A hollow-core photonic bandgap fiber polarization controller

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A polarization controller was built by pressurizing laterally three segments of a commercial hollow-core photonic bandgap fiber. By varying the magnitudes of the applied pressures, the output state of polarization showed a good coverage of all the possible polarization states on the surface of the Poincaré sphere.

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Optical polarization controllers (PCs) have been widely used in fiber sensors and communication systems. Compared with their bulk counterparts, all-fiber in-line PCs have the advantages of easier alignment, smaller insertion loss, and full compatibility with optical fiber systems. Several techniques have been reported for building all-fiber PCs in conventional single mode fibers (SMFs), including bending the fiber into loops to induce linear birefringence and rotating the loops to control the state of polarization (SOP) [1,2], using three surface pressing components with 45° between each to produce elastic-optically induced birefringence on the fiber [3], and using microheaters deposited on short sections of polarization maintaining fiber to thermally induce differential phase changes between orthogonal polarizations [4].

Hollow-core photonic bandgap fibers (HC-PBFs) have been a subject of continuing interest over the past ten years or so [5]. Comparing with a conventional SMF, a HC-PBF guides light in its air core and has several important advantages, including reduced Kerr nonlinearity [6], novel dispersion characteristic [7], higher phase sensitivity to acoustic pressure [8], and potentially lower transmission loss. These unique properties would help to improve the performance of certain optical fiber devices and sensor systems [9].

To realize the full potential of HC-PBFs, it is often necessary to splice HC-PBFs with conventional fiber components to form functional circuits or subsystems. To this end, low loss and robust splicing between these fibers is important and has been a topic of considerable interest [10]. Alternatively, in-line components may be built directly on HC-PBFs, and this avoids the problems associated with splicing different types of optical fibers. There are active researchers along this line; HC-PBF based fiber polarizers [11], wavelength filters [12], and couplers [13,14] are demonstrated or proposed. Terrel *et al.* reported a PC made by twisting three sections of an HC-PBF [15]. This PC makes use of the inherent birefringence of the HC-PBF, and the lengths of the twisted sections are chosen to be the beat length of the HC-PBF. For an HC-PBF with no or low birefringence, the beat length of the fiber would become too long to build compact devices.

In this Letter, we report a PC made by applying pressures laterally to three segments of an HC-PBF. The principle, theoretical modeling, and experimental characterization of the HC-PBF PC are presented in the following paragraphs.

Figure 1 shows the principle and the experimental setup of the PC. Light from a distributed-feedback laser emitting at the wavelength of 1550 nm is launched into a polarizer. The output from the polarizer is coupled into the HC-PBF PC, and the output end of the HC-PBF is spliced to a section of conventional SMF-28 fiber, which is further connected to a commercial polarization analyzer that allows the SOP of the output light to be traced on the Poincaré sphere.

The PC was made on a HC-1550-02 fiber manufactured by Crystal Fiber A/S by applying lateral pressures to three segments of fiber, and the directions of the applied pressures change by 45° from one segment to another as shown in Fig. 1. The original buffer coating of the fiber was not removed for easy handling. Each pressurized segment has a length of ~20 mm and was fixed between two plates to which variable pressure can be applied.

An elasticity model for computing the deformations of the HC-PBF, when it is subjected to different lateral pressures, was constructed [16], and the simulation showed that the lateral pressure can result in deformation of the fiber's hollow core as well as the cells in the fiber's air-silica cladding, both of which induce linear birefringence to the HC-PBF.

With the elasticity model, deformations of the HC-PBF's cross-sectional profile when subjected to different lateral pressures were simulated. The deformed profiles are then imported into the finite-element analysis solver

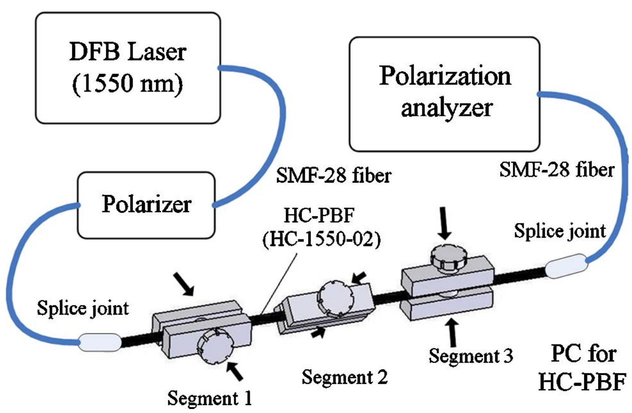

Fig. 1. Experimental setup of the PC.

