Record Bandwidth, Spectrally Flat Coupling With Microbend Gratings in Dispersion-Tailored Fibers

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***Abstract*—-We demonstrate resonant grating couplers with the broadest bandwidth (565 nm) reported to date, using microbend gratings in dispersion-optimized few-mode fibers. Control of modal dispersion enables the demonstration of spectrally flat ($<$ 0.25-dB ripple) coupling. This enables a compact (1 cm), broad-band (110 nm) variable optical attenuator, which is highly cost-effective, since device assembly simply involves pressing an as-drawn fiber between two corrugated blocks.**

***Index Terms*—Attenuators, broad-band, gratings, microbend, optical fiber dispersion, optical phase matching, variable optical attenuator (VOA).**

I. Introduction

RESONANT couplers, such as microbend-induced long-period fiber gratings (LPGs) induce coupling between two copropagating modes in a fiber by phase-matching the relevant modes [1]. This is an attractive mode-coupling technique, since the coupling strength can be varied simply by changing the amplitude of the microbend perturbation[2]. While this process enables arbitrarily strong coupling, the resonant nature of coupling leads to strong spectral dependence—typically, strong ($\sim$10 dB) coupling occurs over a spectral range of 1–2 nm. Poole *et al.* first demonstrated that this coupling bandwidth can be substantially increased (20-dB coupling over 20 nm) by inducing coupling between two modes that have identical group velocities [3]. Recently, we demonstrated that the differential dispersion in few-mode fibers could be tailored to yield arbitrary control of the mode-conversion bandwidth [4]. While matching the group velocities of the modes lead to enhanced bandwidth, the spectra are still highly wavelength dependent, since phase is a wavelength-dependent quantity.

Recently, Li *et al.* demonstrated that the group velocity, as well as dispersion, could be matched for core to cladding mode coupling with microbend gratings to yield spectrally insensitive resonant couplers [5]. While spectra that are flat over 100 nm were demonstrated, the fabrication technique entails etching a single-mode fiber down to very small dimensions (diameter $\sim$30 μm) to achieve the desired dispersive properties for the coupled mode (a cladding guided mode, in this case). The cost-effective nature of such filters would be greatly enhanced, if phase matching to higher dispersive orders can be achieved in as-drawn fibers, eliminating the need for further processing.

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In this letter, we report the demonstration of microbend-induced LPGs in a specially designed few-mode fiber, with record 3-dB bandwidths of 565 nm. The coupling is spectrally flat over a bandwidth of 110 nm. This feature is utilized to demonstrate broad-band spectrally flat variable optical attenuators (VOAs), with continuous tunability from 0 to 10 dB, and a spectral tilt of $<$0.25 dB. This is enabled by a unique fiber design that allows simultaneously matching the phase, group delay, and dispersion, as well as the dispersion slope, of the LP_{01} and LP_{11} modes. This is the first demonstration, to the best of our knowledge, of dispersion engineering in fibers that enables phase matching over as many as three higher order dispersive terms. Since the fiber design involves dispersion engineering, which is a mature technology in the context of dispersion engineered transmission fibers, standard processing techniques yield a fiber that can be used for inducing microbend gratings, enabling highly cost-effective VOAs.

II. Device Principle

The spectral characteristics of LPGs that couple the LP_{01} and LP_{11} modes can be described by a detuning parameter δ

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

where λ is the operating wavelength, Λ is the grating period, and $\Delta\beta$ is the difference in propagation constants between the LP_{01} and LP_{11} modes. At resonance, $\delta = 0$, and maximum coupling is achieved. Away from resonance, the magnitude of coupling decreases as δ increases. Thus, the spectral characteristics of grating coupling are dependent on the spectral evolution of the parameter δ, which in turn depends on the spectral evolution of $\Delta\beta$. This dependence may be represented as a Taylor series about the resonance wavelength

$$\begin{aligned}\delta(\lambda) =& \frac{1}{2}\left(\Delta\beta'(\lambda)\Delta\lambda + \frac{\Delta\beta''(\lambda)}{2!}\Delta\lambda^2 + \frac{\Delta\beta'''(\lambda)}{3!}\Delta\lambda^3 + \cdots\right)\\ &\propto \left\{\Delta\tau(\lambda)\Delta\lambda + \Delta D(\lambda)\Delta\lambda + \Delta D'(\lambda)\Delta\lambda^3 + \cdots\right\}\end{aligned} \tag{2}$$

