess the suitability of this method for highly birefringent fibers.

This work may pave the road for fast polarization-based distributed sensing in standard single-mode fibers [21], as well as complete characterization of fiber links, when used in combination with other techniques such as P-OTDR.

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### Table 1. Summarized Results

| FUT    | mean(B) | σ12   | Corr. Coeff. |
|--------|---------|-------|--------------|
| 1 km   | 1.4e−8  | 3.1e−9| 0.91         |
| 4 km   | 5.3e−8  | 4.1e−9| 0.92         |
| 10 km  | 4.5e−8  | 7.2e−9| 0.81         |

*Descriptions for each result in the main text.*

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