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to compute the birefringence and the mode field profiles of the orthogonal polarizations of the fundamental mode [17,18]. Figure 2 shows the deformed profile around the core region of the HC-1550-02 fiber when it is subjected to a lateral pressure of 10^8 Pa. The red pattern shows the deformed profile, while the black one shows the original profile of the HC-PBF. We calculated the pressure-induced birefringence of the HC-PBF as the function of the applied lateral pressure at a wavelength of 1550 nm, and the results are shown as the blue (▼) curve in Fig. 3. The results for HC-PBFs with the same core and inner microstructure but different thicknesses of the outer solid silica cladding (T_c) were also shown in Fig. 3. The pressure-induced birefringence increases with the applied lateral pressure. Using a polynomial fit, it can be calculated that for a pressurized segment length of ~20 mm, a phase delay ($\Delta\varphi$) of 2π between two orthogonal linear polarizations can be achieved with an applied lateral pressure of $\sim 7.5 * 10^6$ Pa for the HC-1550-02 fiber and the required pressure reduced to $\sim 1.25 * 10^6$ Pa when the thickness of the outer silica cladding is reduced to 10 μm.

Discussion of the light SOP out of the PC may be facilitated by a representation of the SOP on the surface of a Poincaré sphere. As shown in Fig. 4, points P and Q on the Poincaré sphere represent horizontal and vertical states of a fixed laboratory reference system, while points H and V represent ±45° states. R and L represent right- and left-handed circular states. The action of a variable linear birefringence segment is to rotate the SOP on the sphere surface about an axis of OA, where OA is in the equatorial plane and the angle between OA and PQ represents the direction of the applied lateral pressure in the reference system [3].

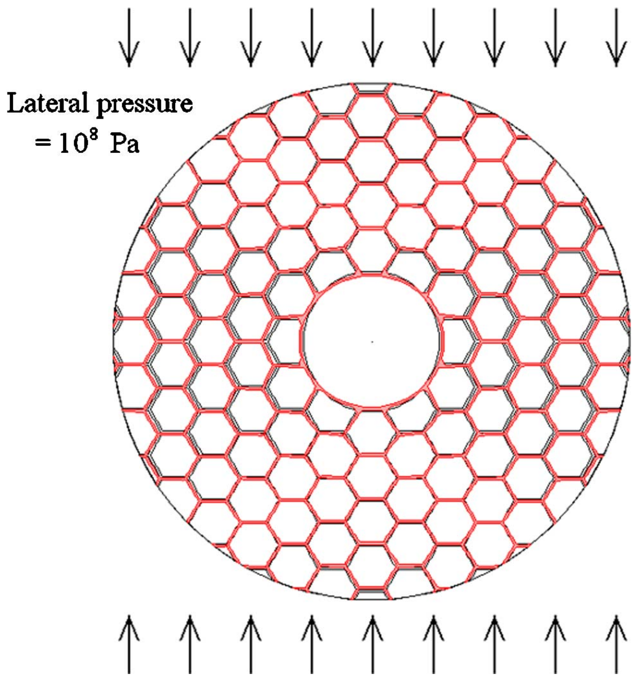

Fig. 2. (Color online) Deformed profile (red solid line) of HC-PBF, when the fiber is under a lateral pressure of 10^8 Pa. For comparison, the original profile is shown in the black hollow line.

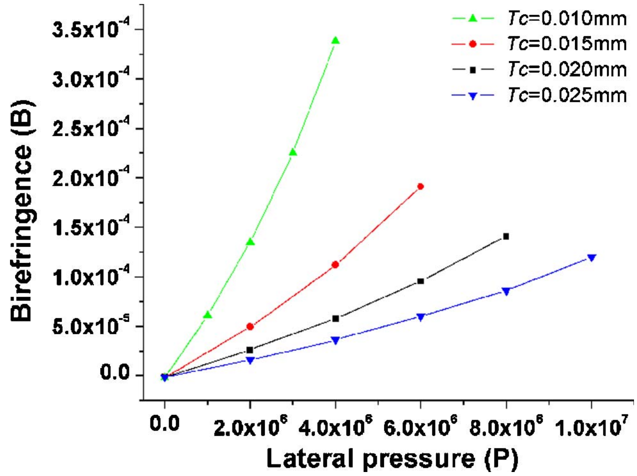

Fig. 3. (Color online) Induced birefringence of HC-PBF as the function of applied lateral pressure for different thicknesses of the outer solid silica cladding (T_c).

