Bandwidth control of long-period grating-based mode converters in few-mode fibers

Siddharth Ramachandran, Zhiyong Wang, and Man Yan

OFS-Fitel Research Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Received January 8, 2002

Control of the group-velocity differences between two distinct modes in a few-mode fiber can be used to define the spectral characteristics of long-period gratings written in them. Using this effect, we report the demonstration of strong mode conversion (>99%) with long-period fiber gratings over what is believed to be a record bandwidth of 63 nm. These novel spectra are obtained from gratings written in specially designed few-mode fibers in which the grating phase-matching condition is satisfied over a large spectral range. We show that the bandwidths of such mode converters can be tailored by suitably altering the design of the few-mode fibers. The polarization-dependent coupling for the mode converters varies by less than 0.004% over the entire spectrum.

OCIS codes: 060.4510, 060.2280, 060.2340, 350.2770.

Long-period fiber gratings (LPG) offer coupling between copropagating modes of a fiber and are potentially useful as spectral-shaping elements and mode-conversion devices. Such mode couplers have recently become immensely attractive because they permit dispersion and dispersion-slope compensation using higher-order modes of a fiber.[1,2] But LPGs are traditionally narrow band, and, although they offer strong (>20- or 30-dB) mode coupling, the spectral width of such coupling is typically limited to a range 0.5–2 nm. This limited range is expected of any interferometric device in which the phase-matching condition between two optical modes is satisfied only at a specific resonant wavelength. This limits the utility of interferometric devices as broadband devices that can act on an entire communication band. However, if a fiber waveguide were engineered to yield two modes with identical group velocities, the LPG phase-matching condition would be satisfied over a large spectral range, yielding broadband LPG.

Broadband mode conversion induced by coupling between two copropagating modes with identical group indices was first demonstrated by Poole *et al.*[2] They used periodic microbends to couple between the fundamental mode and an LP_{11} mode close to cutoff. Strong mode conversion (>10 dB over 74 nm) was achieved, but microbend gratings couple spatially symmetric modes to antisymmetric modes, which makes them inherently polarization sensitive. In addition, microbend gratings are also lossy and hard to implement compared with UV-induced gratings. This concept was extended to induce coupling between the core mode and a cladding mode of conventional single-mode fibers,[3] where the chosen higher-order cladding mode had a group velocity that matched that of the core mode. But the ability to tailor such a spectrum (control its bandwidth and strength, for example) is limited, since the dispersion properties of cladding modes are not amenable to arbitrary control as core-guided modes would be. In addition, these gratings are not suitable for mode-conversion schemes, since a cladding-guided mode cannot be propagated for long distances (as would be needed, for example, in higher-order-mode dispersion-compensation schemes). Broadband spectra have also been realized by writing short conventional LPGs with very large index perturbations[4] ($\Delta n \sim 0.1$). This technique has yielded 20-dB bandwidths of up to 37 nm but suffers from polarization dependence, high insertion losses, and inherent instabilities typical of gratings with large index perturbations.

In this Letter we report the demonstration of UV-induced LPGs in specially designed few-mode fibers that offer highly efficient (>99%), polarization-independent mode coupling between two symmetric core-guided modes over what is believed to be the largest bandwidth (63 nm) reported to date. We achieve this by engineering a fiber waveguide with two guided modes that have identical group velocities in the spectral range of interest. We demonstrate that we can accurately control the bandwidth of such mode converters by tailoring the dispersion properties of the few-mode fiber itself.

The resonance condition for LPGs can be characterized by a phase-matching relationship given by

$$\delta(\lambda) = \frac{1}{2}\left[\frac{2\pi}{\Lambda} - \Delta\beta(\lambda)\right], \tag{1}$$

where δ is a detuning parameter, Λ is the grating period, and $\Delta\beta$ is the difference in propagation constants between the two modes. The spectral dependence of the resonant wavelength, λ_{res}, on the grating period, Λ, depends on the dispersive properties of the modes of the fiber:

$$\lambda_{\text{res}} = \Delta n \Lambda\,, \tag{2}$$

$$\frac{\mathrm{d}\Lambda}{\mathrm{d}\lambda_{\text{res}}} = \frac{\Delta n_g}{\Delta n^2}\,, \tag{3}$$

where Δn is the difference in the effective indices between the two modes and Δn_g is the corresponding difference in the group indices. For two well-guided modes of a fiber, the slope of the phase-matching curve [Eq. (3)] does not change sign, and the resonance wavelength varies monotonically with grating period [Eq. (2)]. In such cases the 20-dB bandwidth of a uniform grating of length L that offers 30-dB maximal coupling can easily be shown to be

$$\Delta\lambda = \frac{0.0955\,\lambda_{\text{res}}^{2}}{L\Delta n_g}\,. \tag{4}$$

