Adiabatic Coupling in Tapered Air–Silica Microstructured Optical Fiber

J. K. Chandalia, B. J. Eggleton, R. S. Windeler, S. G. Kosinski, X. Liu, and C. Xu

***Abstract*—We study adiabatic mode propagation in tapered air–silica microstructured optical fibers and demonstrate efficient coupling into a robust high-delta microstructured fiber. In the waist region of the taper, the core mode is tightly confined by the air holes and exhibits properties similar to a high-delta waveguide such as enhanced peak intensity and widely flattened anomalous dispersion. We exploit these properties to generate tunable self-frequency shifting Raman solitons over the communications window from 1.3 μm to 1.65 μm, with over 60% conversion efficiency. These fiber devices are practical for several reasons: they can be fusion spliced to standard single-mode fibers with relatively low loss, they are mechanically strong, due to the supporting cladding, and because the mode is isolated from the surrounding air interface, they can potentially be recoated allowing for packaging.**

***Index Terms*—Nonlinear optics, optical fiber devices, optical propagation, optical waveguide theory, raman scattering, waveguide couplers.**

I. INTRODUCTION

AIR–SILICA microstructured fibers (ASMFs) incorporate air holes within the cladding region that run along the length of the fiber [1]. Recently, there has been renewed interest in such fibers because the microstructured region provides extra degrees of freedom in manipulating mode propagation [2]. For example, these fibers allow for both the group velocity dispersion and the mode-field diameter to be controlled. This can be exploited in a range of different applications, including compensating chromatic dispersion [3], and allows for fiber designs with very small effective area for enhanced nonlinear interactions [4]. In particular, Ranka *et al.* [4] recently exploited the unique properties of an ASMF to generate an ultrabroad optical continuum and to demonstrate soliton propagation at near-visible wavelengths. These results were obtained by exploiting the high-peak intensity in the small silica core and the anomalous dispersion at near-visible wavelengths. Although these fibers have interesting and attractive properties, several practical difficulties exist. For example, many of these unique properties are found in microstructured fibers that have an extremely small core. Coupling light into such a fiber is difficult, and, although efforts of splicing ASMFs to conventional fibers have been reported [5], efficient coupling into sophisticated ASMFs in which the mode field diameter is strongly distorted by the air holes remains a challenge.

In this letter, we study mode propagation in tapered ASMFs. In particular, we demonstrate efficient coupling into a high-delta ASMF, which exhibits similar dispersion characteristics and enhanced peak intensity to those fibers reported in [4] but can be fusion spliced to standard single-mode fibers (SMFs) with relatively low loss. Furthermore, because of the supporting cladding region, the tapered ASMF is mechanically stronger and more robust than tapered conventional fibers that have demonstrated similar nonlinear effects [6], and also exhibits negligible sensitivity to external index, potentially allowing for packaging. We describe the new method of tapering ASMF fibers, and, as an example of the potential application of such a device, we present experimental results that demonstrate low-loss tunable Raman soliton formation.

II. DEVICE CHARACTERISTICS

Fig. 1 shows (a) a schematic of the tapered ASMF device; (b) a cross-sectional SEM picture of the tapered ASMF; and (c) a photograph of the untapered ASMF fiber. The ASMF fiber has an 8-μm germanium-doped core ($\Delta \sim 0.35\%$), an inner cladding region of approximately 40 μm, and an outside diameter of 132 μm (see [7] and [8] for more details). The fundamental mode of the untapered ASMF is well matched to standard SMF, ensuring low loss due to splicing (<0.1 dB).

The fiber is tapered by heating and stretching in a flame to reduce the outer diameter while maintaining the same cross-sectional profile. The flame temperature is chosen such that the fiber viscosity is low enough for the fiber to stretch without breaking but not so low that the air holes collapse, ensuring that the fiber cross section does not change throughout the taper. The ASMF can be tapered down to less than 10 μm in outer diameter with a waist length of 10–20 cm. Tapering of the ASMF is adiabatic so that the fundamental mode evolves into the fundamental mode of the central silica region, where it is confined by the ring of air holes. Because the mode is confined within the air ring, the total fiber diameter can be maintained at an acceptable level, which increases robustness and allows for packaging. In addition, the fundamental mode is guided in the germanium-doped core after adiabatic expansion, allowing for splicing to standard fibers.

