Anomalous bending effect in photonic crystal fibers

Haohua Tu, Zhi Jiang, Daniel. L. Marks, and Stephen A. Boppart*

Biophotonics Imaging Laboratory, Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
*Corresponding author: boppart@uiuc.edu

Abstract: An unexpected transmission loss up to 50% occurs to intense femtosecond pulses propagating along an endlessly single-mode photonic crystal fiber over a length of 1 m. A specific leaky-fiber mode gains amplification along the fiber at the expense of the fundamental fiber mode through stimulated four-wave mixing and Raman scattering, leading to this transmission loss. Bending near the fiber entrance dissipates the propagating seed of this leaky mode, preventing the leaky mode amplification and therefore enhancing the transmission of these pulses.

OCIS codes: (190.4370) Nonlinear optics, fibers; (060.5295) Photonic crystal fibers; (190.7110) Ultrafast nonlinear optics

References and links

1. A. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman & Hall, New York, 1983).
2. J. P. Koplow, D. A. V. Kliner, and L. Goldberg, "Single-mode operation of a coiled multimode fiber amplifier," Opt. Lett. **25**, 442-444 (2000), http://www.opticsinfobase.org/abstract.cfm?URI=ol-25-7-442
3. M. Nielsen, N. Mortensen, M. Albertsen, J. Folkenberg, A. Bjarklev, and D. Bonacinni, "Predicting macrobending loss for large-mode area photonic crystal fibers," Opt. Express **12**, 1775-1779 (2004).
4. J. C. Baggett, T. M. Monro, K. Furusawa, and D. J. Richardson, "Comparative study of large-mode holey and conventional fibers," Opt. Lett. **26**, 1045-1047 (2001), http://www.opticsinfobase.org/abstract.cfm?URI=ol-26-14-1045
5. G. Agrawal, *Nonlinear Fiber Optics* (Academic, San Diego, Calif., 2007), p. 27, p. 373.
6. N. Mortensen and J. Folkenberg, "Near-field to far-field transition of photonic crystal fibers: symmetries and interference phenomena," Opt. Express **10**, 475-481 (2002).
7. J. M. Dudley, L. Provino, N. Grossard, H. Maillotte, R. S. Windeler, B. J. Eggleton, and S. Coen, "Supercontinuum generation in air–silica microstructured fibers with nanosecond and femtosecond pulse pumping," J. Opt. Soc. Am. B **19**, 765-771 (2002), http://www.opticsinfobase.org/abstract.cfm?URI=josab-19-4-765.
8. D. A. Akimov, E. E. Serebryannikov, A. M. Zheltikov, M. Schmitt, R. Maksimenka, W. Kiefer, K. V. Dukel'skii, V. S. Shevandin, and Y. N. Kondrat'ev, "Efficient anti-Stokes generation through phase-matched four-wave mixing in higher-order modes of a microstructure fiber," Opt. Lett. **28**, 1948-1950 (2003), http://www.opticsinfobase.org/abstract.cfm?URI=ol-28-20-1948
9. S. O. Konorov, E. E. Serebryannikov, A. M. Zheltikov, P. Zhou, A. P. Tarasevitch, and D. von der Linde, "Generation of femtosecond anti-Stokes pulses through phase-matched parametric four-wave mixing in a photonic crystal fiber," Opt. Lett. **29**, 1545-1547 (2004), http://www.opticsinfobase.org/abstract.cfm?URI=ol-29-13-1545
10. R. H. Stolen, J. E. Bjorkholm, and A. Ashkin, "Phase-matched three-wave mixing in silica fiber optical waveguides," Appl. Phys. Lett. **24**, 308-310 (1974).
11. R. H. Stolen, "Phase-matched-stimulated four-photon mixing in silica-fiber waveguides," IEEE J. Quantum Electron. **11**, 100-103 (1975).
12. P. L. Baldeck and R. R. Alfano, "Intensity effects on the stimulated four photon spectra generated by picosecond pulses in optical fibers," J. Lightwave Technol. **5**, 1712-1715 (1984).
13. B. T. Kuhlmey, R. C. McPhedran, and C. Martijn de Sterke, "Modal cutoff in microstructured optical fibers," Opt. Lett. **27**, 1684-1686 (2002), http://www.opticsinfobase.org/abstract.cfm?URI=ol-27-19-1684
14. T. P. White, B. T. Kuhlmey, R. C. McPhedran, D. Maystre, G. Renversez, C. M. de Sterke, and L. C. Botten, "Multipole method for microstructured optical fibers. I. Formulation," J. Opt. Soc. Am. B **19**, 2322-2330 (2002), http://www.opticsinfobase.org/abstract.cfm?URI=josab-19-10-2322
15. B. T. Kuhlmey, T. P. White, G. Renversez, D. Maystre, L. C. Botten, C. M. de Sterke, and R. C. McPhedran, "Multipole method for microstructured optical fibers. II. Implementation and results," J. Opt. Soc. Am. B **19**, 2331-2340 (2002), http://www.opticsinfobase.org/abstract.cfm?URI=josab-19-10-2331

