Highly Nonlinear Bismuth-Oxide Fiber for Supercontinuum Generation and Femtosecond Pulse Compression

Juliet T. Gopinath, Hanfei M. Shen, Hideyuki Sotobayashi, *Senior Member, IEEE*, Erich P. Ippen, *Fellow, IEEE*, Tomoharu Hasegawa, *Associate Member, IEEE*, Tatsuo Nagashima, and Naoki Sugimoto

***Abstract*—Highly nonlinear normally dispersive bismuth-oxide fiber shows promise for applications such as supercontinuum generation and femtosecond pulse compression in the telecommunications-wavelength range. To generate a wideband and flat supercontinuum spectrum, the balance between fiber nonlinearity and normal group velocity dispersion (GVD) is important. Highly nonlinear bismuth-oxide fiber exhibits a large nonlinearity due to the small effective area and nonlinear index of the host glass material. The fiber also has a relatively flat dispersion profile over a large wavelength range. Utilizing these features, we generate a smooth unstructured supercontinuum between 1200 and 1800 nm. This supercontinuum is passed through a grating pair, and pulses, originally of 150-fs length, are compressed to 25 fs.**

***Index Terms*—Nonlinear fiber, nonlinear optics, pulse compression, ultrafast nonlinear optics.**

I. Introduction

RECENT advances in the development of novel fibers such as photonic crystal fibers [1], [2], microstructure fibers, [3] and other highly nonlinear solid-core fibers [4]–[7] have sparked renewed interest in fiber nonlinear optics. These fibers have high nonlinearities due to their small core and, in some cases, material composition [8], [9]. They also have unique dispersion profiles, enabled by the influence of waveguide dispersion balancing that of the material dispersion. These characteristics have allowed nonlinear experiments to be performed with much lower powers than previously possible. Applications include frequency metrology [10], medical imaging [11], spectroscopy [12], characterization of broadband devices such as photonic crystals [13], [14], and communications systems.

Broad spectra can be generated directly from mode-locked (pulsed) lasers [15], [16] or, alternatively, by seeding a nonlinear fiber with input pulses of high peak power [17]. A Cr:YAG laser operating at 1550 nm has produced 20-fs pulses and a spectrum with a 190-nm full-width-at-half-maximum bandwidth [18]. An optical parametric amplifier with stretcher/compressor has been used to generate 14.5-fs pulses at the same wavelength [19]. While these mode-locked lasers can produce extremely short pulses along with broad spectra, they also often require costly state-of-the-art components, expensive pumps, and are bulky. A less complex and more flexible alternative is supercontinuum generation and pulse compression using a highly nonlinear fiber such as bismuth-oxide fiber.

In this paper, we demonstrate wideband flat supercontinuum generation in a highly nonlinear bismuth-oxide fiber [5]–[7]. This fiber has a conventional step-index structure with a small solid core, but it exhibits many of the properties of photonic crystal and microstructure fibers. Its nonlinearity, $\sim 1100 \pm 15\% \ (\mathrm{W} \cdot \mathrm{km})^{-1}$, stemming from its small core size (1.7-μm diameter) and the high nonlinearity of the bismuth-oxide glass, is about two orders of magnitude larger than that of standard single-mode fiber. Supercontinuum spanning from 1200 to 1800 nm has been generated in a short 2-cm piece of this fiber with sub 0.5-nJ pulse energies. These pulses, with input durations of 150 fs, have been compressed at the output to 25 fs using a simple grating pair.

II. Design Theory of Supercontinuum Generation in Highly Nonlinear Fiber

The optimum technique for the production of supercontinuum depends upon the parameters of the laser source to be used and the needs of the application. In an optical fiber, supercontinuum generation falls into two main categories. The spectrum can be broadened in an anomalous-dispersion fiber, in which nonlinearity and group velocity dispersion (GVD) cause compression of the input pulse. Alternatively, supercontinuum can be generated in a normal-dispersion fiber. In the latter case, the pulse lengthens as it propagates, while self-phase modulation causes spectral broadening.

The anomalous-dispersion fiber generates the broadest spectra, but it is often structured and noisy due to pulse breakup, modulation instability, and other nonlinear effects [20]. The spectral variation and noise associated with supercontinuum spectra produced in this manner cause difficulty in some applications and make balanced detection a necessity [13]. On the other hand, smooth Gaussian-like spectra can be produced with the normal-dispersion fiber. Modulation instability cannot

Manuscript received November 15, 2004. This work was supported in part by Air Force Office of Scientific Research (AFOSR) and Office of Naval Research (ONR).

J. T. Gopinath, H. M. Shen, and E. P. Ippen are with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

H. Sotobayashi is with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA. He is also with the National Institute of Information and Communication Technology, Tokyo, Japan.