For a conventional 1-cm-long LPG the 20-dB bandwidth is typically $\Delta\lambda \sim 1$ nm. Thus, although a LPG can be used to provide strong resonant mode coupling, its utility is limited to a very small wavelength range (a few nanometers) of operation.

In this Letter we consider a specially designed few-mode fiber in which the LP_{02} mode transitions from the high-index core to a lower-index cladding as the wavelength of operation is increased. When the LP_{02} mode and the fundamental mode (the LP_{01} mode) are well guided and reside predominantly in the core of the fiber, the ray picture for waveguides accurately predicts that group velocity $v_g(\text{LP}_{02}) < v_g(\text{LP}_{01})$. Since the LP_{02} mode travels at steeper bounce angles than the LP_{01} mode, it is expected to travel more slowly through the waveguide. Correspondingly, $n_g(\text{LP}_{02}) > n_g(\text{LP}_{01})$ and $\Delta n_g = n_g(\text{LP}_{01}) - n_g(\text{LP}_{02}) < 0$.

At longer wavelengths, when the LP_{02} mode begins to transition from the high-index core to the surrounding lower-index cladding, the mode picture is better suited to providing an intuitive understanding of the mode evolution. As the wavelength of operation is increased, the power fraction of the LP_{02} mode in the cladding increases, and its group velocity approaches that of the cladding (which is higher than that of the core, since it has a lower index of refraction than the core). Now, $n_g(\text{LP}_{02}) < n_g(\text{LP}_{01})$ and $\Delta n_g < 0$ [the LP_{01} mode continues to be well guided, and thus no significant change is expected for n_g (LP_{01})].

Thus, Δn_g changes sign, implying that the slope of the phase-matching relationship [Eq. (3)] changes polarity. The result is a turn-around point (TAP) in the phase-matching curve, as shown in Fig. 1(a). Inspection immediately reveals that large bandwidths are attainable if the grating period (shown by the dashed lines) is chosen to couple at the TAP.

The bandwidth of the grating can no longer be determined from Eq. (4) as $\Delta n_g = 0$. Expanding $\Delta\beta$ as a Taylor expansion [in Eq. (1)] and retaining the next higher-order term (the next higher-order term is the modal dispersion, $D \sim \mathrm{d}^2\beta/\mathrm{d}\lambda^2$), the 20-dB bandwidth of TAP gratings that offer 30-dB maximal coupling can be obtained:

$$\Delta\lambda = \frac{0.63\lambda_{\text{res}}}{(L\Delta Dc)^{1/2}}\,, \tag{5}$$

where ΔD is the difference in dispersion between the two modes and c is the velocity of light in vacuum.

Thus, engineering a fiber waveguide to have identical group velocities for two modes may yield a broadband grating if a LPG is written to couple at the TAP. In addition, controlling the differential dispersion between the two modes would allow shaping of the spectrum and control of the bandwidth of the LPG.

Several fibers that had similar dispersion values for the fundamental mode but different dispersion values for the LP_{02} mode were fabricated. Thus, several fibers with different ΔD [see Eq. (5) for definition] were obtained. The grating period for the LPGs written in the fibers was adjusted to yield a resonance at the TAP for each fiber.