#92551 - $15.00 USD Received 7 Feb 2008; revised 2 Apr 2008; accepted 2 Apr 2008; published 7 Apr 2008

16. J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys. **78**, 1135-1184 (2006).

1. Introduction

It appears to be an empirical rule that bending is always associated with fiber transmission loss. This effect is well understood in multimode and single-mode conventional fibers [1] and has been employed in single-mode operation from a multimode fiber amplifier [2], permitting the construction of ultrahigh power fiber lasers. Bending loss has also been studied in photonic crystal fibers (PCFs) [3, 4], and is found to be comparable to that of the conventional fibers with similar mode area [4]. In this study, we find a departure from this rule in certain single-mode PCFs transmitting femtosecond pulses. This is caused by progressive nonlinear energy conversion from a fundamental (core) fiber mode to specific leaky-fiber mode so that localized bending can effectively enhance fiber transmission by interrupting this conversion. Since leaky (radiation) fiber modes have not been known to affect guided-mode nonlinear fiber-optic processes [5], the observed intermode conversion is in itself an interesting phenomenon and worth future investigation.

2. Experiment

The schematic of our fiber-optic experiment is shown in Fig. 1. The main laser source is a 250 kHz regenerative amplifier (Reg9000, Coherent, Santa Clara, CA) pulsed at 813 nm with ~25 nm FWHM bandwidth. The pulse width is controlled by the compressor of the laser to yield positively-chirped 210 fs pulses, as measured by an autocorrelator. The pulse energy (incident laser power) is varied by a neutral-density filter (NDF) within 0.08-0.28 μJ (20-70 mW). The alternative source is a Ti:sapphire oscillator with a tuning range of 690-1020 nm (Mai Tai HP, Spectra-Physics, Mountain View, CA), producing 80 MHz ~100 fs pulses with ~10 nm FWHM bandwidth. The pulse energy (incident laser power) is varied by the NDF within 0.25-5 nJ (20-400 mW). A 0.40-NA, 5.0-mm diameter aspheric lens (C110TME, Thorlabs, Newton, NJ) couples the ~1 mm diameter beam from either laser into an endlessly single-mode PCF (LMA-10, Crystal Fibre A/S, Denmark).

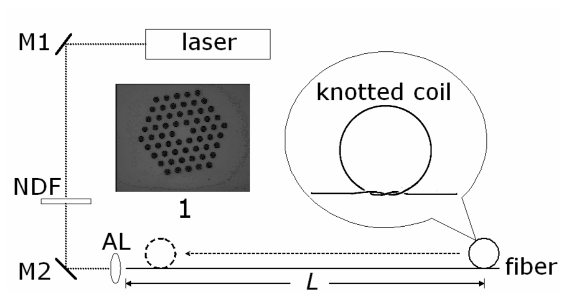

Fig. 1. Experimental setup: M1, M2, mirrors; NDF, neutral density filter; AL, aspheric lens; Insert 1, cross section image of LMA-10 fiber.