T. Hasegawa, T. Nagashima, and N. Sugimoto are with the Research Center, Asahi Glass Company, Kanagawa-ku, Yokohama-city, Kanagawa 221-8755, Japan.

Digital Object Identifier 10.1109/JLT.2005.855872

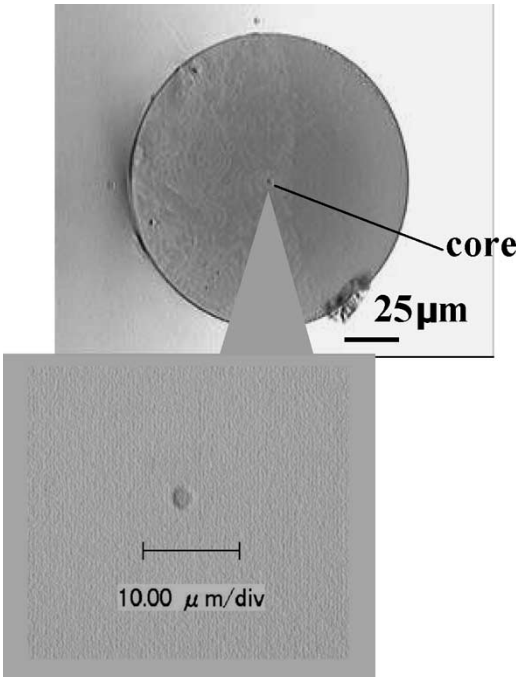


Fig. 1. Cross-section of highly nonlinear bismuth-oxide fiber.

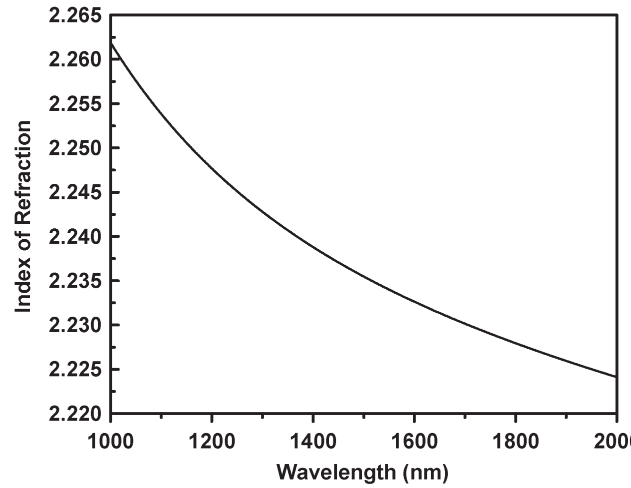


Fig. 2. Index of refraction versus wavelength for bismuth-oxide glass.

occur, and the pulse propagates as a single pulse with high coherence. Because normal dispersion acts to linearize the chirp produced by self-phase modulation, the accumulated chirp of a pulse propagating through the normal-dispersion fiber can be more easily compensated at the output. Thus, supercontinuum spectra produced in the normal-dispersion fiber are better suited for pulse compression. A bismuth-oxide-based glass fiber is a newly developed fiber with sufficiently high nonlinearity to permit stable supercontinuum generation at low powers under conditions of normal dispersion [5]–[7].

In a normal GVD fiber, supercontinuum generation can be described by the nonlinear Schroedinger equation. Second-order dispersion and the Kerr effect must be included. The ratio of $\sqrt{L_\mathrm{d}/L_\mathrm{nl}}$, where L_d is the dispersive length, and L_nl, the nonlinear length, governs the amount of spectral broadening achievable in a normal-dispersion fiber [21], [22]. The spectral broadening factor, which is defined as the ratio of the 3-dB bandwidth of the supercontinuum to that of the initial spectrum, is approximately proportional to $\sqrt{L_\mathrm{d}/L_\mathrm{nl}}$. The dispersive length can be written as $L_\mathrm{d} = \tau_o^2/\beta_\mathrm{av}$, where τ_o is the pulsewidth parameter, and β_av is the average second-order dispersion. The nonlinear length is defined as $L_\mathrm{nl} = 1/\gamma P_o$, where P_o is the peak power of the input excitation, and γ, the nonlinear coefficient. Thus, $\sqrt{L_\mathrm{d}/L_\mathrm{nl}}$ can be written as $\sqrt{(\tau_o^2 P_o \gamma)/\beta_\mathrm{av}}$. The nonlinear coefficient γ is defined as $\gamma = (2\pi n_2/\lambda A_\mathrm{eff})$, where n_2 is the material nonlinear refractive index coefficient, λ is the wavelength, and A_eff is the effective core area of the fiber. The spectral broadening factor can be improved by increasing the nonlinear index coefficient γ of the fiber and by using pulses with high peak powers. The nonlinear coefficient can be increased by the use of a material with high nonlinearity and a reduction in the effective core area of the fiber. GVD limits the maximum amount of spectral broadening possible. Therefore, the balance between the nonlinear coefficient and the GVD is important.

