Polarization controller for hollow-core fiber

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We demonstrate a universal polarization controller for hollow-core fibers, a simple device consisting of three twisted fiber sections that makes use of the inherent birefringence of the air-core fiber. The device 5% bandwidth at 1550 nm is calculated from measured data to be ~13 nm. © 2007 Optical Society of America

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Air-core fibers offer many promising applications, in particular, where high peak powers and/or low optical nonlinearities are required. As these fibers are beginning to be assembled into systems for research [1], it is becoming important to develop optical components made entirely of air-core fibers for much the same reasons that sparked the development of conventional fiber components three decades ago. One simple and yet widely used component is the fiber polarization controller (PC). Currently, this functionality is not available in air-core fibers. In conventional fibers, polarization control is routinely achieved by bending the fiber into loops, which induces a strain-induced birefringence, and rotating the loops to control the state of polarization (SOP) [2]. However, bending does not significantly alter the birefringence of an air-core photonic bandgap fiber (PBF), because most of the fiber mode energy propagates through the strain-free air core. Thus, polarization control using loops [2] or pressure plates is not useful for air-core fibers.

In 1979, Ulrich and Simon [3] demonstrated that twisting a conventional fiber alters the output SOP, provided the length of the twisted section is comparable to one beat length. A PC can then be made by concatenating three twisted fiber sections, each one beat length long [4]. Since the beat length of a conventional fiber is typically 1 m or more [5], such devices would be very long, and this approach has never been used. In contrast, for a PBF, whose beat length is typically much shorter (a few millimeters to a few centimeters) [6–8], such a device is quite practical.

In this Letter, we demonstrate that this principle can be applied to achieve polarization control in an air-core fiber. We confirm experimentally that twisting an air-core fiber between two fixed points spaced by approximately one beat length significantly and predictably alters the output polarization. Our measurements are in good agreement with a Jones matrix model of birefringence in a twisted fiber. This agreement shows, in particular, that whatever internal deformation takes place in an air-core fiber when it is twisted has minimal effect on polarization. We then use this principle to demonstrate a simple, short, and effective PC in an air-core fiber by applying an adjustable twist to three fiber segments. The bandwidth of this device is measured to be ~13 nm (for control to within 5% of the same SOP).

A birefringent fiber may be viewed as a series of short fractional wave plates, each with a certain linear birefringence oriented along some axis, in addition to some circular birefringence. When the fiber is twisted, two mechanisms modify this birefringence. First, the axes of the individual wave plates are rotated relative to one another. Second, the fiber may experience a shear strain, which induces circular birefringence. In a conventional fiber, strain-induced circular birefringence is significant [3]. In a PBF, very little power propagates in the silica regions where the strain is confined, so we believe that this second effect is negligible.

The goal of this work was to develop a universal PC in an air-core fiber, i.e., a device that can, at a given signal wavelength, transform an arbitrary input SOP into an arbitrary output SOP. Although twisting the free end of a fiber will, in general, alter the SOP of the output signal, this approach does not offer enough degrees of freedom to make a universal PC. Instead, as illustrated in Fig. 1, one must necessarily apply the twist somewhere *along* the fiber, between two fixed points. This kind of twist is also often necessary because a PC is typically installed not at the end but somewhere along its length.

Written in the basis of the fiber's principal axes, the Jones matrix M of a birefringent fiber of length L twisted at its *end* by an angle τ is given by [9]

$$M = \begin{pmatrix} P & -Q^* \\ Q & P^* \end{pmatrix},\ P = \cos(\Delta) - i\left(\frac{\delta_l}{2}\right)\frac{\sin(\Delta)}{\Delta},$$

$$Q = \left(\frac{\tau + \delta_c}{2}\right)\frac{\sin(\Delta)}{\Delta},\ \Delta = \left[\left(\frac{\delta_l}{2}\right)^2 + \left(\tau + \frac{\delta_c}{2}\right)^2\right]^{1/2}, \tag{1}$$

where δ_l and δ_c are the linear and circular phase delays of the fiber, respectively. This model assumed that twisting does not deform the fiber structure, so both δ_l and δ_c are independent of τ. The dependence on the fiber length L in this Jones matrix is contained in δ_l and δ_c, which are connected to L via the fiber beat length $L_b = 2\pi L(\delta_l^2 + \delta_c^2)^{-1/2}$. Two limiting cases provide some insight. For $L \ll L_b$, and $\Delta \approx \tau$, the Jones matrix M becomes the matrix for a rotation by τ, corresponding to the physical rotation of the fiber's

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Fig. 1. Configuration of a single full twist applied to a length of fiber to alter the polarization of the signal at the fiber output end.