The PCF has a cross section shown in Fig. 1, a core diameter of 10±1 μm, a mode field diameter (635-980 nm) of 7.5±1 μm, an NA (at 780 nm) of 0.09±0.01, a zero dispersion wavelength of 1195±15 nm, and an attenuation (700-1000 nm) of <7 dB/km. The initial ~15 mm of the fiber is firmly mounted on a 3-axis fiber positioner, which maximizes the light coupling from free space to fiber. The coupling efficiency (CE) is measured from the ratio of the maximized power exiting the fiber to the incident laser power, and is equal to the launching efficiency of the fiber if the transmission loss in the short (<2 m) fiber length is neglected.

#92551 - $15.00 USD Received 7 Feb 2008; revised 2 Apr 2008; accepted 2 Apr 2008; published 7 Apr 2008

3. Results and discussions

The CE of the fiber is measured by the oscillator at 813 nm to be 55% (with ±3% variation from individual cleavages), independent of the incident power, fiber length (0.3-2 m), and fiber bending of a radius as small as 10 mm. Surprisingly, the same measurement on a 1.25-m fiber using the amplifier (70 mW) yields a CE value of 21-50% which depends sensitively on the spatial orientation of the fiber beyond the ~15 mm initial mounted section, termed as freely coiling section. Also, once the CE is maximized at any given spatial orientation, its value can be varied across the same range (i.e., 21-50%) by simply bending the freely coiling section (with a radius of >10 mm) without any optical realignment. The largest CE can only be attained by bending the fiber location immediately behind the ~15 mm mounted section. Since the largest CE approximates that obtained from the oscillator, the launching efficiency of the fiber is similar for the two laser sources. Thus, the smaller CE observed in the amplifier case must be associated with a nonlinear fiber transmission loss which is bend-sensitive and suppressible by the localized bending near the fiber entrance.

To avoid any bending effect, we keep the 1.25-m fiber lying straight on a flat surface in the direction parallel to the incident laser beam. In this case the CE is obtained at 45%, while the spatial far-field pattern of the light exiting the fiber observed from an infrared card has a circular center surrounded by six satellites, as diagrammed in Fig. 2(a). In contrast, once a small stress is applied to the fiber exit end without affecting the overall straight orientation of the fiber, the CE decreases to 21% while the far-field pattern shrinks into a hexagon shape with an area slightly smaller than that of the circular center [Fig. 2(a)]. Such stressed-state and relaxed-state can be switched back and forth by applying and removing the stress, accompanied by the corresponding switching of the CE and far-field pattern. The hexagon-shaped pattern can be attributed to the core mode of the PCF [6]. The reason the six weak satellite spots are not observed is due to the limited dynamic range of the infrared card. The same hexagon-shaped pattern is consistently observed from the fiber transmission experiments using the oscillator. The extreme sensitivity of the satellite far-field pattern to the stress suggests that it is associated with specific leaky fiber mode. If the fiber is kept straight except that a small bend (with a bend radius as large as 100 mm) is introduced at the fiber exit end, the same CE and far-field pattern results are obtained as in the case of the stressed fiber state. Such extraordinary bend sensitivity implies that the effective mode area of the leaky mode reaches hundreds of μm^2 [4], much larger than that of the core mode (~44 μm^2).

A running-coil experiment is conducted to examine the possible connection between the observed bending effect and the leaky mode. The 1.25-m fiber is kept straight except that a self-sustainable knotted coil of 12.7-mm radius is introduced at the fiber exit end (Fig. 1). Since the leaky mode can be sufficiently dissipated at a bend radius of 100 mm or larger, while the core mode does not encounter appreciable transmission loss at a bend radius of 10 mm or smaller, the coil radius of 12.7 mm allows independent measurement of the magnitudes of the leaky mode and the fundamental mode, as described below. This coil can be freely moved toward the fiber entrance by a finger without altering the overall fiber orientation and coil radius (Fig. 1). The dependence of the CE on the straight fiber length from the fiber entrance to the coil location (L) (Fig. 1) is measured at an incident amplifier power of 70 mW [Fig. 2(a)] or 20 mW [Fig. 2(b)]. In both cases, the CE attains a larger value at shorter L, and can be extrapolated to 51% (i.e., the launching efficiency) at L=0 (i.e., the fiber entrance). The far-field pattern of the exiting beam is always observed at the core mode while no above stress effect is observed from such a coil-bearing fiber. These results can be readily understood if the leaky mode is amplified along the fiber section in front of the coil at the expense of the core mode until it is completely dissipated by the coil, and the remaining core mode propagates along the fiber section behind the coil with no transmission loss or additional intermode conversion. Consistently, we obtain identical CE and far-field results from other coil-bearing fibers with or without the fiber section behind the coil, or with a straight or bended section behind the coil. The amplification can therefore be attributed to certain stimulated process associated with the leaky mode.