The bismuth-oxide fiber used in this experiment had a nonlinearity of $1100 \pm 15\%$ $(\mathrm{W} \cdot \mathrm{km})^{-1}$. This was caused by the highly nonlinear nature of the bismuth-oxide glass, approximately an order of magnitude larger than standard silica fiber, and the small effective core area of the fiber, 3.3 $\mu\mathrm{m}^2$. The core diameter of the fiber was 1.7 μm and was made feasible by the high-index contrast of the fiber. The refractive index of the core was 2.22, and that of the cladding, 2.13. The refractive index of the core is increased by doping it with In_2O_3. The fiber is single mode at 1550 nm and becomes multimode at 1400 nm. Fig. 1 shows a cross section of the fiber and Fig. 2 shows a plot of the refractive index of the bismuth-oxide glass as a function of wavelength. The material-dispersion relation for the core can be estimated using the Sellmeier equation [23]:

$$n = \sqrt{a + \frac{b\lambda^2}{\lambda^2 - c} + d\lambda^2}$$

with $a = 1.0, b = 3.93225, c = 0.04652,$ and $d = -0.00796.$

Fig. 3 shows a simulation of the fiber dispersion versus wavelength, with the material and waveguide components plotted separately. The dispersion of the fiber is calculated for the lowest order HE mode, assuming a step-index fiber with a core-cladding index difference of 0.09. The mode propagation constant is solved iteratively and the mode index and dispersion of the fiber [24] are calculated in turn. Thus, the dispersion of the waveguide balances that of the material, resulting in relatively flat total dispersion between 1200 and 1800 nm.

Fig. 4 shows the simulation results of supercontinuum generation. The fiber length is 2 cm. The input pulses are 150-fs-duration sech-shaped pulses with a center wavelength of 1540 nm and a peak power of 2.6 kW. These parameters correspond to the pulses used in the experiments described below. In this case, the dispersion length is 0.0258 m, and the nonlinear length is 3.9×10^{-4} m. The resulting 3-dB spectral width is 200 nm, which corresponds to a spectral broadening factor of 10. The spectral shape is smooth and flat and is suitable for pulse compression.

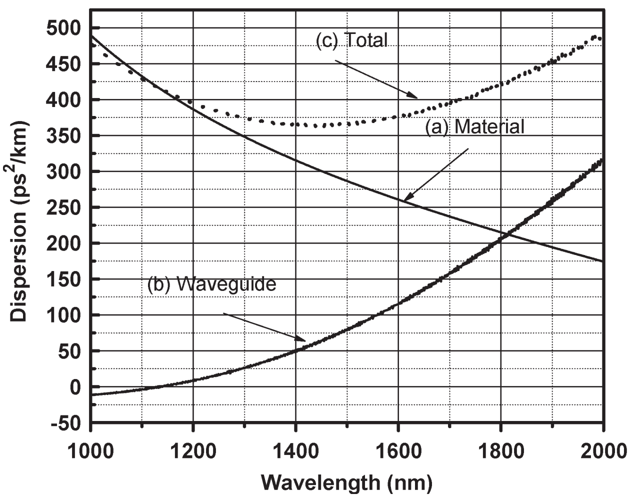


Fig. 3. Dispersion as function of wavelength for (a) bismuth-oxide glass (material), (b) waveguide, and (c) total dispersion of the fiber.

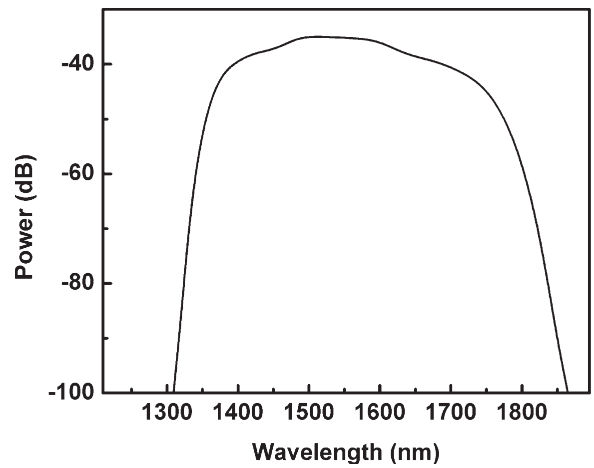


Fig. 4. Simulation results for supercontinuum generation in 2 cm of bismuth-oxide fiber with 2.6 kW of peak power incident at 1540 nm.

