Lifting polarization degeneracy of modes by fiber design: a platform for polarization-insensitive microbend fiber gratings

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Polarization dependence in microbend gratings is an inherent problem, even in perfectly circular fibers, since antisymmetric modes are almost degenerate linear combinations of four distinct, polarization-sensitive modes. We demonstrate a novel fiber design that lifts polarization degeneracies of the antisymmetric modes to solve this problem. By intentionally exacerbating the polarization splittings, we achieve coupling to only the polarization-insensitive doublet, over wavelength ranges exceeding 100 nm, thus demonstrating a device with practical usable bandwidths. This allows all previous applications envisaged with UV-induced long-period gratings to be realized with the significantly lower-cost microbend technology platform. © 2005 Optical Society of America

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Microbend-induced fiber gratings[1,2] function as copropagating couplers that resonantly couple symmetric and antisymmetric modes in fibers. Their primary attraction is their low cost and their tunability, since the amplitude and period of microbend perturbations can be easily varied. This makes tunable filters possible, such as dynamic gain equalizers[3] and variable optical attenuators.[4,5] A debilitating drawback with such gratings is that they are inherently polarization dependent, even in perfectly circular fibers. This is because antisymmetric modes are actually almost degenerate linear combinations of four distinctly polarized vector modes with different propagation constants.

Demonstrated means to circumvent this problem rely on averaging the grating response for orthogonal states of polarization (SOPs) of light by forcing it to see both SOPs.[3,6] However, such techniques do not address the fundamental problem and negate the low-cost, low-loss, or tunability features of microbend-induced gratings (MIGs). Alternatively, MIGs in very thin fibers (outside diameter ~10 μm) can be shown[7] to preferentially couple light only to polarization-insensitive HE_{21} modes, but this requires fibers that are impractically thin for device applications.

In this Letter we demonstrate a novel fiber designed to lift the polarization degeneracy of the antisymmetric LP_{11} mode so the resonances of its vector components are separated by a wide spectral range. Hence, microbends induced in this fiber yield polarization-insensitive HE_{21} coupling over bandwidths greater than 90 nm, yielding a polarization-dependent coupling- (PDL-) free device over that range. We believe this is the first demonstration of a practical fiber design to solve an inherent and fundamental problem with MIGs. In addition, all the other advantages of MIGs—simplicity, low-cost assembly, wavelength and strength tunability, and very low insertion losses (0.2 dB)—are retained.

Solutions of the scalar wave equation for fibers yield eigenmodes such as the LP_{01} (fundamental) and LP_{11} (first higher-order) modes. However, the rigorous vector solution reveals that the LP_{11} mode comprises four almost degenerate modes—TE_{01}, HE_{21}^{even}, HE_{21}^{odd}, and TM_{01}. Figure 1(a) illustrates the scalar power distribution of the LP_{11} mode, as well as the electric field vectors for its four distinct vector mode counterparts. The propagation constants for the vector modes are slightly different. This is expected, since the TE mode has an electric field tangential to the waveguide boundary [Fig. 1(a)], while the field of the TM mode is normally incident. Since the phase shift at an index boundary depends on the incidence angle of the electric field vector, the propagation constants for TE_{01} and TM_{01} will differ.

The resonant wavelength λ_{res} of a MIG is given by

$$\lambda_{res} = \Lambda(n_1 - n_2), \tag{1}$$

where n_1 and n_2 are the effective indices of the two coupled modes and Λ is the grating period. Since the propagation constants are slightly different for the vector components of the LP_{11} mode, slightly different resonant wavelengths result for the same grating. In addition, the input SOP defines the efficiency of grating coupling to the TE or TM mode (the HE mode is polarization insensitive, since it comprises a mixture of the TE and TM modes). Hence, the grating resonance will shift (in wavelength) as the input SOP