#92551 - $15.00 USD Received 7 Feb 2008; revised 2 Apr 2008; accepted 2 Apr 2008; published 7 Apr 2008

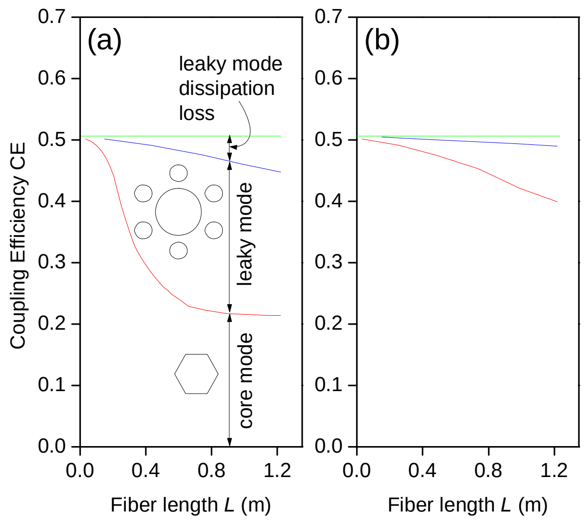

Fig. 2. Coupling efficiency (CE) of a 1.25-m LMA-10 fiber as a function of fiber length L measured from the running-coil experiment (red line) and the shortening-length experiment (blue line); the green line indicates CE vs. L relation of a straight or randomly oriented LMA-10 fiber coiled at the fiber entrance; (a) 70 mW incident amplifier power; (b) 20 mW incident amplifier power.

A shortening-length experiment is conducted to quantify the leaky mode amplification. The 1.25-m fiber is kept straight while the length of the fiber is shortened progressively by cleaving the fiber exit end. The dependence of the CE on the straight fiber length L is measured at an incident amplifier power of 70 mW [Fig. 2(a)] or 20 mW [Fig. 2(b)]. Similarly, the CE can be extrapolated to the launching efficiency at the fiber entrance, indicating that the leaky mode is not (significantly) excited by the incident laser. In the higher-power case, the CE increases slightly with deceasing L [Fig. 2(a)] while the far-field pattern of the exiting beam evolves from the shape of the leaky mode to that of the core mode. Thus, the power of the leaky mode accumulated over a given L can be estimated from the difference of the CE at this length from the shortening-length experiment and the running-coil experiment, while the corresponding power of the core mode is simply represented by the CE from the running-coil experiment [Fig. 2(a)]. It can be clearly seen that the majority of the core mode has been converted to the leaky mode after a straight fiber length of 1 m [Fig. 2(a)]. The CE from the shortening-length experiment (i.e., the total power of the two modes) decreases appreciably with increasing L (from 50% to 45% for L =1.25 m) due to the dissipation of the amplified leaky mode. This dissipation loss of >400 dB/km can be suppressed by coiling the fiber near its entrance, yielding an anomalous bending effect that enhances the fiber transmission [Fig. 2(a)]. Because the intermode energy conversion is a stimulated process, a randomly-oriented fiber produces the leaky mode less efficiently than the same fiber if it is straightened, while the fiber dissipates the leaky mode less efficiently than the straightened fiber if it ends with the coil. The overall effect is that the CE of the fiber along its length L falls within the range of the two CE vs. L curves from the running-coil and shortening-length experiments. As a result, we typically observe that the localized coiling at the fiber entrance increases the CE by a factor of two for the 1.25-m fiber. All the above discussion is applicable to the lower-power case except that all the effects are much smaller [Fig. 2(b)], confirming the nonlinear nature of these effects. The results of Fig. 2(a) and 2(b)

#92551 - $15.00 USD Received 7 Feb 2008; revised 2 Apr 2008; accepted 2 Apr 2008; published 7 Apr 2008

are highly reproducible among different experiments on the same fiber or experiments on other LMA-10 fibers.