We investigated mode propagation in the tapered ASMF using the beam propagation method (BPM) [7], [8]. Fig. 2(a) shows the structure we modeled with parameters used in the experiments described below. The outer diameter is tapered

---

Manuscript received September 5, 2000; revised October 27, 2000.

J. K. Chandalia, B. J. Eggleton, R. S. Windeler, and S. G. Kosinski are with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA (e-mail: egg@lucent.com).

X. Liu and C. Xu are with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733.

Publisher Item Identifier S 1041-1135(01)00483-9.

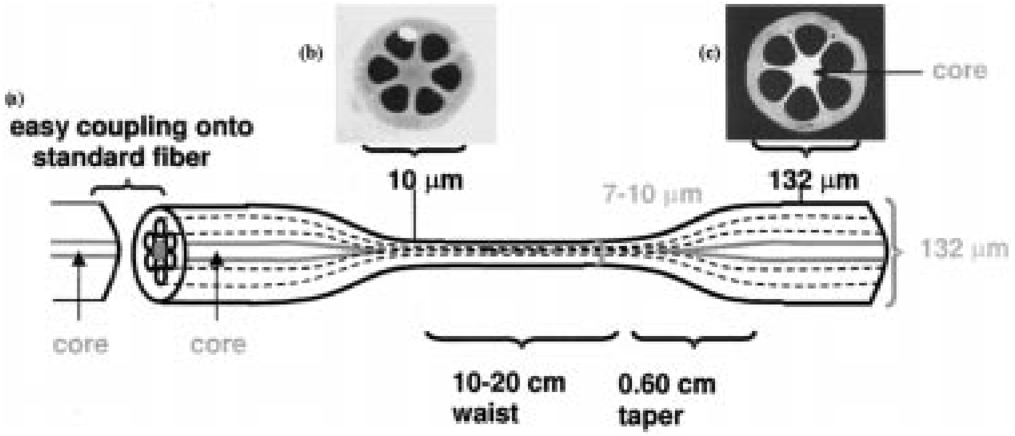

Fig. 1. (a) Schematic of the tapered ASMF fiber. (b) Cross section of the untapered ASMF fiber (outer diameter = 132 μm). (c) Cross section of tapered ASFM with an outer diameter of 10 μm.