III. Experimental Results

A. Supercontinuum Generation in 2-cm Fiber

For the experiments discussed here, an optical parametric oscillator (OPO), synchronously pumped at 82 MHz by a Ti:Sapphire laser, is used as the signal source. We note, however, that similar pulse characteristics are now also available from more compact mode-locked fiber lasers. The OPO is tunable between 1400 and 1600 nm and produces 150-fs pulses. In Fig. 5(a), the experimental setup for supercontinuum generation is shown. The OPO pulses are passed through an isolator, and then spatially filtered with a 3-cm length of single-mode fiber. This 3-cm fiber does not chirp the pulses significantly due to its short length. An aspheric lens, with numerical aperture of 0.5, is then used to couple the pulses into a length of highly nonlinear bismuth-oxide fiber. The output is collimated with a reflecting objective, and sent to an optical spectrum analyzer, autocorrelator, or grating compressor. The reflecting objective had $\sim 30\%$ loss.

Spectra from a 2-cm length of fiber, embedded in two connected ceramic ferrules with a thin coating of wax and with polished ends, are shown in Fig. 6. The coupling loss was 6 dB, and the OPO input was centered at 1540 nm. Supercontinuum is produced from 1200 nm to > 1700 nm, with 32 mW of output average power, and a 3-dB width of 170 nm. (The optical spectrum analyzer had a ranged limited to < 1700 nm.) For an average power of 32 mW exiting the fiber, the pulsewidth was 865 fs; for a power of 21.4 mW, the pulsewidth was 759 fs; for a power of 14 mW, the pulsewidth was 724 fs, and for a power of 7 mW, the pulsewidth was 488 fs. The spectral widths and spectral shapes agree well with the simulation results. Insufficient attenuation of cladding modes causes the interference seen in the center of the spectra. Optical wave breaking is responsible for the shoulders apparent in the spectra. This effect occurs in regimes where the effects of self-phase modulation are much larger than that of GVD [25].

Fig. 7 shows typical spectra obtained for input wavelengths of 1450, 1500, and 1540 nm, with the 2-cm length of fiber. The power is kept constant for the three measurements. The spectra generated at the three different wavelengths are very similar, indicative of the relatively flat dispersion profile of the fiber shown in Fig. 3. A more complete evaluation of the long wavelength extent of the spectra was obtained by using a standard tunable spectrometer in addition to the OSA. As shown for the case of the 1540-nm input, the spectrum extends to about 1800 nm.

B. Femtosecond Pulse Compression

Pulse-compression experiments were performed for spectra generated with the 1540-nm input. A grating pair, providing -6400 fs^2 of dispersion, is shown in Fig. 5(b). Two gold 75-lines/mm gratings, separated by 8.5 cm, were used to compress the pulses. The compressor had 5 dB of loss, with 6 mW of average power exiting the grating pair. Fig. 5(c) shows a schematic of the broadband autocorrelator used to measure the compressed pulses. It consisted of two metallized beamsplitters, a speaker to dither the delay, a parabolic mirror to focus light onto a detector, and a GaAs light-emitting diode (LED) used as a two-photon-absorption detector. In order to estimate the pulsewidth, the PICASO phase-retrieval algorithm was used to fit the spectrum and autocorrelation [26]. The pulses were compressed to 25 fs. A typical autocorrelation is shown in Fig. 8. The time-bandwidth product of our compressed pulses, assuming a sech pulse envelope, was 0.49. Higher order chirp as well as the roll off in spectral efficiency of the gratings for wavelengths shorter than 1500 nm probably limits the compressed pulsewidth.

C. Supercontinuum Generation in a 1-m Length of Fiber

If only broad spectra are required for an application, and not short pulses, a longer length of the highly nonlinear bismuth-oxide fiber may offer some advantages. A 1-m length of highly nonlinear bismuth-oxide fiber, with ends prepared by a standard fiber cleaver, was used to produced the spectra shown in Fig. 9. In this case, we used an aspheric lens to collimate the output.