To understand the stimulated process in the 1.25-m fiber during the running-coil experiment, we also measure the spectrum of the scattered leaky mode at L=1.20 m by a sensitive spectrometer (USB4000, Ocean Optics, Dunedin, FL) approaching the coil [Fig. 3(a), 3(b)]. The spectrum of the core mode is simultaneously measured by another spectrometer (USB2000, Ocean Optics, Dunedin, FL) approaching the fiber exit end [Fig. 3(c), 3(d)]. In the lower-power case, the spectrum of the scattered leaky mode has two dominant spectral features located symmetrically to the blue and the red of the center wavelength of the incident pulses [Fig. 3(b)]. Since the corresponding Stokes shift (210 cm^{-1}) is much smaller than the Raman shift (440 cm^{-1}), the stimulated process can be attributed to a phase-matched four-wave mixing (FWM) process. Efficient FWM generated in guided higher-order modes have been demonstrated in multimode microstructured silica fibers [7-9]. However, in such FWM the anti-Stokes and the Stokes pulses are generated in the same mode as the pump pulses so that no intermode energy conversion is encountered. The observed FWM bears closer resemblance to the early reports of the multimode FWM in conventional multimode fibers [10, 11]. The qualitative difference between the two is that the reported multimode FWM involves higher-order guided modes having a comparable mode area as that of the fundamental mode, while the observed FWM involves the leaky mode having a mode area much larger than that of the fundamental mode. The FWM gain of the medium overcomes the transmission loss of the leaky mode, allowing it to be amplified along the fiber.

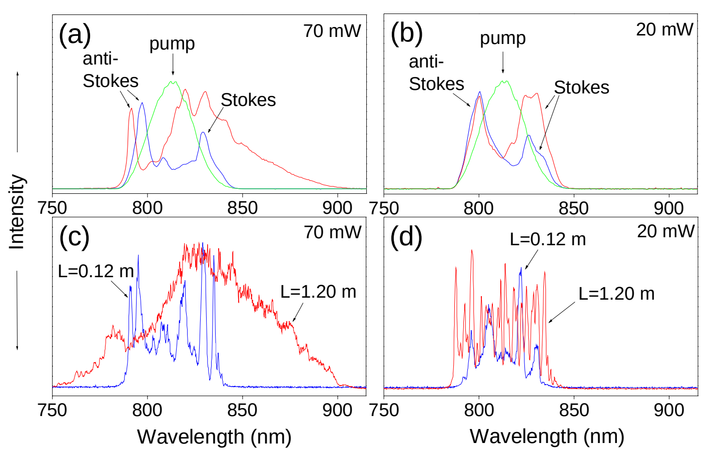

Fig. 3. (a). Spectrum of the incident amplifier pulses (green line); spectra of the leaky mode at L=1.20 m (red line) and L=0.12 m (blue line) at 70 mW incident amplifier power; (b) spectrum of the incident amplifier pulses (green line); spectra of the leaky mode at L=1.20 m (red line) and L=0.12 m (blue line) at 20 mW incident amplifier power; (c) spectra of the core mode at L=1.20 m (red line) and L=0.12 m (blue line) at 70 mW incident amplifier power; (d) spectra of the core mode at L=1.20 m (red line) and L=0.12 m (blue line) at 20 mW incident amplifier power.

In the higher-power case, the spectrum of the scattered leaky mode has a red-shifted broadened Stokes component and a blue-shifted anti-Stokes component in comparison to the lower-power case [Fig. 3(a)]. Because the spectrum of the core mode has asymmetrically red-shifted components not observable in the lower-power case [Figs. 3(c), 3(d)], stimulated Raman scattering (SRS) plays a significant role and interferes with the FWM. The red-shift of the Stokes component can be attributed to the SRS because the red edge of the FWM Stokes component falls within the Raman gain peak, while the corresponding spectral broadening is

#92551 - $15.00 USD Received 7 Feb 2008; revised 2 Apr 2008; accepted 2 Apr 2008; published 7 Apr 2008

likely due to the combined effect of self-phase modulation, cross-phase modulation and group velocity dispersion [12].