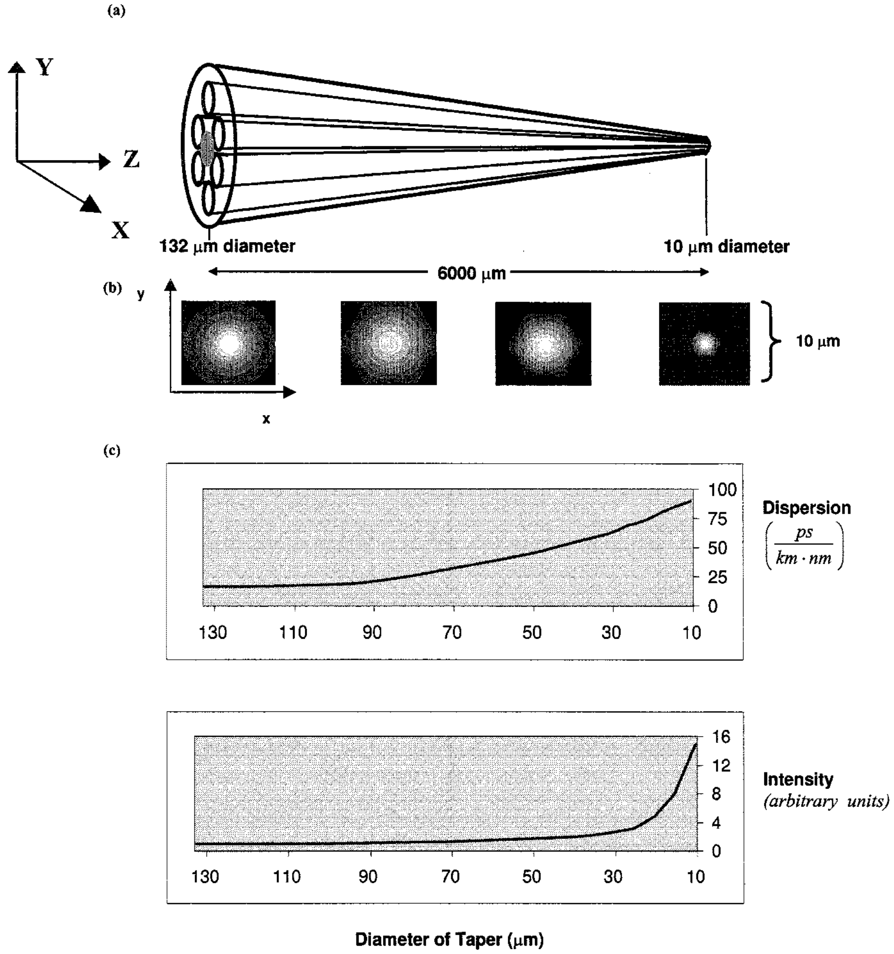

Fig. 2. (a) Schematic of the taper. (b) Calculated cross-sectional intensity plots at different points along the taper. (c) Dispersion and intensity along the taper calculated for propagation at a wavelength of approximately 1.5 μm.

"adiabatically" [9] from 132 μm down to 10 μm over a 6000-μm length; note that the cross section remains the same. Fig. 2(b) illustrates the evolution of the fundamental mode of the ASMF by showing the mode intensity at different distances along the taper. Fig. 2(c) shows the effect of decreasing mode size on intensity and dispersion. Initially, the dispersion is similar to that of standard fiber (~17 ps/nm/km at a nominal wavelength of 1.5 μm), but as the mode becomes confined by the air holes, the waveguide dispersion dominates and increases to ~100 ps/nm/km and becomes widely flattened with wavelength [10]; this is similar to the fibers described in [4], [6]. The decrease in mode diameter also leads to a significant increase in intensity, approximately 15–20 times the original intensity.

Fig. 3 shows the output of the tapered ASMF with parameters described above when light from a standard SMF, centered at a wavelength of 1.5 μm, is coupled into the fiber. Note that

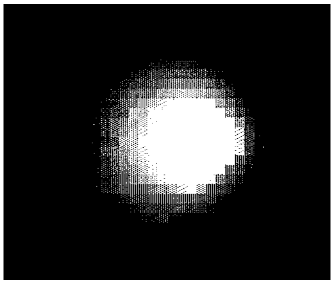

Fig. 3. Near-field output from tapered ASMF fiber with 1.5-μm launched light.

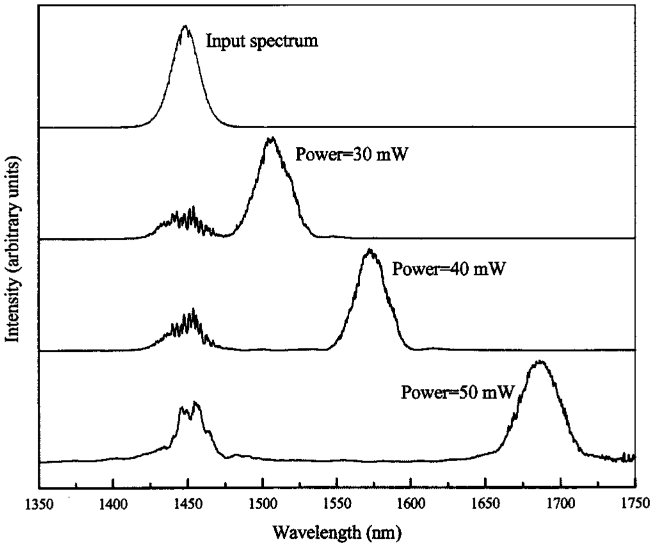

Fig. 4. Output spectra for different values of incident peak power.

the output at the end of the tapered fiber is still the fundamental mode, illustrating that the taper does not introduce coupling between modes. For the fundamental mode, the power loss due to the taper is less than 0.1 dB. In addition, we know that the light traveling through the taper is confined by the air holes because when we surround the tapered region by an index-matching fluid, the additional power loss through the index-matched taper is negligible. Recoating the fiber is feasible because the taper is robust and insensitive to the index outside the air holes.

