Strain effects on two-mode fiber gratings

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The spectral, interferometric, and polarization properties of mode-coupling fiber gratings under strain are described. The grating is formed by photosensitivity that uses modal interference in the two-mode fiber. Theoretical and experimental results show the possibilities of using the fiber grating for optical switches, tunable filters, interferometric sensors, and polarizers.

In-line fiber-optic gratings formed by photosensitivity are finding wide application areas, including narrow-band optical filters, fiber lasers with Bragg grating mirrors, and intermodal coupling devices in few-mode fibers. With the development of highly efficient gratings and side-writing technology, permanently photoinduced grating devices are expected to replace some of the conventional fiber-optic components for telecommunications and fiber sensors. Compared with the reflective gratings written in single-mode fibers, mode-coupling gratings in birefringent fibers or few-mode fibers are inherently transmitting devices that can be useful for many applications. Recently a side-writing technique was applied to fabricate mode-coupling gratings in telecommunication fibers with the flexibility of choosing the operational wavelength. The tuning of the grating over a limited range was also described by twisting or stressing the fiber. Because fibers with circular cores have four almost degenerate LP modes, the spectral response of the grating was rather complicated. It was reported that a two-mode fiber with an elliptical-core geometry supports LP modes and modes with stable intensity lobe orientations. In such fibers the degeneracy is lifted between guided modes. It is also well known that the beat length and the grating period can be tuned by application of longitudinal strain to the fiber. Therefore much cleaner spectral behavior and controlled tuning of the gratings are expected when an elliptical-core two-mode fiber is used and tuned by longitudinal strain.

In this Letter we describe the response of a mode-coupling grating that couples light between LP modes and LP modes in elliptical-core two-mode optical fibers to longitudinal strain for its spectral, interferometric, and polarization characteristics. The experimental results have implications for fiber-optic digital switches, tunable wavelength filters, strain sensors, and polarizers.

To introduce coupling between the symmetric (LP) and the antisymmetric (LP) modes, one must create the refractive-index change that breaks the symmetry of the cross-sectional index profile of the core with the longitudinal periodicity of the modal beat length (LB). This could easily be accomplished by launching the writing optical beam with equal power for the two modes in the same polarization direction, producing a periodically varying modal interference pattern with the period of LB in the fiber. With high enough writing-beam power, the interference pattern induces a permanent refractive-index change in the core. Once written, the permanent grating can couple small optical signals in the two modes at wavelengths similar to that of the writing beam. This approach of writing the grating has a limited range of operating signal wavelength because the photosensitivity occurs at the UV or green wavelength. A side-writing technique would eliminate this limitation.

Now we consider mode coupling in a fiber that has a grating with a period of A. When only the LP mode is excited at z = 0 with intensity I0, the intensity of mode LP becomes

\[ I_{11}(z) = I_{01} \frac{\gamma^2}{\gamma^2 + (\theta/2)^2} \sin^2 \left( \left[ \frac{\gamma^2}{2} + (\theta/2)^2 \right] \frac{z}{2} \right), \]

where \( \gamma \) is the coupling coefficient per unit length and \( \theta = 2\pi[(1/A) - (1/LB)] \) represents the magnitude of phase mismatch between the mode beating and the grating period. The maximum coupling occurs when \( \theta = 0 \), and little coupling takes place as \( \theta \) deviates from zero. When an unstrained fiber section of length L is elongated by \( \delta L \), the grating period \( L \) changes by \( \delta L = \delta L/L \), whereas the beat length \( L \) changes by \( \delta L/L = \alpha(\delta L/L) \). This difference in \( \delta L \) and \( \delta L \) can be used advantageously to tune \( \theta \) in order to control the amount of light coupling. The relationship between \( \theta \) and \( \delta L \) is

\[ \theta = 2\pi \frac{1}{L} \left( \frac{1 - \delta L}{L_0} - \frac{1}{L_0} \left( 1 - \alpha \frac{\delta L}{L_0} \right) \right). \]

Light from a linearly polarized Ar laser at 514.5 nm was launched into an elliptical-core (4.1 \( \mu m \times 2.2 \mu m \)) germanium-doped two-mode fiber. The cutoff wavelength for the LP mode was 633 nm. The modal beat length of the fiber was measured to be approximately 200 \( \mu m \) in the blue-green wavelength range. The polarization state of the writing beam was oriented along the major axis of the core ellipse, and the length of the fiber was 2 m. To prevent external perturbation during the writing process, we placed the fiber in a straight glass tube.
The two modes were excited with equal power, and the launched power was 40 mW with an exposure time of 20 min.