where the primes represent derivatives with respect to wavelength and $\Delta\lambda$ is the difference between the wavelength of interest and the resonant wavelength. These derivatives are related to physically relevant parameters: $\Delta\beta' \sim \Delta\tau$, the differential group delay, $\Delta\beta'' \sim \Delta D$, the differential dispersion, and $\Delta\beta'' \sim \Delta D'$, the differential dispersion slope. Thus, fibers designed with identical group delays, dispersions, and dispersion slopes for two modes are expected to exhibit broad-band wavelength-insensitive coupling.

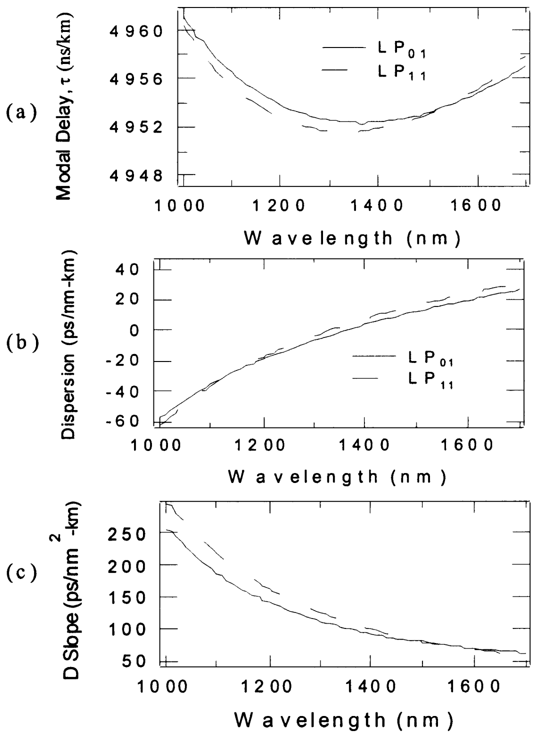

Fig. 1. Taylor terms (2) for LP_{01} and LP_{11} modes. (a) Group delay. (b) Dispersion. (c) Dispersion slope. Close match of curves enables broad-band spectrally flat response.

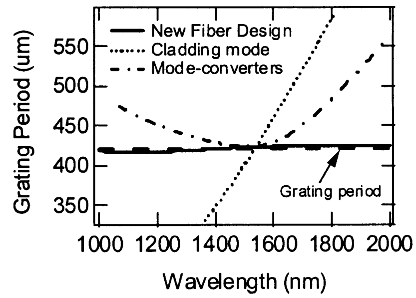

Fig. 2. Grating PMC for various fibers. PMC of new few-mode fiber design is almost invariant with wavelength. Implies phase matching is wavelength insensitive over a large spectral range.

III. Dispersive Fiber Characteristics

A few-mode fiber with a peak Δn of 2% was designed to yield identical values for the group velocity, dispersion, and dispersion slope, for the core-guided LP_{01} and LP_{11} modes. The fiber preform was fabricated by modified chemical vapor deposition, which is an established technique for realising complex waveguide structures. Fig. 1 shows the dispersive properties of the fabricated fiber. As expected, the LP_{01} and LP_{11} modes have identical group delays and dispersion slopes, and almost similar dispersions, in the 1500-nm range. The dispersion measurements on this fiber showed negligible departures from the design target.

The dispersive properties of the fiber can be used to determine the grating phase-matching curve (PMC), which is a plot of the grating period at the resonant condition [detuning $\delta = 0$, in (1)] as a function of wavelength. The PMC for this fiber is shown in Fig. 2. Also shown for comparison are the PMCs for a conventional LPG that couples the core mode with a cladding mode, and a dispersion tailored fiber for mode converters, in which the group velocities of the two modes match at a certain wavelength (for more details on this fiber, see [4]). In addition, Fig. 2 shows a horizontal dashed line representing the grating period used in this experiment.