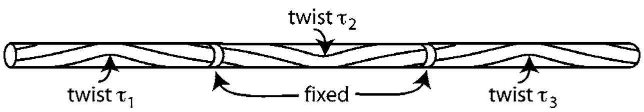

Fig. 2. A twist-based polarization controller.

principal axes: the Jones matrix in a fixed laboratory coordinate system is the identity matrix, and the polarization is unchanged. At the other extreme ($L \gg L_b$) and $\delta_l^2 + \delta_c^2 \gg \tau^2$, the polarization eigenstates in the principal axis frame are not significantly altered by a twist. In a fixed laboratory frame, the polarization eigenstates simply follow the fiber's rotation, as in a polarization-maintaining fiber. Between these two limiting cases, e.g., when $L \approx L_b$, the Jones matrix depends strongly on τ, and twisting the fiber has a significant effect on polarization.

The Jones matrix for a fiber segment twisted at the *midpoint* between two clamped points (Fig. 1) is the product of two matrices M_+ and M_- of the form of Eq. (1). M_+ is the Jones matrix of the first portion of the fiber (twisted by $+\tau$), and M_- is the Jones matrix of the second portion (twisted by $-\tau$). Inspection of Eq. (1) reveals that M_+ is not generally the inverse of M_-, so the effects of the two segments do not cancel each other, and such a twisted element may alter the SOP significantly.

We used this Jones matrix formalism to investigate a twist-based air-core PBF PC numerically. Three twisted segments were modeled, each with $L = L_b$ (see Fig. 2). For a fixed input polarization, the twist angle in each section was varied from −180° to +180° in 1.8° increments. The output SOP obtained for each combination of angles (τ_1, τ_2, τ_3) was plotted on the same Poincaré sphere. The result is shown in Fig. 3, where the Poincaré sphere is projected onto a plane for clarity. Coverage of the sphere is clearly complete. Hence, by properly selecting the three angles, the output SOP can be made to be any polarization. The same complete coverage was obtained for all randomly selected input SOPs.

To confirm the validity of the Jones matrix results, we tested the effects of a twist on the output SOP of a 20 cm section of air-core fiber (Crystal Fibre's HC-1550-02). The fiber ends were held in place by using epoxy or wax, and the twist was applied with a rotation stage epoxied or waxed to a short length of the fiber at its center. Such short lengths of epoxy induce negligible birefringence in conventional fibers [10]. Additionally, we observed that applying a pressure to the PBF that is much larger than these attachments likely impart to it has little effect on polarization. This is expected, since the PBF mode is guided mostly in air, which has no elasto-optic effect. Consequently, these attachments had an insignificant impact on the birefringence and on the effect of the twist. Using bulk optics, polarized light from a laser at 1545.3 nm was coupled into the PBF. The fiber output end was butt coupled to a length of SMF-28 fiber to filter out any other modes excited in the PBF. For a fixed input SOP, we measured the evolution of the output SOP as an incrementally larger twist was applied to the fiber, in 15° increments, from 0° to 180°, then from 0° to −180°. The result is shown in Fig. 4(a) for a linear input SOP. As predicted by the model, twisting the fiber changes the output SOP over a large portion of the Poincaré sphere. Similar agreement was observed for other input SOPs.

To compare this measured data with the model, we assumed that the birefringence was uniform along the fiber length; thus we used the same values for δ_l and δ_c in M_+ and M_-. The parameters used to fit the simulations to the experimental data were the angle of the fiber principal axes in the laboratory frame (which were unknown to us), as well as δ_l and δ_c. Also, a small linear birefringence (total phase delay of 0.6 rad) and its orientation in the laboratory frame were also fitted to account for the birefringence of the PBF input lead and the SMF-28 fiber output lead. The predicted evolution of the output SOP is plotted in Fig. 4(b). It agrees well with experimental results [Fig. 4(a)]. The fitted values are $\delta_l = -22.6$ rad and $\delta_c = -6.6$ rad, which correspond to a beat length of 5.3 cm. This is in reasonable agreement with independent measurements of the birefringence of an-

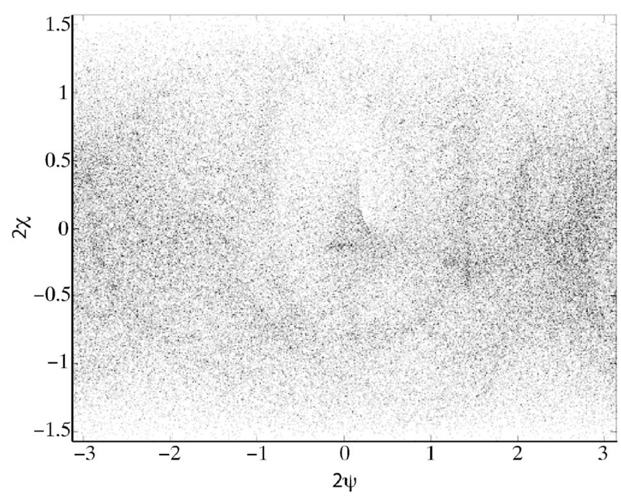

Fig. 3. Simulation of a three-twist polarization controller (see text).