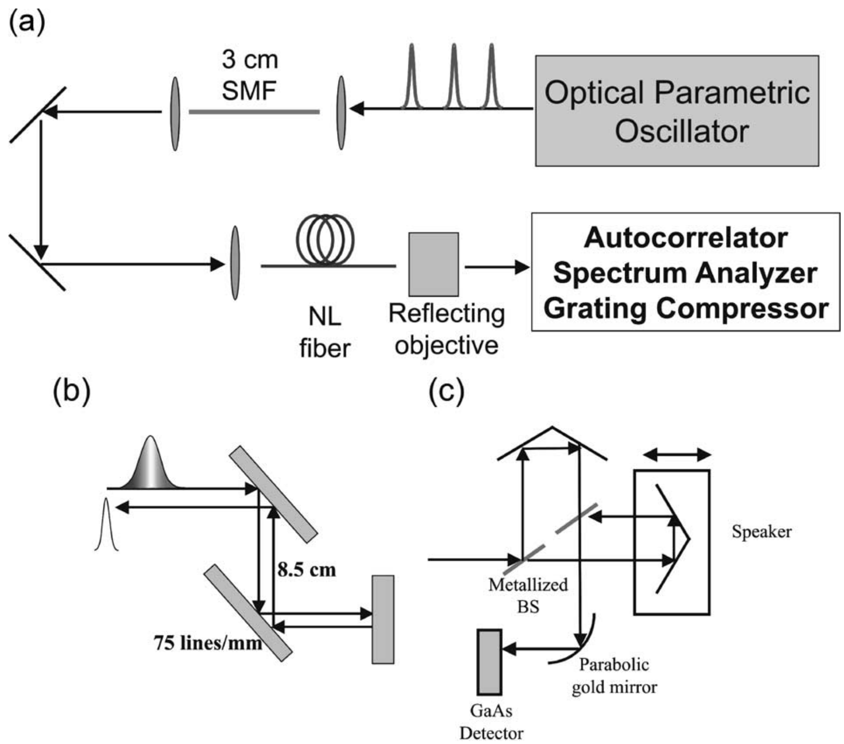


Fig. 5. Experimental setup for (a) supercontinuum generation in highly nonlinear bismuth-oxide fiber, (b) subsequent pulse compression using a grating pair, and (c) broadband autocorrelator.

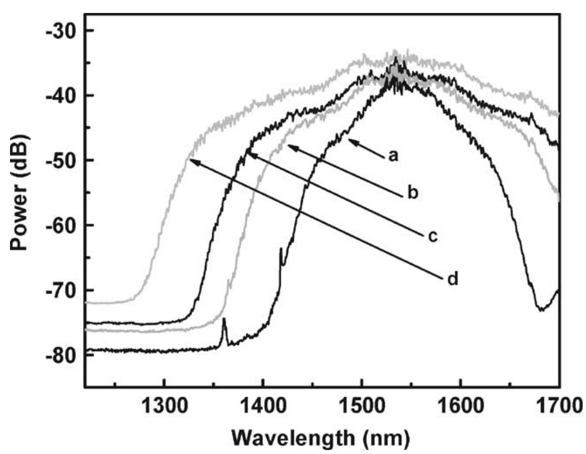


Fig. 6. Spectra as a function of input power produced in a 2-cm length of fiber at an input wavelength of 1540 nm. Average powers exiting the fiber were (a) 7 mW, (b) 14 mW, (c) 21.4 mW, and (d) 32 mW. Insufficient attenuation of cladding modes causes the interference apparent at the center of the spectra.

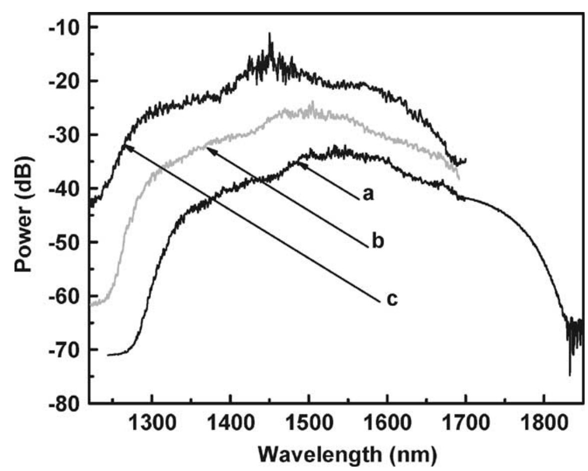


Fig. 7. Spectra as a function of input excitation wavelength from a 2-cm fiber at an average input power of 32 mW. Input wavelengths were (a) 1540 nm, (b) 1500 nm, and (c) 1450 nm. An optical spectrum analyzer was used for the spectra up to 1700 nm, and a spectrometer was used from 1700–1900 nm. The spectra are vertically offset for ease of viewing.

The input excitation was 1540 nm and the maximum average output power 34 mW. The spectrum generated from 1200 to $>$ 1700 nm is very similar to that produced in the 2-cm length. After 2 cm of highly nonlinear fiber, the pulse broadens to 800 fs, and the effect of self-phase modulation is greatly decreased. Nevertheless, some additional spectral shaping is evidenced by the reduction of the shoulders due to optical wavebreaking. Effective suppression of cladding modes is another advantage of the longer 1-m length of fiber. At the maximum output power, the output pulsewidth was estimated to be 80 ps, using an analytical expression for chirped pulse propagation derived from the nonlinear Schroedinger equation.