Figure 1(b) shows the spectrum of light in the LP_{01} mode after the LP_{02} mode has been stripped out for a 1-cm-long LPG in a fiber with differential dispersion, $\Delta D \sim 130$ ps/nm km. The grating period for coupling at the TAP of this fiber is 120.2 μm—at this period the resonance of the phase-matching curve is satisfied at two distinct wavelengths because of the existence of a TAP, as shown in Fig. 1(a). The resultant spectrum yields more than 99% mode conversion over a record wavelength range of 63 nm. In comparison, a 20-dB strong resonance in a conventional LPG typically extends over ~1 nm. The insertion loss of this LPG is <0.2 dB. In addition, we may easily tune the wavelength range of such coupling by scaling the fiber dimensions, thus facilitating a mode converter that works in either the *C* or the *L* band. These characteristics make these LPGs very attractive as mode converters for higher-order-mode dispersion compensation.

As is evident from Eq. (5), designing fibers with different differential dispersion values (ΔD) would permit tuning of the bandwidth of the grating

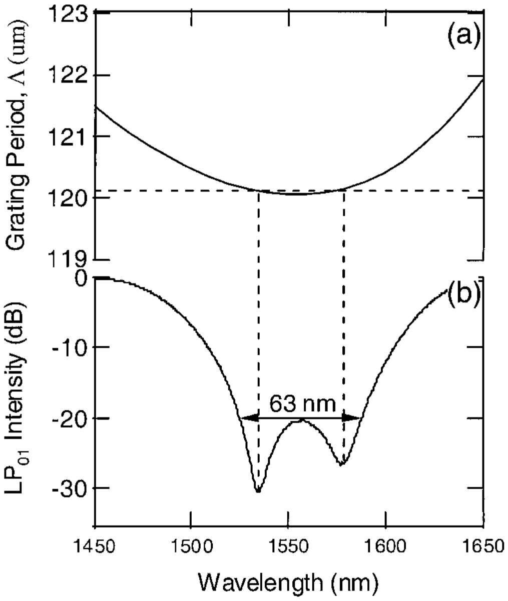

Fig. 1. (a) Simulation: Grating phase-matching curve in dispersion-tailored fibers. Large bandwidths are obtained at the TAP. (b) Experiment: Resultant TAP LPG spectrum. The peak coupling is >30 dB more than the 20-dB (99%) coupling over 63 nm. Grating period $\Lambda = 120.2$ μm, $\Delta n \sim 5 \times 10^{-4}$. The dashed lines indicate the grating period and show the correspondence between the phase-matching relationship and the grating spectrum obtained.

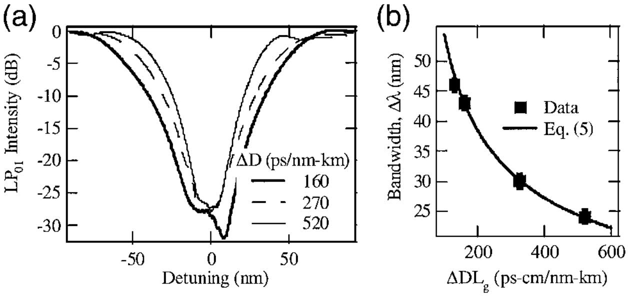

Fig. 2. Control of the LPG spectra by fiber design. (a) Experimental spectra show that the bandwidth increases as ΔD of the fiber decreases. (b) Grating bandwidth versus ΔDL_g, where L_g is the grating length. The experimental data show an excellent match with the theoretical predictions of Eq. (5).

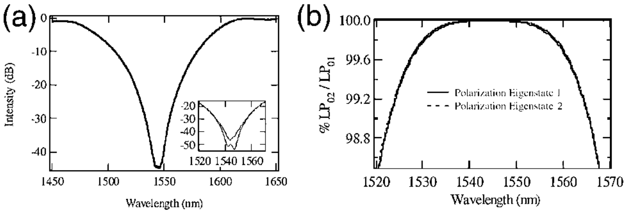

Fig. 3. Polarization dependence of TAP LPG. (a) Spectrum for a strong mode converter; the inset shows the polarization-dependent response of the residual fundamental mode. (b) Polarization response of the LP$_{02}$ mode, deduced from the data in (a). The spectra are barely distinguishable. The peak coupling changes by 0.0002 dB; the 20-dB bandwidth, by 0.2 nm.

resonance. Figure 2(a) is a comparison of the spectra of TAP LPGs written in fibers with ΔD values of approximately 160, 270, and 520 ps/(nm-km). As expected, fibers with larger differential dispersion show a narrower resonance. Note that the values quoted here are the differential dispersion values (i.e., $\Delta D = D_{01} - D_{02}$) and do not correspond to the dispersion of the LP$_{02}$ mode alone. In fact, TAP grating bandwidths are independent of the dispersive characteristics of individual modes and are a function only of the difference in dispersion values between the two modes.