The bandwidth or spectral characteristics of grating coupling can be determined by physical inspection of the PMCs in Fig. 2. In the case of an LPG coupling to a conventional cladding mode, the slope of the curve is steep and monotonic, which implies that the line represented by the grating period intersects the PMC at only one wavelength—this is the wavelength at which phase matching is obtained and strong coupling occurs. The detuning parameter δ rapidly diverges away from this wavelength for this case, leading to diminished coupling, and thus, a spectrally sharp resonance. In the case of the mode-converter fiber, the PMC has a minima and the line representing the grating period "intersects" the PMC over a larger wavelength range, leading to coupling over a large bandwidth. Nevertheless, the PMC still has strong wavelength dependence; likewise, the spectrum is also highly wavelength dependent. Finally, in the case of the fiber design reported here, the PMC is essentially flat throughout a spectral range spanning an octave. As is evident, the line representing the grating period is coincident with the PMC over the whole spectral range. Note that the PMC for this fiber is not strictly horizontal (as designed) but possesses a small amount of curvature due to small differences in the dispersive properties for the two modes. Nevertheless, the deviation is negligibly small, and thus, broad-band spectrally flat coupling should be expected. Spectrally flat coupling also requires that the coupling coefficients be spectrally insensitive. The calculated coupling coefficients (deduced from overlap integrals between the two mode fields) for this fiber varied by approximately $+/-1\%$ in the 1500–1600-nm spectral range, which results in a negligible ($+/-0.2$ dB) variation in the coupling strength of a 5-dB strong grating.

IV. Microbend Grating Spectra

Microbend-induced gratings were obtained by pressing the fiber between two corrugated aluminum blocks that were machined to yield the desired periodicity of corrugations. The grating period, as deduced from the PMC in Fig. 2, was 425 μm. Fig. 3 shows the spectrum of a 1-cm-long microbend grating induced in this fiber. Mode strippers were employed at the input and output of the grating to remove unwanted modal interference effects. The 3-dB spectral width is a record value of 565 nm, owing to the dispersive characteristics described in Section III. Note that strong spectral dependence is observed in the wavelength ranges where the PMC, shown in Fig. 2, has some curvature. However, since the dispersive parameters are especially well matched in the 1500-nm range, the coupling is also spectrally flat in that range. The flat spectral region extends over more than 100 nm, as is evident from Fig. 3. Coupling at the resonance requires control of the grating period to within 0.5 μm. While such a high level of accuracy is not feasible with machined corrugated blocks, tilting the fiber with respect to the grating block facilitates fine-tuning the grating period to

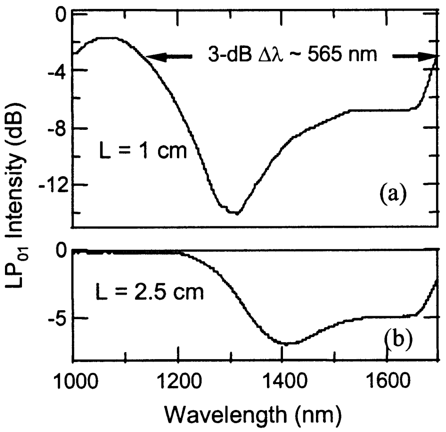

Fig. 3. Microbend grating spectrum in few-mode fiber. (a) Grating length = 1 cm. Record 3-dB bandwidth (565 nm) due to flat PMC shown in Fig. 2. Spectrally flat coupling in 1550-nm region, where dispersion parameters of fiber are identical (see Fig. 1). (b) Longer grating to measure full spectral shape: insertion loss ~ 0.2 dB.

achieve the broad-band resonance. The insertion loss for this grating, along with the mode strippers, was only 0.2 dB, as is expected of microbend gratings. A grating length of 2.5 cm was needed to measure the insertion loss, because some spectral features of the broad 1-cm grating resonance fell outside the measurement range (1000–1700 nm).

Savin *et al.* [2] demonstrated that changing the pressure of the corrugated blocks impressed upon a fiber, leads to a change in coupling strength. Varying the pressure applied on the few-mode fiber alters the grating strength without perturbing its spectral shape. Thus, the spectrally flat coupling in the 1500-nm range (shown in Fig. 3) is maintained for any grating strength. This characteristic yields a wavelength-insensitive VOA. Fig. 4(a) shows the spectral characteristics in the C-band, while Fig. 4(b) shows spectra over a 100-nm range approximately covering the C- and L-bands. In both cases, spectrally flat coupling is obtained as the grating strength is varied between 0 and 10 dB. Fig. 4(c) shows the spectral tilt (defined as the maximum attenuation variation across the spectral band, with respect to the value at the center of the band) for various attenuation levels.

