Use of highly elliptical core fibers for two-mode fiber devices

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The four complex, almost degenerate, second-order eigenmodes of a two-mode fiber having a circular core are reduced to two nondegenerate, linearly polarized second-order eigenmodes with stable-intensity lobe positions in a highly elliptical core fiber. Existing two-mode-fiber devices can be improved by this stabilization of the second-order modes. Practical sensors employing the two spatial modes as the two arms of an interferometer are described. The two arms of an interferometer of this type can have the same group delays, while the difference in phase delays is large.

Recently a number of fiber-optic components made in two-mode optical fibers have been demonstrated with excellent performance in the laboratory environment; these components include as intermodal couplers,1 highly selective modal filters,2 and acousto-optic single-sideband frequency shifters.3,4 These devices have demonstrated the basic principles of means for more-or-less complete control of the two spatial modes guided in the fiber and thus form the basis for constructing many new two-mode fiber-optic components and systems for use in sensors, signal processing, and communications. The feasibility of practical implementation of these devices, however, was obstructed by the instability of the second-order-mode lobe orientation.2 In this Letter we propose using a fiber with a highly elliptical core geometry to fix the lobe orientation of the second-order modes. The use of highly elliptical core two-mode fibers not only makes the practical implementation of existing components already mentioned possible but also opens up the possibility for many new components and systems yet to be invented. We describe the modal characteristics of highly elliptical core fibers. Schemes for implementation of interferometric systems with two-mode fibers are discussed. Finally, we discuss the two-mode fiber as a balanced interferometer, based on the fact that the two spatial modes have identical group velocities at some optical frequency.

Single-mode fibers with circular cores support two orthogonal polarization modes with the same spatial intensity distribution, which is the LP01 mode in the weakly guiding approximation [Fig. 1(a)]. The next four higher-order modes have almost the same propagation velocities and cross-sectional optical intensity distributions. In the weakly guiding approximation, these four modes become degenerate (i.e., have the same propagation velocity) and are denoted as LP11 modes [Fig. 1(b)]. Fibers operating in this regime are what we call two-mode optical fibers. In fact, the so-called two-mode fiber supports six modes (namely, the three modes shown in Fig. 1 plus the cross-polarized version of each of these).

In two-mode fiber-optic devices, such as intermodal couplers, modal filters, and acousto-optic frequency shifters, it is necessary to control the spatial distribution of the optical intensity with reference to the symmetry axes of the devices. The true second-order modes of a circular core fiber, TE01, TM01, even HE21, and odd HE21 modes, have slightly different propagation velocities. Therefore, when more than one of these modes are copropagating in a two-mode fiber, the intensity distribution of the second-order mode varies down the length of the fiber. Moreover, the cross-sectional intensity distribution of the second-order mode changes in response to environmental changes, which induce differential phase shifts between the almost degenerate four eigenmodes. The instability of the second-order mode pattern can limit the practicality of two-mode fiber devices.

One approach to the mode-pattern stabilization that we propose is to use an optical fiber with a highly elliptical core geometry. For a given core geometry, this fiber guides only one spatial mode (LP01) for wavelengths longer than a particular value, as is the case with fibers having circular cores. The two polarization eigenmodes, however, will have different propagation velocities owing to the asymmetry of the core geometry. For wavelengths slightly shorter than the critical value, the next higher-order mode with greater propagation velocity compared with that of the fundamental mode is guided. The important aspect of the highly elliptical core fibers is that only two second-order modes (LP*11; see Fig. 2) propagate instead of four. In this case the intensity distribution of the second-order modes is uniquely defined and stable. Over a large region of the optical spectrum, this fiber guides only four modes (two polarization modes each of, depending on the core size, the LP01 and LP11 modes).

Fig. 1. Guided modes in circular core optical fibers with one of the two orthogonal polarizations. (a) LP01 mode, (b) LP11 mode.

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for the fundamental and second-order modes) instead of six, as is the case for fibers with circular cores. The separation between the cutoff wavelengths for the LP_{01}^{even} and the LP_{00}^{odd} modes will increase with increasing core ellipticity.

Figure 2 shows the far-field radiation pattern from a fiber having a highly elliptical core (4.1 × 2.2 μm, Δ = 3 × 10^{-3}) for the LP_{01}, LP_{11}^{even}, and LP_{11}^{odd} modes. The fiber was provided by Polaroid Corporation. The LP_{11}^{even} mode, which has high-intensity lobes along the long axis of the core ellipse, has a cutoff wavelength around 633 nm. The LP_{11}^{odd} mode, which has high-intensity lobes along the short axis of the core ellipse, has a cutoff wavelength shorter than 488 nm. Therefore, the desired optical wavelength range of two-mode operation in this fiber is between 488 and 633 nm.

The propagation constants of the LP_{01} and both the LP_{11}^{even} and LP_{11}^{odd} modes were measured for the Polaroid fiber at an optical wavelength below the cutoff of the LP_{11}^{odd} mode (λ = 479 nm) by using the prism output coupling technique.\(^6\) The propagation constant splitting between the LP_{11}^{even} and LP_{11}^{odd} modes was seen to be comparable with the propagation constant difference between the LP_{01} and LP_{11}^{even} modes. Specifically, the beat length between the LP_{01} and LP_{11}^{even} modes was 206 μm, and the beat length between the LP_{11}^{even} and LP_{11}^{odd} modes was 1.4 times longer.