All the supercontinuum and pulse-compression experiments were performed with fiber with cleaved or polished ends. However, some applications may require connectorized and spliced nonlinear fiber. It is possible to splice the highly nonlinear bismuth-oxide fiber to a single-mode fiber, for ease of use. Currently, the splicing loss is around 1.76 dB/splice [6].

IV. Conclusion

Highly nonlinear bismuth-oxide fiber has been used to generate smooth unstructured spectra at telecommunications

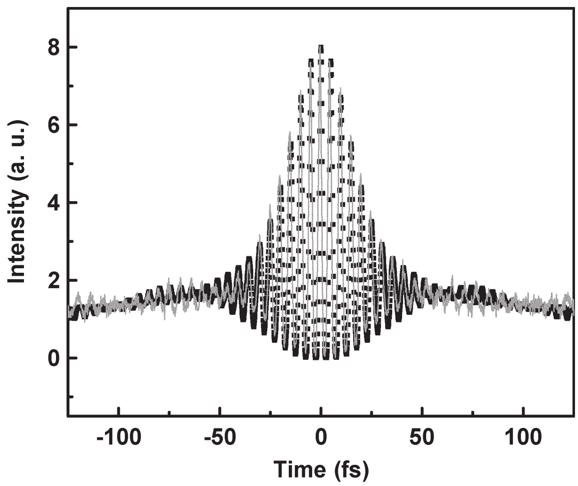


Fig. 8. Interferometric autocorrelation of compressed pulses produced with 2 cm of fiber and a grating compressor. The PICASO phase-retrieval algorithm was used to fit the data, and a pulsewidth of 25 fs is extracted. (Solid line: experimental result, black dots: retrieved autocorrelation).

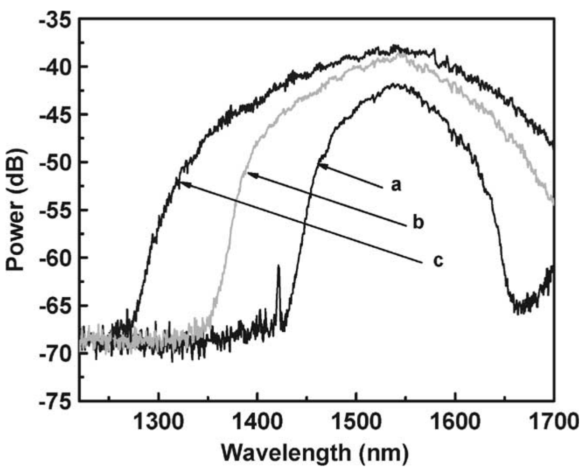


Fig. 9. Spectra as a function of input power produced in a 1-m length of fiber at an input wavelength of 1540 nm. Average input powers and pulse energies were (a) 10 mW/0.12 nJ, (b) 20 mW/0.24 nJ, and (c) 34 mW/0.41 nJ.

wavelengths in very short lengths. Pulses have also been compressed from 150 to 25 fs, using a 2-cm length of this fiber. Broad, somewhat smoother, Gaussian-like spectra suitable for applications such as medical optical coherence tomography, which do not require pulse compression, have been produced with a 1-m length of this fiber. These results show that highly nonlinear step-index bismuth-oxide fiber is a promising tool for applications requiring broad spectra and/or short pulses in the 1200–1800 nm wavelength regime. Potential applications include frequency metrology, spectroscopy, communications, characterization of broadband devices, and medical imaging techniques such as optical coherence tomography.

ACKNOWLEDGMENT

The authors gratefully acknowledge valuable advice and technical contributions from P. T. Rakich, J. W. Sickler, K. Taira, F. O. Ilday (Massachusetts Institute of Technology), T. E. Murphy (University of Maryland, College Park), F. Koizumi (Asahi Glass Company), and K. S. Abedin (National Institute of Information and Communications Technology).

REFERENCES

[1] J. C. Knight, J. Arriaga, T. A. Birks, A. Blanch-Ortigosa, W. J. Wadsworth, and P. S. J. Russell, "Anomalous dispersion in photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 12, no. 7, pp. 807–809, Jul. 2000.

[2] H. Ebendorff-Heidepriem, P. Petropoulos, S. Asimakis, V. Finazzi, R. C. Moore, K. Frampton, F. Koizumi, D. J. Richardson, and T. M. Monro, "Bismuth glass holey fibers with high nonlinearity," *Opt. Express*, vol. 12, no. 21, pp. 5082–5087, Oct. 2004.

[3] J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Optical properties of high-delta air-silica microstructure optical fibers," *Opt. Lett.*, vol. 25, no. 11, pp. 796–798, Jun. 2000.

[4] R. E. Slusher, G. Lenz, J. Hodelin, J. Sanghera, L. B. Shaw, and I. D. Aggarwal, "Large Raman gain and nonlinear phase shifts in high-purity As_2Se_3 chalcogenide fibers," *J. Opt. Soc. Amer. B*, vol. 21, no. 6, pp. 1146–1155, Jun. 2004.