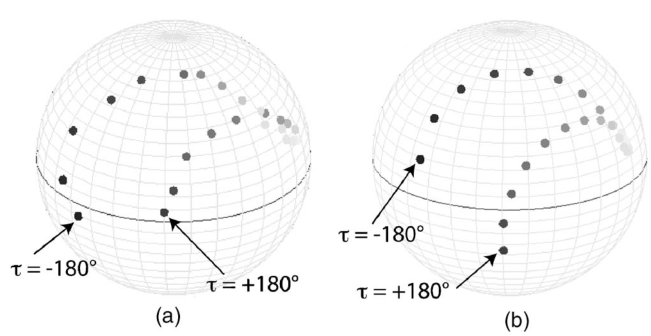

Fig. 4. Evolution of the output SOP on the Poincaré sphere for different twist angles applied to a 20 cm PBF. (a) Experimental data for a linear input polarization, and (b) simulation of experimental data.

other section of the same fiber, which gave $L_b \approx 7.5$ cm. The difference between Figs. 4(a) and 4(b) is greatest when the fiber is twisted the most, which may indicate that twisting a PBF causes the birefringence to vary a little (i.e., that δ_l and δ_c depend somewhat on τ). But this disagreement is small, and it has no detrimental effects on the performance of the PC. The main conclusions are that the effect of a twist on a 20 cm air-core fiber is sizable and that it is well predicted quantitatively by basic principles.

We constructed an air-core fiber PC by twisting the same PBF between fixed ends at three adjacent 6 cm long segments (see Fig. 2). This device was tested by launching 1550 nm polarized light into it. With a fixed input polarization, the twist angle in each section was varied randomly, and the output SOP was recorded with a polarization analyzer. As shown in Fig. 5, the output SOP covers the entire Poincaré sphere. The same conclusion was reached for different input SOPs, confirming that a set of three twisted PBF sections constitutes a universal PC. Throughout the experiments, the degree of polarization (DOP) of the output signal was observed to be high ($>96\%$). Within the ±2% instrument accuracy, there was no apparent correlation between the measured DOP and the amount of twist applied to the fiber.

Since the phase delay $\Delta\varphi$ accumulated by two orthogonally polarized signals as they travel through a fiber depends on wavelength, in general, two signals with different wavelengths but the same polarization will exit a fiber with different polarizations. This limits the wavelength range that can be simultaneously controlled by a given PC. For a twist-based PC made from HC-1550-02 fiber and operating at $\sim$1550 nm, using our birefringence measurements of HC-1550-02, we calculated a bandwidth of $\sim$13 nm. Within this range, more than 95% of the power is in the desired SOP at the PC output. In contrast, a conventional loop PC has a bandwidth of several tens of nanometers. One reason for this lower bandwidth is that each section is one beat length long, compared with a quarter of a beat length in a conventional fiber PC. Another reason is that the beat length of this PBF increases with wavelength. Hence, at wavelengths other than the center wavelengths the length of each section is not exactly L_b, and the PC alters the SOP of each wavelength differently. However, in spite of its small bandwidth, this PC is still a very useful device for controlling the SOP of laser light at a single wavelength. The bandwidth could be greatly increased by using a fiber with a birefringence that does not decrease with wavelength or that ideally increases linearly with wavelength, in which case L_b would be independent of wavelength.

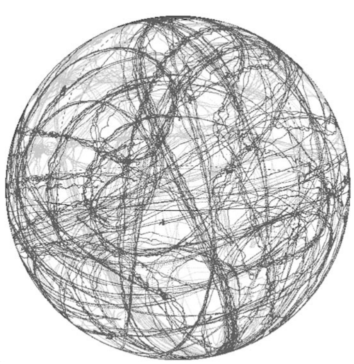

Fig. 5. Output polarization corresponding to a fixed input polarization as the twist angles are varied.

Polarization-dependent loss (PDL) is often present in fiber polarization controllers, and quantifying it is relevant for some system applications. Experimental determination of PDL in air-core fibers has been reported to be difficult and unreliable because of large fluctuations in the measured PDL [6], as we also observed, perhaps as a result of polarization-dependent coupling. Further studies beyond the scope of this work are needed to elucidate this effect.

In conclusion, the evolution of polarization at the output of a twisted air-core fiber was measured to vary substantially with twist angle when the section length is approximately equal to the beat length, in good quantitative agreement with a Jones matrix model. This principle was used to demonstrate a simple and practical universal polarization controller made of three twistable sections of air-core fiber. The bandwidth of this device is measured to be $\sim$13 nm.

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