For an arbitrary input SOP(S) on the surface of the Poincaré sphere shown in Fig. 4, the first pressure segment rotates S along the circle SS', where S' is the SOP of the output light from the first segment, and it can be modified by the lateral pressure to any point in the circle. Then light S' enters segment 2, where another lateral pressure is applied with the direction of 45° differing from segment 1. Thus the SOP (S'') of the light out of segment 2 rotates on the sphere surface about the axis of OC, where OC is also in the equatorial plane of the sphere and vertical to OA. The third segment, again, rotates the S'' on the sphere surface about the axis of OA. Figure 4 gives a visualization of the evolution of the SOP through the three lateral pressure segments of the PC. It can be seen that the PC can transform a general input state S into any output state S'''.

To test the performance of the HC-PBF, the pressure applied to segment 1 was first increased gradually, while the pressures to the other two segments are kept

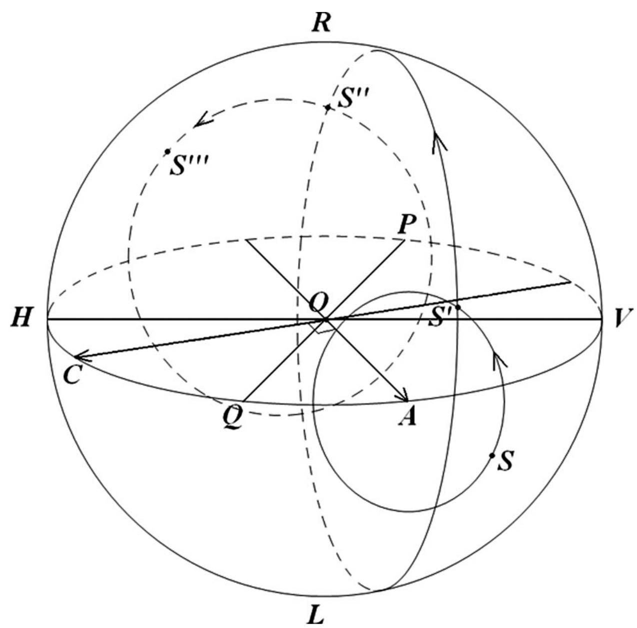

Fig. 4. Evolution of the state of polarization on the Poincaré sphere surface.

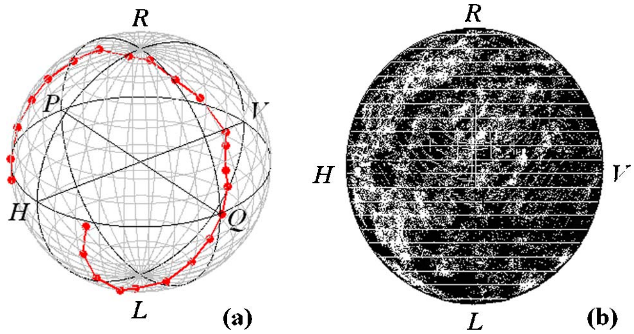

Fig. 5. Output SOPs with varying applied lateral pressure(s): (a) only the pressure to segment 1 is varied; (b) pressures applied to all three segments are varied randomly.

constant. The output SOPs from the PC were plotted in Fig. 5(a), and the evolution of the output SOP follows approximately a circle, which is in agreement with the theoretical predictions. The deviation from the ideal circular trajectory may be due to the inherent birefringence of the HC-PBF [1], which would be reduced largely by the advanced fiber manufacture technology. Furthermore, this deviation would have no detrimental effects on the performance of the PC. This is verified by varying randomly the pressures applied to all three segments, when the input light was kept at a fixed linearly polarized state. The output polarization states from the PC illustrated a good coverage of all the possible polarization states as shown in Fig. 5(b). Similar results were obtained for other input SOPs.

Comparing with the PC based on twisting HC-PBFs [15], the current PC may be constructed with HC-PBFs with little or no intrinsic birefringence. It should be noted that the intrinsic birefringence of HC-1550-02 fiber is a residual effect due to manufacturing imperfections. The fiber is not intended to have any birefringence. The inherent birefringence of the fiber causes a wavelength dependent phase delay between the two orthogonal SOPs, and for the same SOP at the input, lights out of the PC may have different SOPs for different wavelengths; this narrows down the bandwidth of the PC [15].

In conclusion, an in-line PC was proposed and studied theoretically and experimentally. Variable lateral pressures were applied to three segments of a HC-PBF and the output SOP showed a good coverage of all the possible polarization states on the surface of the Poincaré sphere, indicating a universal control of the polarization state may be achieved. This scheme may be applicable to HC-PBFs with little or no inherent birefringence.

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