Long-period fiber gratings based on periodic microbends

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We demonstrate a new type of high-performance long-period fiber grating based on arc-induced periodic microbends. The fabrication method is simple and does not require special fibers. Flexibility in controlling the filter parameters makes it possible to produce arbitrary filter profiles by use of a simple apodization technique, which is difficult to do with conventional long-period gratings. © 1999 Optical Society of America

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Long-period fiber gratings (LPFG's) are attractive fiber-optic devices for use as band-rejection filters with compactness, low insertion loss, and low backreflection.[1] These gratings are of particular interest as gain-flattening filters for erbium-doped fiber amplifiers[2] and as optical sensors for measuring the temperature or the refractive index of liquids.[3] One usually fabricates a LPFG by use of UV radiation to induce a periodic index change of the fiber core.[1] The periodic index grating couples the core mode to the dissipating cladding modes, and mode coupling takes place effectively only at resonant wavelengths at which the grating period matches the beat lengths of the coupling optical modes. Since the coupled cladding modes are rapidly attenuated by the fiber jacket, the LPFG has loss peaks at those resonant wavelengths.

Although the UV-based fabrication method is a well-established technology, it has problems. It requires complex and time-consuming processes, including hydrogen loading, UV writing, and annealing. The need for a large number of photomasks with various periods is also a practical problem. Another difficulty with UV-induced LPFG's lies in the control of filter parameters. The resonance wavelength of the filter depends not only on the grating period but also on the coupling strength or the index modulation amplitude of the grating, because the increment of average core index by UV radiation induces a change in the beat length of two coupled modes. Therefore one should carefully select the grating period, considering both the rejection wavelength and the efficiency of the grating to be produced. This fact makes it more difficult to implement the apodization technique for tailoring a filter profile. The nonuniform coupling strength induces position-dependent variation of the local resonance wavelength, which results in an unintentional chirping effect.

Recently several nonphotosensitive methods of LPFG fabrication have been reported. They used physical deformation of the fiber,[4,5] diffusion of the core dopant,[6] or core-index variation[7,8] produced by CO_2 lasers or electric arcs. The reported gratings, however, had poor optical performance compared with conventional UV gratings and still retained some of the above-mentioned problems.

In this Letter we propose and demonstrate a new type of LPFG based on periodic microbends induced by electric arcs. The fabrication method is very simple and can be applied to any type of optical fiber including conventional single-mode fibers. In the microbend-based grating the resonance wavelength is independently determined by the grating period and is not affected by the coupling strength. This feature permits easy control of filter parameters such as center wavelength, bandwidth, rejection efficiency, and the filter profile of the grating. Here we demonstrate LPFG's based on periodic microbends whose filter profiles can be controlled by simple apodization techniques. The utilization of the LPFG as a broadband $LP_{01}-LP_{11}$ mode converter in a two-mode fiber is also described.

The LPFG fabrication method is shown in Fig. 1. An unjacketed optical fiber is held straight by two fiber holders, separated by 5.5 cm, which limits the maximum grating length. One of the fiber holders is then displaced (by ~100 μm) in the direction orthogonal of the fiber axis so that a lateral stress is induced on the fiber between the two fiber holders. When a local section of the fiber is heated by application of an electric arc; the fiber is slightly deformed owing to the lateral stress, creating a microbend. The amplitude of the microbend is controlled by the duration of the arc and is typically less than 1 μm. Most of the originally applied lateral stress remains in the fiber. By translating the electrodes by the grating period and applying electric arcs, one can create successive microbends without additional displacement of the fiber holder. In this way a permanent microbend structure is inscribed in an optical fiber, as shown in Fig. 1(c). The entire writing process is automatically controlled by a computer while the transmission spectrum of the grating is monitored.

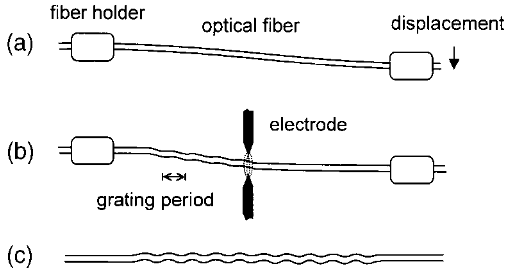


Fig. 1. Fabrication of a LPFG based on periodic microbends by use of an electric arc.