[5] K. Kikuchi, K. Taira, and N. Sugimoto, "Highly nonlinear bismuth oxide-based glass fibres for all-optical signal processing," *Electron. Lett.*, vol. 38, no. 4, pp. 156–157, Feb. 2002.

[6] N. Sugimoto, T. Nagashima, T. Hasegawa, S. Ohara, K. Taira, and K. Kikuchi, "Bismuth-based optical fiber with nonlinear coefficient of 1360 $W^{-1}km^{-1}$," presented at the Optical Fiber Communication Conf. Postdeadline, Los Angeles, CA, 2004, PDP26.

[7] J. T. Gopinath, H. M. Shen, H. Sotobayashi, and E. P. Ippen, "Smooth supercontinuum generation with highly nonlinear bismuth-oxide fiber," presented at the Lasers and Electro-Optic Society (LEOS) Annu. Meeting, Rio Grande, Puerto Rico, Oct. 2004, WD2.

[8] G. Lenz, J. Zimmerman, T. Katsufuji, M. E. Lines, H. Y. Hwang, S. Spälter, R. E. Slusher, S. W. Cheong, J. S. Sanghera, and I. D. Aggarwal, "Large kerr effect in bulk Se-based chalcogenide glasses," *Opt. Lett.*, vol. 25, no. 4, pp. 254–257, Feb. 2000.

[9] J. M. Harbold, F. O. Ilday, F. W. Wise, and B. G. Aitken, "Highly non-linear Ge-As-Se and Ge-As-S-Se glasses for all-optical switching," *IEEE Photon. Technol. Lett.*, vol. 14, no. 6, pp. 822–824, Jun. 2002.

[10] B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jorgenson, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared," *Opt. Lett.*, vol. 29, no. 3, pp. 250–252, Feb. 2004.

[11] W. Drexler, U. Morgner, F. X. Kaertner, C. Pitris, S. A. Boppart, X. D. Li, E. P. Ippen, and J. G. Fujimoto, "In vivo ultrahigh-resolution optical coherence tomography," *Opt. Lett.*, vol. 24, no. 17, pp. 1221–1223, Sep. 1999.

[12] J. Shah, "Ultrafast spectroscopy of semiconductors and semiconductor nanostructures," in *Springer Series in Solid-State Sciences*, vol. 115. New York: Springer, 1999.

[13] P. T. Rakich, J. T. Gopinath, H. Sotobayashi, C. W. Wong, S. G. Johnson, J. D. Joannopoulos, and E. P. Ippen, "Broadband supercontinuum-based measurements of high-index contrast photonic bandgap devices from 1 to 2 μm," presented at the *Proc. Lasers and Electro-Optic Society (LEOS) Annu. Meeting*, Rio Grande, Puerto Rico, Oct. 2004, Th13.

[14] R. T. Neal, M. D. C. Charlton, G. J. Parker, C. E. Finlayson, M. C. Netti, and J. J. Baumberg, "Ultrabroadband transmission measurements on waveguides of silicon-rich silicon dioxide," *Appl. Phys. Lett.*, vol. 83, no. 22, pp. 4598–4600, Dec. 2003.

[15] R. Ell, U. Morgner, F. X. Kaertner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, and B. Luther-Davies, "Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser," *Opt. Lett.*, vol. 26, no. 6, pp. 373–375, Mar. 2001.

[16] D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, and T. Tschudi, "Semiconductor saturable-absorber mirror-assisted kerr-lens modelocked Ti:sapphire laser producing pulses in the two-cycle regime," *Opt. Lett.*, vol. 24, no. 9, pp. 631–633, May 1999.

[17] J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum," *Opt. Lett.*, vol. 28, no. 8, pp. 643–645, Apr. 2003.

[18] D. J. Ripin, C. Chudoba, J. T. Gopinath, J. G. Fujimoto, E. P. Ippen, U. Morgner, F. X. Kaertner, V. Scheuer, G. Angelow, and T. Tschudi,