The spectra of the leaky mode and the core mode are similarly measured at L=0.12 m after the fiber is shortened. In this case, the spectrum of the leaky mode is similar in both the higher- and lower-power cases and resembles that in the lower-power case at L=1.20 m [Figs. 3(a), 3(b)], while the spectrum of the core mode in the higher-power case has no asymmetrically red-shifted components [Fig. 3(c)]. Thus, the FWM is responsible for early-stage leaky mode amplification regardless of the incident amplifier power. The infection point at L=0.25 m in the CE vs. L curve from the running-coil experiment [Fig. 2(a)] marks the transition of the intermode energy conversion from a FWM-dominated process to a SRS-dominated process. Invoking the SRS at this length further enhances the intermode conversion and magnifies the anomalous bending effect. The FWM dominates for short fibers because the FWM gain is typically larger than the Raman gain, while the SRS dominates for long fibers because it is difficult to maintain the phase matching of the FWM over long fiber lengths [5].

A numerical study has shown that the second mode of an endlessly single-mode PCF has a propagation constant β with a large imaginary part, i.e., a large transmission loss, which is linked to the cladding-filling state of the corresponding mode field [13]. This suggests that the observed leaky (cladding) mode is likely related to the often ignored higher-order modes of endlessly single-mode PCFs. With the development of the rigorous multipole method to calculate the modes of the PCFs [14, 15], it is possible to predict the phase-matching condition of the FWM according to the established techniques [9, 11] and explain the surprising FWM (or SRS) efficiency from the apparently small overlap integral between the core mode and the leaky (cladding) mode. Such theoretical analysis may be combined with the detailed experiments on both far-field and near-field patterns of the exiting beam to decipher the leaky mode (e.g., to answer whether the Stokes and the anti-Stokes components are generated in one leaky mode or in two different leaky modes). These topics will be investigated in the future. Here we simply point out that pumping the fiber at the zero dispersion wavelength of the leaky mode (i.e., in a normal dispersion region of the fundamental mode) may be necessary for the phase-matching [9]. Experimentally, the phase-matching is not uniquely satisfied in LMA-10 fiber because the same anomalous bending effect is also found in another similarly microstructured fiber (LMA-15, Crystal Fibre A/S, Denmark) having a larger core diameter of 15 μm. We speculate that such bending suppressible nonlinear transmission loss may be widely present in other supercontinuum (SC)-generating PCFs pumped in the normal dispersion region of the fundamental fiber mode, which have a coherence advantage over PCFs pumped in the corresponding anomalous dispersion region [16]. If such loss occurs, the localized bending near the fiber entrance provides an easy solution to enhance the fiber transmission and improve the SC generation.

4. Conclusions

We demonstrate that localized bending may enhance the transmission of femtosecond laser pulses in PCFs. This effect has been attributed to the FWM-assisted leaky mode amplification at the expense of the fundamental fiber mode. The finding invalidates the conventional wisdom that leaky fiber modes always suffer loss along the fiber and can always be ignored in understanding nonlinear fiber-optic effects. In fiber-optic SC applications, the transmission loss due to leaky mode amplification is undesirable and can be easily suppressed by the localized bending. On the other hand, the nature of the leaky mode and the phase-matching condition of the FWM are of theoretical importance. The surprisingly efficient energy exchange channel between the leaky fiber mode(s) and core fiber mode(s) may lead to useful applications such as new fiber-optic parametric amplifiers or oscillators.

Acknowledgments

This research was supported in part by the National Science Foundation (BES 03-47747, BES 05-19920, and BES 06-19257, S.A.B.) and the National Institutes of Health (Roadmap Initiative 1 R21 EB005321, and NIBIB 1 R01 EB005221, S.A.B.).