Equation (5) indicates that the bandwidth of TAP gratings is inversely proportional to $(\Delta DL_g)^{1/2}$. Figure 2(b) shows the experimental and theoretical dependence of the grating bandwidth with respect to the parameter ΔDL_g, where L_g is the grating length. The expected theoretical behavior of the grating bandwidth is plotted as the solid curve in Fig. 2(b). The excellent match between the prediction and the data indicates that Eq. (5) accurately describes the behavior of LPG spectra in dispersion-tailored fibers. The data in Fig. 2 represent the first experimental demonstration of design flexibility in the bandwidths of broadband mode converters by engineering of the dispersion of fiber waveguides. In recent years the field of fiber waveguide design has evolved into a highly mature technology platform that can yield very accurate dispersion maps for transmission as well as dispersion-compensating fibers. Since the spectra of TAP LPG are critically controlled by the dispersion properties of fiber waveguides, this broadband mode-conversion technique allows for generating complex grating spectra simply by design of a fiber with suitable dispersion.

The applicability of a TAP LPG is practical only if it operates in a polarization-independent fashion. We tested the gratings for their polarization response by measuring the variation in output intensity of the LP$_{02}$ mode with respect to variations in the input polarization state. No measurable change was detected within the measurement accuracy of the external-cavity laser and photodetector that were used (measurement accuracy, ~0.02 dB). Significantly higher accuracy can be achieved by measurement of the amount of residual fundamental mode in the fiber after the LP$_{02}$ mode is stripped out—for a sufficiently strong LPG, a minuscule amount of the fundamental mode would remain, and small changes in the intensity if the fundamental mode would result in large variations on a log (dB) scale. Figure 3(a) shows the grating spectra for one of the strongest TAP LPGs fabricated; the peak coupling efficiency is ~45 dB, with a 40-dB bandwidth of 10 nm and a 20-dB bandwidth of 43 nm. We choose the strongest LPG that we wrote for this investigation, since it requires the largest Δn_{UV} and polarization dependence of gratings increases with Δn_{UV}. The inset of Fig. 3(a) shows the spectra of two orthogonal polarizations corresponding to the largest deviations in grating strength. Figure 3(b) shows the spectral response of the LP$_{02}$ mode calculated from the data in Fig. 3(a). The spectrum is shown on a linear scale because small deviations from unity are more visible. Even then, the two spectra are barely distinguishable. Variations in input polarization caused the coupling efficiency to range from 99.9960% to 99.9996%, corresponding to a negligible change for applications in optical communications systems. The 20-dB bandwidth also shows a negligible change of ~0.2 nm.

In summary, we have demonstrated LPG mode converters with strong (>99%) mode coupling over a record bandwidth of 63 nm. These gratings are polarization insensitive and have an insertion loss of less than 0.2 dB. The spectra and bandwidths of these gratings are directly related to the dispersive properties of the fiber itself, and we demonstrate that this relationship can be exploited to tailor LPG mode-conversion bandwidths accurately by design of few-mode fibers with special dispersive properties.

S. Ramachandran's e-mail address is sidr@bell-labs.com.

References

1. S. Ramachandran, B. Mikkelsen, L. C. Cowsar, M. F. Yan, G. Raybon, L. Boivin, M. Fishteyn, W. A. Reed, P. Wisk, D. Brownlow, R. G. Huff, and L. Gruner-Nielsen, IEEE Photon. Technol. Lett. **13,** 632 (2001).
2. C. D. Poole, J. M. Weisenfeld, D. J. DiGiovanni, and A. M. Vengsarkar, J. Lightwave Technol. **12,** 1746 (1994).
3. V. Grubsky and J. Feinberg, Opt. Lett. **25,** 203 (2000).
4. C. D. Poole, H. M. Presby, and J. M. Meetser, Electron. Lett. **30,** 1437 (1994).