After the writing process, the mode-coupling characteristics of the grating were measured with the setup shown in Fig. 1, where the probe-beam intensity was less than 1 mW at 514.5 nm. A mode stripper (three loops with 5-mm diameter) was used at the input end to excite only the \( \text{LP}_{01} \) mode. We carefully adjusted the orientation of the loops to avoid polarization cross coupling. Another mode stripper was used at the output end to eliminate the coupled \( \text{LP}_{11} \) mode. The second mode stripper could be moved along the fiber length for the measurement of the throughput power as a function of the coupling length. A minimum throughput of 10% was achieved when the fiber length between the two mode strippers was 100 cm. At the minimum throughput, the 100-cm-long fiber section between the mode strippers was strained. Figure 2 shows the transmitted power as a function of fiber elongation and demonstrates the expected switching behavior as \( \theta \) tunes away from zero. The fiber elongation needed for a complete switching was approximately 600 \( \mu \)m, which was longer than the theoretical value of 240 \( \mu \)m. The discrepancy is believed to come from the elongation of the soft fiber jacket before the fiber was actually elongated. The experimental results indicate that the two-mode fiber grating can be used for a mechanically operated digital optical switch.

Another fiber grating was fabricated with a technique similar to that described above for the demonstration of an in-line modal interferometer as depicted in Fig. 3(a). The 48-cm-long sections of the fiber provided approximately 50% mode coupling and played the role of 3-dB directional couplers in a conventional Mach–Zehnder interferometer formed with single-mode fibers. We strained the 40-cm-long section of fiber between the coupling regions to obtain the regular interferometric output shown in Fig. 3(b). The amount of elongation needed to produce a \( 2\pi \) phase difference between the \( \text{LP}_{01} \) and \( \text{LP}_{11} \) modes was approximately 260 \( \mu \)m. The fringe visibility was less than optimum because of the deviation of the mode-coupling ratio from 50%. The first fringe taken at small elongation deviated from an ideal sinusoidal curve because of the mode coupling in the elongated section. The interferometer configuration can be used as an interferometric sensor for strain and temperature measurements.

To investigate the wavelength and polarization properties of the grating in response to strain, we fabricated another grating with a writing-beam intensity of 50 mW at 488 nm and 10 min of exposure time. For a greater tuning range, we formed the grating while the two-mode fiber was under strain, which made it possible to tune the grating period...
in both positive and negative directions. The length of the grating was 60.5 cm. Figure 4 shows the probe signal output at much lower optical intensity as a function of strain for different wavelengths. The magnitude of elongation was referenced to the original elongation at the time of writing the grating. As expected from Eqs. (1) and (2), maximum coupling occurred when the phase-matching condition \( \theta = 0 \) was satisfied for each wavelength. The shift of the coupling peaks as a function of the wavelength generally matches with the dispersion of the beat length. The FWHM of the coupling peaks was approximately 200 µm, which agreed well with theoretical prediction. The spectral behavior of the grating can be used for a tunable optical filter.

Figure 5 shows the transmission of the probe beam through the fiber grating described above for two orthogonal polarization states. Because the modal beat lengths are different for the two eigenpolarization states when the fiber is strained, the probe beam with a polarization state orthogonal to that of the writing beam required a different amount of strain for maximum coupling. The separation of the two peaks was approximately 200 µm. When used as a polarization filter, this device demonstrated 11 dB of extinction ratio.

In summary, we investigated the response of the mode-coupling grating made by photosensitivity to longitudinal strain. Experimental results show the possibility of using the grating for digital switching, interferometric sensors, tunable filters, and polarizers.

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References