Elasto-optic alignment of birefringent axes in polarization-holding optical fiber

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A nondestructive technique for the accurate alignment of the birefringent axes of high-birefringence optical fibers at an arbitrary position is demonstrated by using an elasto-optic effect. Alignment accuracy of less than 0.5° is achieved, and the slow and fast birefringent axes can be easily distinguished. A high-birefringence-fiber directional coupler with less than −28 dB polarization cross coupling, constructed by using this technique, is described.

The use of birefringent fiber in optical-fiber sensors is a straightforward approach to providing polarization stability and avoiding signal fading. In constructing such systems it is often desirable to manufacture in-line fiber devices, such as polarizers,[1] directional couplers,[2] and modulators, in which the light remains guided by the fiber throughout the device. When birefringent fiber is used in such devices, new precautions must be taken in that the principal axes of the fiber must be accurately aligned with certain transverse device axes in order to avoid polarization cross coupling. This requires the capability of aligning the principal axes of a birefringent fiber at arbitrary positions along the length of the fiber where devices are to be located. Considerable effort has been devoted to developing fibers with special outer geometries keyed to the principal axes, e.g., D- and square-shaped fibers.[3,4] However, a simple, accurate alignment technique that can be used to construct in-line devices in the more common round polarization-holding fibers, where no reference plane is available externally, has not yet been described.

Simpler schemes, involving alignment of the internal structure that provides the birefringence either by direct observation under a microscope or by analyzing the diffraction pattern obtained with side illumination of the fiber, are often accurate to only a few degrees. Moreover, the fiber typically has to be tranferred from the alignment apparatus to the device substrate, a process that may cause further errors.

Transverse force applied to a fiber can be used for both functional and diagnostic purposes. For example, it can be used to provide a desired degree of birefringence in a basically nonbirefringent fiber[5] or to couple mutually orthogonal polarization modes in a highly birefringent fiber.[6] Or it can be used to measure the polarization state of light propagating in a nonbirefringent fiber at a particular location in the fiber.[7] In this Letter we describe a new application of transverse stress on a fiber in which the stress is used to orient accurately the principal axes of a highly birefringent fiber as required for fabrication of birefringent fiber devices.

This alignment technique provides an accuracy better than ±0.5° with a simple detection system and also gives a direct identification of the fast and slow axes. In addition, the alignment is performed directly on the device substrate, so that no errors associated with fiber transport are present.

An optical wave linearly polarized along one of the birefringent axes of an unperturbed polarization-holding fiber maintains its state of polarization as it propagates along the fiber. However, when a section of the fiber is laterally squeezed in an arbitrary direction, as in Fig. 1, the orientation of the birefringent axes in that section is changed and coupling occurs between the two original polarization eigenmodes of the fiber, unless the stress is along one of the principal axes. The amount of optical-power cross coupling will be determined by the direction and magnitude of the applied lateral stress and the length of the fiber over which the stress is applied.

A polarization-maintaining fiber presents a well-defined intrinsic birefringence $B_{\text{int}} = \beta_s - \beta_f = 2\pi/L_B$, where β_s and β_f are the effective propagation constants for the slow and fast eigenmodes of polarization and L_B is the beat length between these modes. An exter-

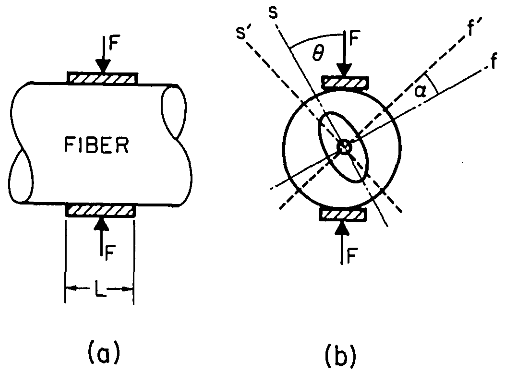

Fig. 1. A birefringent fiber with lateral stress applied at an arbitrary angle θ with respect to the unperturbed slow axis s, producing perturbed slow and fast axes s' and f', respectively.