Three gratings were fabricated in standard telecommunication single-mode fibers (core diameter, 9.2 μm; $\lambda_{\mathrm{cutoff}} \simeq 1280$ nm) at the same period of 620 μm but with different amplitudes and numbers of microbends. Figure 2 shows the transmission spectra of the three gratings. The arc current was ~13 mA for all cases. Although the gratings had different rejection efficiencies and filter bandwidths, the resonance peaks coincided at the same wavelength. This result verifies that the resonance wavelengths are determined only by grating period and are not affected by grating amplitude or rejection efficiency. The background loss was less than 0.2 dB. The two notches, at the wavelengths 1389 and 1521 nm, correspond to coupling to cladding modes $\mathrm{LP}_{13}^{\mathrm{clad}}$ and $\mathrm{LP}_{14}^{\mathrm{clad}}$, respectively. Note that the microbend grating couples the LP_{01} core mode to antisymmetric cladding modes ($\mathrm{LP}_{1m}^{\mathrm{clad}}$ modes) because of the antisymmetric feature of the microbends, whereas conventional LPFG's couple to symmetric cladding modes ($\mathrm{LP}_{0m}^{\mathrm{clad}}$ modes).

The polarization and the temperature dependence of the grating were investigated. In principle, each antisymmetric cladding mode ($\mathrm{LP}_{1m}^{\mathrm{clad}}$ mode) is composed of four different almost-degenerate modes, and minute differences in their propagation constants cause the polarization dependence of the microbend-based grating. For two orthogonal polarization states of the input light, we observed 0.8- and 1.0-nm splitting in the resonance wavelengths of the $\mathrm{LP}_{13}^{\mathrm{clad}}$ and the $\mathrm{LP}_{14}^{\mathrm{clad}}$ mode coupling, respectively. Figure 3 shows the shift of the resonance wavelength (for the $\mathrm{LP}_{14}^{\mathrm{clad}}$ mode) versus temperature change. The slope of the wavelength shift was increased from 0.076 to 0.18 nm/°C as the temperature increased from 20 to 833 °C. The grating could withstand up to 800 °C without degradation of the filter characteristics. This high thermal stability is another advantage over the UV grating, which starts to be erased at a few hundred degrees Celsius.

The filter spectrum of a uniform grating is a sinc function, as is evident in Fig. 2, but filters with different profiles, such as a Gaussian profile or a specially fitted profile for gain equalization of an erbium-doped fiber amplifier, are often required. Here we demonstrate the flexibility of the filter profile control, using apodization. In the microbend-based grating, as mentioned above, apodization can be directly implemented without an unwanted chirping effect. In the first apodization experiment a Gaussian function was tried for the coupling coefficient, as shown in Fig. 4(a). The coupling coefficient is defined by the overlap integral of the core mode and the cladding mode ($\mathrm{LP}_{14}^{\mathrm{clad}}$ mode in this case) in one microbend.[9] The coupling amplitude was controlled by the duration of the arc, and the grating period was kept constant at 620 μm. Figure 4(b) shows the resultant filter spectrum of the apodized grating (solid curve) with that of the equivalent uniform grating (dashed–dotted curve) for comparison. The Gaussian-apodized grating has the expected Gaussian-shaped filter profile without spectral ripples, which are inherent in the uniform grating.