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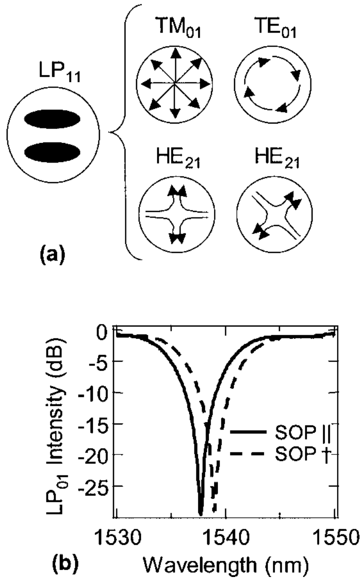

Fig. 1. (a) Scalar (left) and vector (right of brace) representations of the first higher-order antisymmetric mode group (the LP_{11} mode). (b) Polarization-sensitive microbend grating spectra in TWRS fiber arising from vector components of LP_{11}; $\beta_{TM_{01}} \neq \beta_{HE_{21}} \neq \beta_{TE_{01}}$.

is varied. Figure 1(b) illustrates this polarization dependence for resonant spectra in a MIG induced in TWRS fiber.

The magnitude of this splitting is controlled by the waveguide itself. Vector corrections of the propagation constants β for the scalar solution are given by[8]

$$\delta\beta_{TE_{01}} = 0,$$

$$\delta\beta_{TM_{01}} = 2(I_1 + I_2),$$

$$\delta\beta_{HE_{21}}^{\text{even,odd}} = (I_1 - I_2), \tag{2}$$

where I_1 and I_2 are waveguide-dependent quantities:

$$I_1 \propto \int rE(r)\frac{\partial E(r)}{\partial r}\frac{\partial F(r)}{\partial r}\mathrm{d}r,$$

$$I_2 \propto \int E^2(r)\frac{\partial F(r)}{\partial r}\mathrm{d}r, \tag{3}$$

where $E(r)$ is the electric field profile for the scalar mode and $F(r)$ is the normalized index profile of the fiber. Equations (2) and relations (3) indicate that the refractive index profile determines the resonant wavelength splitting [shown in Fig. 1(b) and Eq. (1)], and this forms the basis for exploring the fiber design in this Letter.

A fiber design with widely spaced propagation constants for the TE, HE, and TM modes will yield a MIG that has only one resonance over a broad wavelength range. When the coupled mode in such a fiber is the HE_{21}, the resonance is polarization insensitive. Hence, a PDL-free device is obtained.

Figure 2 shows the canonical refractive index profiles [$F(r)$ in Eq. (3)] used to test this concept, along with the mode profile for the scalar LP_{11} mode [$E(r)$ in Eq. (3)]. Note that the optimized design yields high mode intensities close to the waveguide transition regions. This is indeed what Eqs. (2) and relations (3) demand—large separation in propagation constants require large I_1 and/or I_2 values, which can be obtained when large LP_{11} power resides close to a sharp index step. This yields a fiber designed to have large degeneracy splittings.

MIGs were induced in several fibers with designs similar to that shown in Fig. 2, by pressing the fiber between 5 cm long periodically corrugated blocks and rubber pads. Figure 3(a) shows spectra obtained on one such fiber for grating periods ranging from 750 to 850 μm. Three distinct resonant peaks are obtained, with the center peak (HE_{21}) being the strongest. This is expected, since unpolarized light is used

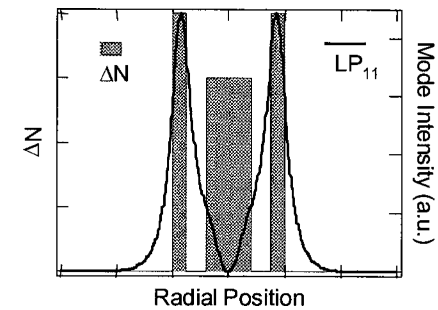

Fig. 2. Index profile (shaded) and LP_{11} mode intensity profile (curve). The LP_{11} mode has high intensity near large index steps leading to large I_1 and I_2 [Eq. (3)]. This yields a large vector correction for the HE_{21} and TM_{01} modes. Hence the three vector components of the LP_{11} mode are substantially separated in resonant wavelength.