nal force at an angle θ from the slow axis as shown in Fig. 1 will induce a birefringence $B_{\mathrm{ext}} = aCfn^3k_0/2d$, whose principal axes will be $\pi/2 - \theta$ away from the corresponding intrinsic birefringent axes. Here a is a constant, equal to 1.58 for round fibers; $C = 3.7 \times 10^{-12}$ m^2/N is the elasto-optical coefficient for fused silica; f is the force applied per unit length of fiber; k_0 is the propagation constant in vacuum; n is the index of refraction of the core; and d is the outside diameter of the fiber.[5] The new birefringent axes at the squeezed section will then be at an angle α from the unperturbed orientation, with α given by

$$\tan 2\alpha = \frac{B_{\mathrm{ext}} \sin 2\theta}{B_{\mathrm{int}} - B_{\mathrm{ext}} \cos 2\theta}, \tag{1}$$

and the magnitude of the resultant birefringence will be

$$B_T = (B_{\mathrm{int}}{}^2 + B_{\mathrm{ext}}{}^2 - 2B_{\mathrm{int}}B_{\mathrm{ext}} \cos 2\theta)^{1/2}. \tag{2}$$

These results may be obtained by using the Poincaré sphere representation of birefringence, in which birefringences are depicted vectorially and therefore the resultant birefringence is a vector sum.[8]

To determine the effect of the applied stress on the light propagating in the fiber, a segment dz of fiber at position z in the squeezed region can be thought of as a retardation plate with phase retardation $\mathrm{d}\psi(z) = B_T(z)\mathrm{d}z$ and principal axes aligned at an angle $\alpha(z)$ from the fiber birefringent axes. Integration along the interaction region yields the total retardation ψ. In the case of uniform stress over a length L, $\psi = B_TL$.

If linearly polarized light is launched along either of the principal axes at the input of the fiber with power P_{in} and an analyzer at the output end is aligned to transmit the optical radiation polarized along the orthogonal direction, the output power measured by a detector after the analyzer is

$$P_{\mathrm{out}} = P_{\mathrm{in}}\left(\sin 2\alpha \sin \frac{\psi}{2}\right)^2. \tag{3}$$

It can be seen from Eqs. (1) and (3) that P_{out} becomes zero when the applied stress is along either of the birefringent axes (θ = 0° or 90°). As $B_{\mathrm{ext}}/B_{\mathrm{int}}$ approaches unity with fixed L, it can be shown that the minimum along the fast axis gets broader while that along the slow axis sharpens. This is explained by the fact that squeezing the fiber parallel to the fast axis increases the net birefringence, whereas along the slow axis the intrinsic and applied birefringences tend to cancel, resulting in a more sensitive dependence on θ as the net birefringence approaches zero. A better resolution is then obtained along the slow axis, and distinction between the two polarization axes can be made by comparing the angular sensitivity of P_{out}.

Further improvement in measurement sensitivity can be achieved by applying a small time-varying modulation B_m added to the bias birefringence B_{ext}. The output signal P_{out} will contain a time-varying component at the modulation frequency with amplitude proportional to $\partial P_{\mathrm{out}}/\partial B_{\mathrm{ext}}$, which is a function of B_{ext}. Heterodyne detection using a lock-in amplifier or a spectrum analyzer can be used with better signal-to-noise ratio than that of dc power measurement by avoiding the relatively large noise at low frequencies.

The experimental setup is shown schematically in Fig. 2. The squeezer was made of two fused-silica blocks. In order to define a small interaction region where a device will eventually be fabricated, one of the squeezing surfaces was made slightly convex. This configuration allows a relatively large stress to be applied without breaking the fiber. Bias stress was applied with weight on top of the squeezer while a piezoelectric transducer (PZT) slab under the bottom block provided a modulation of the stress. The PZT rested on a translation stage such that the fiber could be rolled while squeezed. The rotation angle $\Delta\theta$ is related to the displacement Δx of the base by $\Delta\theta = \Delta x/d$, where d is the outside diameter of the fiber.

Linearly polarized light is launched along one of the principal axes of the fiber. At the output, an analyzer transmits the light that is cross coupled at the squeezed region. By rolling the fiber while monitoring the dc and ac output signals on an oscilloscope and a spectrum analyzer, we can locate the birefringent axes.

Figure 3 shows theoretical and experimental results obtained with a York stress-induced birefringent fiber with an outside diameter of 81 μm and a beat length of 1.95 mm by using a He–Ne laser at 633 nm. The

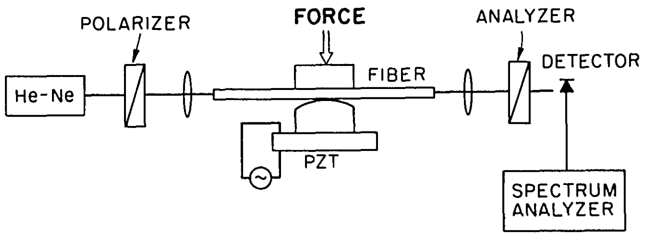

Fig. 2. Experimental setup for alignment of birefringent axes. The fiber is rolled between the squeezing jaws using a translation stage until the desired orientation is achieved.