With the stability of the mode-intensity pattern, enhanced performance of two-mode fiber-optic components, currently constructed with circular core fibers, can be expected, and many new practical devices can be envisaged. For the intermodal coupler and the acousto-optic frequency modulator, the periodic bending of the fiber (which is due to static bending or to acoustic flexural waves) should be codirectional with the long axis of the core ellipse. The modal filter should be made with the long axis of the core ellipse normal to the polished surface of the directional coupler. The accuracy of the alignment of the core elliptic axis in these devices does not critically affect the performance of the devices and thus does not place practical limitations on the use of elliptical core two-mode fibers in them.

Another area of application of two-mode fibers with highly elliptical cores is fiber-optic interferometric sensors. Attempts were made in the past\(^7,8\) to make interferometric sensors using two-mode fibers having circular cores, but these were impractical because of the instability of the second-order modes. The principle of one type of interferometry in highly elliptical core two-mode fibers is the following. Light is excited in the LP_{01} and the LP_{11}^{even} modes of a highly elliptical core fiber with approximately equal intensity. The output radiation pattern will be a superposition of the two modes and will be dependent on the relative phase between them (Fig. 3). When the phase difference between the two modes is \(N\pi\), where \(N\) is an integer, the antisymmetric second-order mode will add to the symmetric first-order mode destructively on one side of the fiber core and constructively on the other. The positions of the dark and bright regions are interchanged for even and odd \(N\)’s. Therefore, by monitoring the intensities of the radiation pattern in the two regions, the optical phase difference between the modes can be measured. Figure 3(b) shows the far-field radiation patterns from the Polaroid elliptical core fiber with approximately equal intensity for the LP_{01} and LP_{11}^{even} modes having progressive phase differences. The phase difference was tuned by stretching a section of the fiber.

Two other embodiments of a two-mode fiber interferometric sensor are illustrated in Fig. 4. In Fig. 4(a), light contained in the LP_{11}^{even} mode of the two-mode fiber is stripped off by coiling a short section of the fiber with a tight radius. Then an intermodal coupler (IMC) converts approximately 50% of the light to the LP_{11}^{odd} mode. The two spatial modes then propagate together through the sensing region where the quantity being sensed perturbs the relative phase difference between them. Effects that can be sensed are axial strain, temperature changes, acoustic pressure, etc. At the end of the sensing region, a second IMC couples the modes with a coupling ratio of approximately 50%.

![Diagram](http://example.com/diagram.png)
Finally, the LP_{10} mode is stripped off and the remaining light intensity is detected. Relative phase shifts between the modes induced in the sensing region will show up as intensity variations at the detector. This system is analogous to a Mach–Zehnder interferometer. The two arms of the interferometer are replaced by the two spatial modes propagating in the two-mode fiber. The IMC used in this sensor configuration can be a static periodic bending coupler or an acoustic frequency shifter described in previous publications. When a frequency shifter is used as one of the IMC’s, the light coupled to (or from) the LP_{10} mode is frequency shifted and provides a naturally heterodyned signal output. In this case environmentally induced differential phase shifts can be measured by measuring the phase shift in the beat signal, whose frequency is the same as that of the acoustic signal in the frequency shifter, and signal fading resulting from environmental phase drift is avoided.

Figure 4(b) shows a different two-mode-fiber interferometric sensor system in which the LP_{11} mode stripper and the IMC are replaced by a misaligned fiber splice. Light from a single-mode fiber is launched asymmetrically into the two-mode fiber to give equal excitations of the two spatial modes. After the sensing region a second misaligned splice taps light from each mode equally into a single-mode fiber. As before, relative phase shifts induced between the two modes in the sensing region will show up as intensity variations at the detector.

Interferometers built with two-mode fibers have some unique characteristics. For the range of optical wavelengths that provides two guided modes in a given fiber, the group velocities of the two modes have similar values even though the phase velocities of the modes are quite different. At a particular wavelength for a given fiber, the group velocities of the two modes are the same, as is the case for circular fibers. The implication of this fact is significant for the interferometric sensors described above. For many interferometric sensor systems, the two arms of the interferometers have different lengths, and the optical source must have a coherence length longer than the optical path-length difference (OPD). This imposes a number of constraints on the optical circuit design and the spectral characteristics of the source. Moreover, even when the OPD is smaller than the coherence length of the source, an additional noise is present owing to the optical-source phase noise, unless the OPD is zero. The OPD that determines the coherency of the interfering optical waves and the phase noise is in fact group delay, rather than phase delay of the optical wave. Therefore, in two-mode-fiber interferometry, in which the group delays for the two arms of the interferometer are the same, an optical source with a short coherence length can be used without losing interference signals even though large phase delays may be employed. The sensitivity of two-mode-fiber interferometers will be smaller than that of the conventional single-mode-fiber interferometers with separate arms. Longer fiber lengths can be used to improve the sensitivity. Furthermore, the source phase noise does not appear as noise in the output of the interferometer. It is also possible to use a short optical pulse as a source for the interferometer since the pulses traveling in the two modes will not be separated in time. The properties of two-mode optical fibers can also be useful for applications in communications and signal processing.

In conclusion, we have shown that by using highly elliptical core fibers, the second-order mode complexity is reduced from four eigenmodes in the circular case to two linearly polarized eigenmodes over a large region of the optical spectrum. This simplification, along with the stabilization of intensity distribution of the modes, greatly enhances the practicality of two-mode-fiber components and systems. Interferometric sensing schemes that make use of two-mode fibers and existing components have been discussed. Interferometry in two-mode fibers has the advantage that the two modes can propagate with equal group velocities while having different phase velocities. Such systems can be useful for many new application areas.

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References