In the second experiment more-complex apodization was tried. The goal of the apodization was to produce a rectangular filter profile with a wide rejection band and a steep slope, which is useful in filtering out a specific band without losing the power in adjacent bands. The ideal apodization function required for this filter profile is a sinc function. However, because of the practical limitation of the grating length,

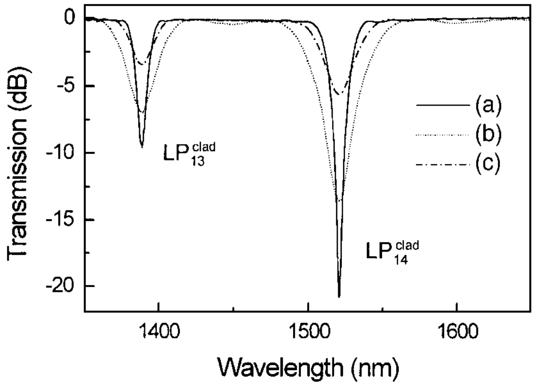


Fig. 2. Transmission spectra of three LPFG's with different amplitudes and numbers of microbends and the same period of 620 μm. 65, 24, and 40 microbends were produced at arc durations of (a) 1.0, (b) 1.7, and (c) 1.0 s, respectively. Optical resolution, 1 nm.

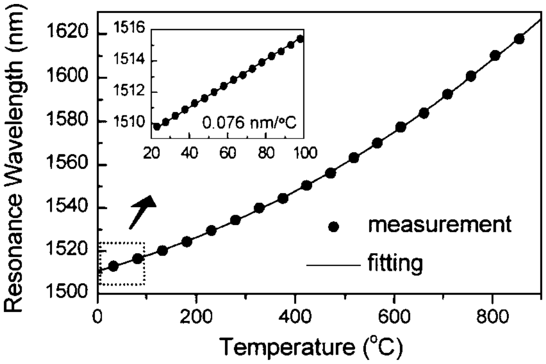
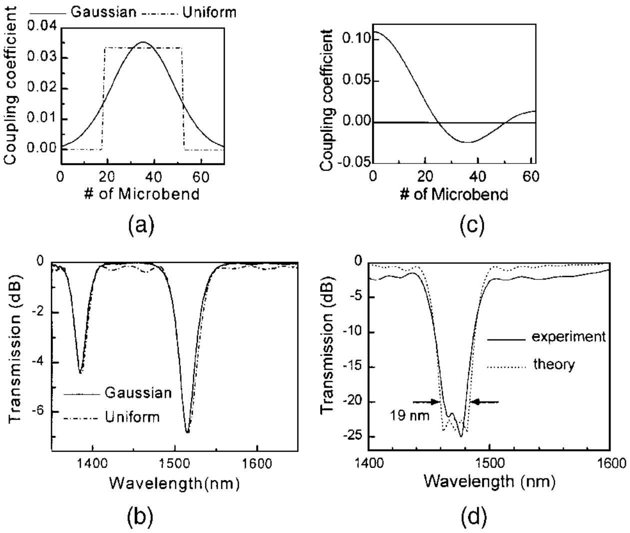


Fig. 3. Resonance wavelength shift of the grating with respect to temperature change.



(a) (c)

(b) (d)

Fig. 4. Profile-controlled LPFG's obtained by use of apodization techniques: (a) Coupling coefficient distribution of Gaussian-apodized, uniform gratings and (b) their experimental filter spectra. (c) Coupling coefficient distribution for a rectangular filter profile and (d) its experimental and theoretical filter spectra. Optical resolution, 1 nm.

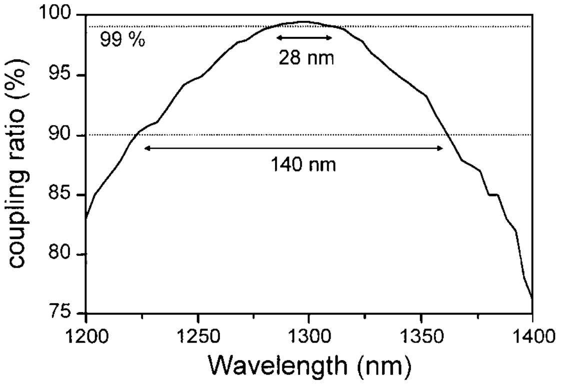


Fig. 5. $LP_{01}-LP_{11}$ mode coupling efficiency of a LPFG in a two-mode fiber.