Attenuation values greater than 10 dB were not achievable in this fiber, because of the inherent polarization sensitivity of microbend gratings. This is because the LP_{11} mode is a superposition of the TE_{01}, TM_{01}, and HE_{21} modes, and each mode has a slightly different PMC. This was confirmed by exciting the grating with polarized light sent through a polarization controller, and observing resonances as deep as 20 dB for specific polarization states which correspond to excitation of only one of the three modes existing in the triplet. However, helically induced microbends [6] or microbends on two orthogonal axes [2], as have been proposed to counteract polarization dependence of microbend gratings, may be implemented to yield strong polarization-insensitive VOAs.

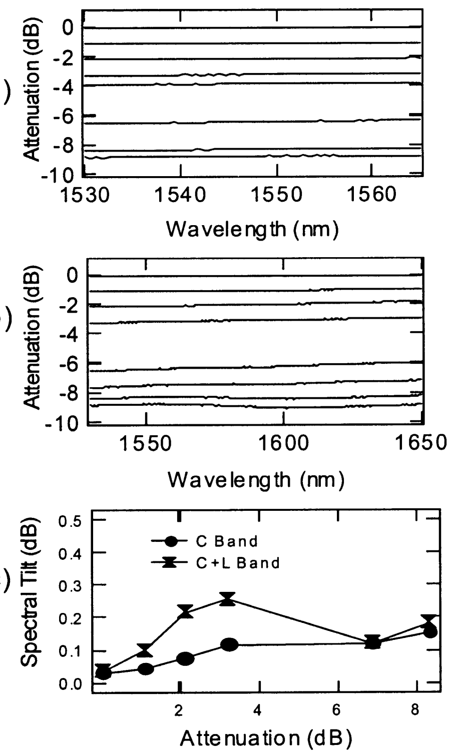

Fig. 4. VOA operation in flat spectral region. Continuous tuning from 0 to 10 dB. (a) C-band. (b) $C+L$-band (110 nm). (c) Spectral tilt versus attenuation.

V. Summary

We have demonstrated record bandwidth (565 nm) microbend gratings in a specially designed few-mode fiber. The unique design enables matching the phase, group velocity, and dispersion, as well as dispersion slope, of the LP_{01} and LP_{11} modes. This results in a wavelength-insensitive spectral response over 110 nm. The insertion loss is 0.2 dB, the length of the grating is 1 cm, and device assembly simply entails pressing the fiber with two corrugated blocks. Thus, a compact, low-loss, broad-band, and potentially cost-effective VOA is demonstrated.

References

[1] J. N. Blake, B. Y. Kim, and H. J. Shaw, "Fiber-optic modal coupler using periodic microbending," *Opt. Lett.*, vol. 11, pp. 177–179, 1986.

[2] S. Savin, M. J. F. Digonnet, G. S. Kino, and H. J. Shaw, "Tunable mechanically induced long period fiber gratings," *Opt. Lett.*, vol. 25, pp. 710–712, 2000.

[3] C. D. Poole, J. M. Weisenfeld, D. J. DiGiovanni, and A. M. Vengsarkar, "Optical fiber-based dispersion compensation using higher order modes near cutoff," *J. Lightwave Technol.*, vol. 12, pp. 1746–1758, Oct. 1994.

[4] S. Ramachandran, Z. Wang, and M. F. Yan, "Bandwidth control of long-period grating-based mode converters in few-mode fibers," *Opt. Lett.*, vol. 27, pp. 698–700, 2002.

[5] Q. Li, A. A. Au, C.-H. Lin, E. R. Lyons, and H. P. Lee, "An efficient all-fiber variable optical attenuator via acoustooptic mode coupling," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1563–1565, Nov. 2002.

[6] C. D. Pool, C. D. Townsend, and K. T. Nelson, "Helical-grating two-mode fiber spatial-mode coupler," *J. Lightwave Technol.*, vol. 9, pp. 598–604, May 1991.