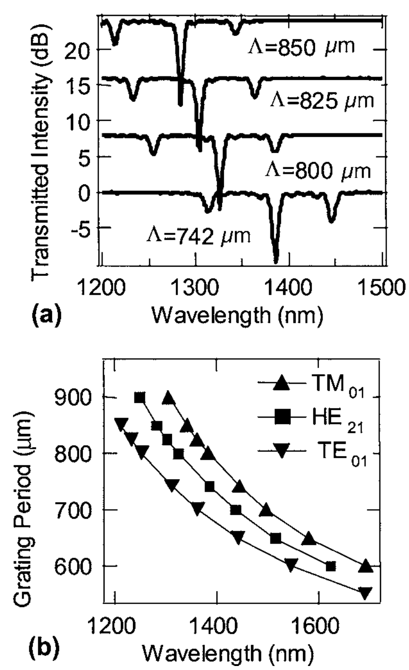

Fig. 3. (a) Grating spectra in designed fiber at different grating periods. Clearly separated resonances for three vector modes. (b) Resultant phase-matching curve shows more than 60 nm separation between the HE_{21} and the TE_{01} or TM_{01} modes.

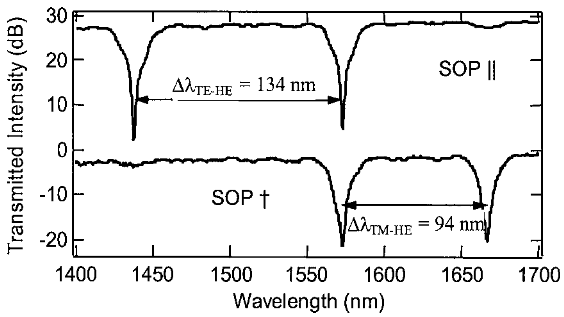

Fig. 4. Polarization-dependent spectrum of MIGs in a novel fiber design. TE or TM coupling changes with the SOP; the HE mode is not perturbed. Large wavelength separation of HE from TE or TM yields a PDL-free device over at least 94 nm.

for characterization, and only the HE mode is polarization insensitive. The other two resonances are only ~3 dB strong, since no more than half of the light exists in one SOP, for an unpolarized source. This confirms that Eqs. (2) and relations (3) adequately describe the polarization-sensitivity phenomena in microbend gratings. Also note that the wavelength separation between the HE and the TE or TM modes is large [60 nm, instead of ~1 nm for TWRS in Fig. 1(b)], as was the intent of this fiber design. Figure 3(b) is a plot of the phase-matching curve for the TE_{01}, HE_{21}, and TM_{01} modes. In a regular fiber, the three curves would have been indistinguishable on this scale.

Figure 4 shows the polarization-dependent spectra of these resonances in a fiber that has been optimized to yield very large degeneracy splittings. Broadband light was sent through a polarizer and polarization controller to control the input SOP at the grating. The spectra clearly illustrate the principle of operation—for an input SOP corresponding to the TE mode, only the TE and HE modes are excited, whereas for the orthogonal SOP, only the TM and HE resonances occur. Of course, the HE_{21} mode is excited regardless of the input SOP, because it is nominally polarization insensitive. However, we found that even the HE_{21} mode has some polarization dependence (evidenced by small shifts in its resonance). This is not expected for this design and is attributed to small geometric and stress ovalities induced during the fiber fabrication process—an issue that should be solvable in a manufacturing process.

Finally, Fig. 4 shows that the optimized fiber design yields resonant wavelength splittings of 94 nm between the HE and TM modes and of 136 nm between the HE and TM modes. Since this device schematic yields a polarization-insensitive resonance specifically for the HE_{21} mode, it would yield PDL-free operation over at least 94 nm, which covers the *C* and *L* bands.

In summary, we propose and demonstrate a novel fiber design that solves the fundamental problem of polarization dependence in MIGs. The design lifts the polarization degeneracy of antisymmetric modes in a fiber, thereby enabling MIG coupling solely to the polarization-insensitive HE_{21} mode. This device schematic facilitates, for what we believe to be the first time, use of low-cost microbend gratings for a variety of dynamic and static spectral shaping applications, which were so far practical only with expensive UV-induced gratings.

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