a part of a half-sinc function was used, as shown in Fig. 4(c). The expected filter profile was calculated and is shown in Fig. 4(d) as dotted curve. The coupling amplitude was also controlled by the arc duration, and the sign changes at the 25th and the 50th microbends were realized by addition of a half-period to the grating period of 600 μm. The experimental filter spectrum is shown in Fig. 4(d) as a solid curve. The filter bandwidth at the -20-dB rejection level was 19 nm, whereas it cannot exceed a few nanometers in a uniform grating. The relatively high insertion loss of 2.5 dB was induced mainly in the front section of the grating, with a high grating amplitude, where the fiber is severely deformed. This loss can be avoided if we design a longer grating with a smaller grating amplitude. If the chirping technique were used simultaneously with apodization, it would be possible to produce more-complex filter profiles, which would be useful for gain equalization of erbium-doped fiber amplifiers.

Another important and unique utilization of the microbend-based LPFG is a $LP_{01}-LP_{11}$ mode converter[10] in a two-mode fiber, in which the LP_{01} core mode is coupled to the LP_{11} core mode in a two-mode fiber instead of the LP_{1m} cladding mode in a single-mode fiber. The mode converter is an essential component in optical devices and sensors based on two-mode fibers, and low insertion loss and high coupling efficiency over a wide spectral range are important. We used a Fujikura panda fiber, which supports two spatial modes near 1300 nm, for the two-mode fiber. The birefringence axis of the two-mode fiber was aligned so that the microbends were formed along the slow axis, and 13 microbends were fabricated at a period of 515 μm. We measured the coupling efficiency by measuring the uncoupled power remaining in the LP_{01} mode by selectively removing the LP_{11} mode with fiber bends after the mode converter. Figure 5 shows the conversion efficiency as a function of wavelength for an unpolarized light source. The maximum coupling efficiency was 99.4% at 1300 nm, with only 0.2 dB of insertion loss, and the bandwidth was 28 nm for >99% coupling and 140 nm for >90% coupling. The wideband coupling resulted from the high coupling strength of the grating and is also related to the mode properties of the two-mode fiber itself.

In conclusion, we have demonstrated a simple method of fabricating high-performance long-period fiber gratings based on arc-induced microbends. The grating has low insertion loss, high thermal strength, and flexibility in control of filter parameters and profiles. This technique can provide practical, low-cost all-fiber filters and (or) mode converters for optical fiber communication and sensor systems.

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References

1. A. M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, T. Erdogan, and J. E. Sipe, J. Lightwave Technol. **14,** 58 (1996).
2. A. M. Vengsarkar, J. R. Pedrazzani, J. B. Judkins, P. J. Lemaire, and N. S. Bergano, Opt. Lett. **21,** 336 (1996).
3. V. Bhatia and A. M. Vengsarkar, Opt. Lett. **21,** 692 (1996).
4. T. J. Cullen, N. E. Jolley, F. Davis, and J. Mun, in *Optical Amplifiers and Their Applications*, A. Willner, M. Zervas, and S. Sasaki, eds., Vol. 16 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1997), p. 231.
5. C. D. Poole, H. M. Presby, and J. P. Meester, Electron. Lett. **30,** 1437 (1994).
6. E. M. Dianov, V. I. Karpov, M. V. Grekov, K. M. Golant, S. A. Vasiliev, O. I. Medvedkov, and R. R. Khrapko, in *Digest of European Conference on Optical Communication* (Institute of Electrical Engineers, London, 1997), paper 2-56.
7. T. Enomoto, M. Shigehara, S. Ishikawa, T. Danzuka, and H. Kanamori, in *Optical Fiber Communication Conference*, Vol. 2 of 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998), paper ThG2.
8. S. G. Kosinski and A. M. Vengsarkar, in *Optical Fiber Communication Conference*, Vol. 2 of 1998 OSA Technical Digest Series (Optical Society of America, Washington, D. C., 1998), paper ThG3.
9. S. H. Yun, I. K. Hwang, and B. Y. Kim, Opt. Lett. **21,** 27 (1996).
10. J. N. Blake, B. Y. Kim, and H. J. Shaw, Opt. Lett. **11,** 177 (1986).