III. NONLINEAR INTERACTIONS

Fig. 4 gives an example of the impressive nonlinear effects in the tapered ASMF; further details are reported in [10]. In this experiment, 1.3-μm laser pulses generated by a femtosecond Ti-sapphire pumped optical parametric oscillator were free-space coupled into the untapered portion of the ASMF and then propagated through the taper. The output spectra from the tapered ASMF measured at different incident peak powers is shown in Fig. 4. Tunable self-frequency shifting solitons were generated over the important communications windows from 1.3 μm to 1.65 μm with input pulse at 1.3 μm [10]. As the light propagates through the ASMF, the light is continually shifted toward the red due to intrapulse Raman scattering, which transfers the energy of the high-frequency part of the pulse spectrum to the low-frequency part [11]; we observe 60% of the input photons being self-frequency shifted. The soliton wavelength can be tuned from 1.2 to 1.8 μm by adjusting the input power. These dramatic results are possible because the fiber exhibits a large anomalous dispersion over a wide wavelength range, which ensures that the pulse is stable against modulational instability at high-peak intensities. These dramatic nonlinear effects confirm the adiabaticity and low loss of the taper.

IV. CONCLUSION

We have demonstrated adiabatic tapering of air–silica microstructured optical fibers. This method is easily executable and reproducible in a tapering station. The tapering station also allows for easy variation of taper parameters such as waist diameter and waist length. In particular, we have tapered a microstructured fiber with a germanium-doped core and inner-cladding region and fabricated samples that demonstrate nonlinear effects while being robust, insensitive to outer index, and easily coupled to standard fiber. The tapered ASMF provides a unique environment for realizing ultrafast nonlinear optical effects such as soliton self-frequency shift and pulse compression, and can be used for dispersion management for wavelengths shorter than the zero-dispersion point of conventional fibers. The combined degrees of freedom that are offered both by the microstructured cladding region, which controls the mode field distribution, and the taper, which controls mode contraction and expansion in the longitudinal direction, should open up other possibilities for designing novel waveguide devices and further exploiting the unique properties of ASMF.

REFERENCES

[1] P. Kaiser and H. W. Astle, “Low-loss single-material fibers made from pure fused silica,” *Bell Syst. Tech. J.*, vol. 53, pp. 1021–1039, 1974.

[2] T. A. Birks, J. C. Knight, and P. S. J. Russell, “Endlessly single-mode photonic crystal fiber,” *Opt. Lett.*, vol. 22, pp. 961–963, July 1, 1997.

[3] J. Broeng, D. Mogilevstev, S. E. Barkou, and A. Bjarklev, “Photonic crystal fibers: A new class of optical waveguides,” *Opt. Fiber Technol.*, vol. 5, pp. 305–330, July 1999.

[4] J. K. Ranka, R. S. Windeler, and A. J. Stentz, “Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm,” *Opt. Lett.*, vol. 25, pp. 25–27, Jan. 1, 2000.

[5] P. J. Bennett, T. M. Monro, and D. J. Richardson, “Toward practical holey fiber technology: fabrication, splicing, modeling, and characterization,” *Opt. Lett.*, vol. 24, pp. 1203–1205, Sept. 1, 1999.

[6] T. A. Birks, W. J. Wadsworth, and P. S. J. Russell, “Supercontinuum generation in tapered fibers,” *Opt. Lett.*, vol. 25, pp. 1415–1417, Oct. 1, 2000.

[7] B. J. Eggleton, P. S. Westbrook, C. A. White, C. Kerbage, R. S. Windeler, and G. Burdge, “Cladding mode resonances in air-silica microstructured optical fibers,” *J. Lightwave Technol.*, vol. 18, no. 8, pp. 1084–1100, 2000.

[8] C. Kerbage, B. J. Eggleton, P. S. Westbrook, and R. S. Windeler, “Experimental and scalar beam propagation analysis of an air-silica microstructured fiber,” *Opt. Express*, vol. 7, pp. 113–123, July 31, 2000.

[9] D. Marcuse, “Mode conversion in optical fibers with monotonically increasing core radius,” *J. Lightwave Technol.*, vol. LT-3, pp. 125–133, 1987.

[10] X. Liu, C. Xu, W. H. Knox, J. K. Chandalia, B. J. Eggleton, S. G. Kosinski, and R. S. Windeler, “Soliton self-frequency shift in a tapered air-silica microstructure fiber,” *Opt. Lett.*, 2000, to be published.

[11] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, CA: Academic, 1989.