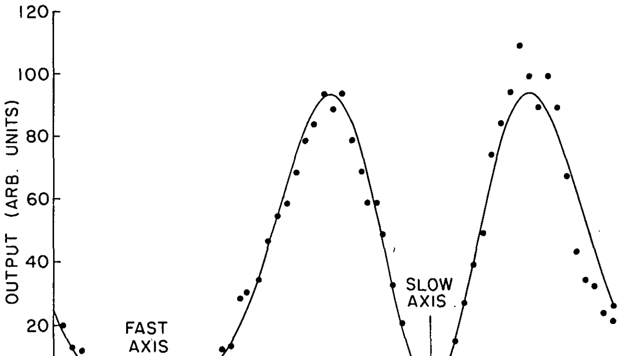

Fig. 3. Experimental results showing the output signal at the modulation frequency (dots). The solid line represents the theoretical curve for the test conditions ($B_{\mathrm{ext}}/B_{\mathrm{int}} \approx 0.4$ and $L \approx 1$ mm).

radius of curvature of the squeezing surface was 30 cm, and the applied bias force was approximately 1.5 N, corresponding to $B_{\text{ext}}/B_{\text{int}} \approx 0.4$. The interaction length was estimated to be about 1 mm. A resolution better than ±0.5° was achieved in the alignment of the slow axis. We point out that use of a lock-in amplifier could provide increased resolution, and use of a broadband source, such that the two polarization modes are no longer coherent at the squeezed region and the output, relaxes the requirements on the polarizers' alignments and extinction ratios.

Variable-directional couplers using birefringent fiber were constructed with fiber aligned as above. Hitachi single-mode stress-induced birefringent fiber was used, having a 125-μm outside diameter and a beat length of 3.3 mm at 820 nm. The couplers are of the mechanically polished type[2] in which fiber is epoxied into grooves in quartz substrate blocks before polishing. In this case we roll the fiber transversely in the groove to align the principal axes with respect to the substrate surface. This is facilitated by making the groove depth less than the fiber diameter. When alignment is obtained, the epoxy is UV cured and the fiber and the substrate are lapped and polished until most of the cladding of the fiber is removed. Two such blocks are put together to form a directional coupler. Polarization cross coupling in 3-dB couplers lower than −28 dB, measured with a multimode laser diode, is reproducibly obtained. One of the polarization-coupling sources is considered to be changes in the birefringence that are caused by tapered cladding removal at both ends of the aligned fiber section, which is inherent in polished couplers. Good alignment accuracy cannot be guaranteed in these segments of fibers, and a slight twist may occur during the alignment procedure. Also, a slight asymmetry in the stress member of the fiber can lead to polarization cross coupling after polishing.

In summary, in this Letter we have described a nondestructive technique for aligning the birefringent axes of round-cladding, polarization-holding optical fibers, allowing for the fabrication of in-line devices. This method provides a means of aligning the orientation of the eigenmodes with a resolution better than ±0.5° and distinguishing between the fast and slow modes. A polarization-maintaining directional coupler is reported that exhibits reproducible polarization cross coupling smaller than −28 dB.

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References

1. R. A. Bergh, H. C. Lefevre, and H. J. Shaw, Opt. Lett. **5**, 479 (1980).
2. R. A. Bergh, G. Kotler, and H. J. Shaw, Electron. Lett. **16**, 260 (1980).
3. R. B. Dyott and P. F. Schrank, Electron. Lett. **18**, 980 (1982).
4. R. H. Stolen, W. Pleibel, and J. R. Simpson, IEEE J. Lightwave Technol. **LT-2**, 639 (1984).
5. Y. Namihira, M. Kudo, and Y. Mushiako, Trans. Inst. Electron. Commun. Eng. Jpn. **J60C**, 391 (1977).
6. R. C. Youngquist, J. L. Brooks, and H. J. Shaw, Opt. Lett. **8**, 656 (1983).
7. N. Chinone and R. Ulrich, Opt. Lett. **6**, 16 (1981).
8. R. Ulrich and A. Simon, Appl. Opt. **19**, 2241 (1979).