"Generation of 20-fs pulses by a prismless Cr^{4+}:YAG laser," *Opt. Lett.*, vol. 27, no. 1, pp. 61–63, Jan. 2002.
[19] M. Nisoli, S. Stagira, S. De Silvestri, O. Svelto, G. Valiulis, and A. Varanavicius, "Parametric generation of high-energy 14.5-fs light pulses at 1.5 μm," *Opt. Lett.*, vol. 23, no. 8, pp. 630–632, Apr. 1998.
[20] K. L. Corwin, N. R. Newbury, J. M. Dudley, S. Coen, S. A. Diddams, B. R. Washburn, K. Weber, and R. S. Windeler, "Fundamental amplitude noise limitations to supercontinuum spectra generated in a microstructured fiber," *Appl. Phys. B*, vol. B77, no. 2–3, pp. 269–277, Sep. 2003.
[21] S. Taccheo and L. Boivin, "Investigation and design rules of supercontinuum sources for WDM applications," presented at the Optical Fiber Communication Conf., Baltimore, MD, 2000, ThA1.
[22] W. J. Tomlinson, R. H. Stolen, and C. V. Shank, "Compression of optical pulses chirped by self-phase modulation in fibers," *J. Opt. Soc. Amer. B*, vol. 1, no. 2, pp. 139–149, Apr. 1984.
[23] E. Hecht, *Optics*. Reading, MA: Addison-Wesley, 2002.
[24] A. Yariv, *Optical Electronics in Modern Communications*. New York: Oxford Univ. Press, 1997.
[25] G. P. Agrawal, *Nonlinear Fiber Optics*. New York: Academic, 1995.
[26] W. Nicholson, J. Jasapara, W. Rudolph, F. G. Omenetto, and A. J. Taylor, "Full-field characterization of femtosecond pulses by spectrum and cross-correlation measurements," *Opt. Lett.*, vol. 24, no. 23, pp. 1774–1776, Dec. 1999.

Juliet T. Gopinath received the B.S. degree in electrical engineering in 1998 from the University of Minnesota, Twin Cities. In 2000, she received the S.M. degree in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT), Cambridge. She was awarded the Ph.D. degree in electrical engineering and computer science from MIT in June 2005.

Her research interests include ultrafast solid-state and fiber lasers, semiconductor saturable absorbers, semiconductor optical amplifiers, and nonlinear processes in fibers.

Ms. Gopinath is the recipient of the National Science Foundation Graduate Fellowship (1998–2001) and the LEOS Graduate Student Fellowship (2003). She is a member of Optical Society of America (OSA) and IEEE Lasers & Electro-Optics Society (LEOS).

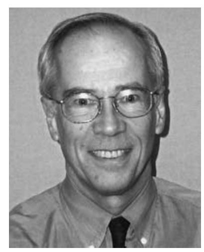
Hanfei M. Shen was born in Shanghai, China, in 1979. He received the B.S.E. degree in nuclear engineering and radiological sciences from the University of Michigan, Ann Arbor, in 2000 and the S.M. degree in electrical engineering and computer science at the Massachusetts Institute of Technology (MIT), Cambridge, in 2002. He is currently working towards the Ph.D. degree at MIT.

His research interests include ultrashort pulse generation and ultrafast phenomena in the near infrared.

Hideyuki Sotobayashi (M'98–SM'04) received the B.E. degree in electronic engineering in 1992 and the M.E. and Dr.Eng. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1994 and 1997, respectively.

In 1997, he joined Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications (MPT), Tokyo. CRL was reorganized as National Institute of Information and Communications Technology (NICT) in 2004. Since 2002, he has been a Visiting Scientist at the Massachusetts Institute of Technology (MIT), Cambridge. His research interests include photonic networks, optical communications, photonic processing, and nonlinear optics.

Dr. Sotobayashi is a member of the Optical Society of America (OSA), the Institute of Electronics and Information Communication Engineers of Japan (IEICE), and the Japan Society of Applied Physics (JSAP).



Erich P. Ippen (S'66–M'69–SM'81–F'84) received the S.B. degree in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1962 and the Ph.D. degree in the same field from University of California, Berkeley, in 1968.

He worked at Bell Laboratories, Holmdel, NJ, for 12 years and in 1980, he joined the faculty of MIT, where he is now Elihu Thomson Professor of electrical engineering and Professor of physics. His research interests have included nonlinear optics in fibers, femtosecond pulse generation, ultrafast processes in materials and devices, photonic-bandgap structures, and ultrafast fiber devices.

Dr. Ippen is a Fellow of the American Physical Society and the Optical Society of America (OSA); and he is a member of the National Academy of Sciences, the National Academy of Engineering, and the American Academy of Arts and Sciences.

Tomoharu Hasegawa (M'04–A'05), photo and biography not available at the time of publication.

Tatsuo Nagashima, photo and biography not available at the time of publication.

Naoki Sugimoto received the M.S. degree in molecular engineering, in 1985 and the Dr.Eng. degree in 2004, both from Kyoto University, Kyoto, Japan.

He joined Research Center, Asahi Glass Co., Ltd., Yokohama, Japan, in 1985, and he is now a Principal Researcher of the Research Center. His research interests have included nonlinear optics in fibers and glass materials, amplification characteristics in erbium-doped high-index fibers, ultrafast processes in glass materials, and glass material design.

Dr. Sugimoto is a member of the Optical Society of America (OSA).