Highly nonlinear bismuth-oxide fiber for smooth supercontinuum generation at 1.5 μm

Juliet T. Gopinath, Hanfei M. Shen, Hideyuki Sotobayashi*, and Erich P. Ippen

Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge MA 02139, USA
** also with National Institute of Information and Communication Technology, Tokyo, JAPAN*
juliet@mit.edu

Tomoharu Hasegawa, Tatsuo Nagashima, and Naoki Sugimoto
Research Center, Asahi Glass Company
1150 Hazawa-cho, Kanagawa-ku, Yokohama-city, Kanagawa 221-8755, JAPAN

Abstract: Short lengths of highly nonlinear bismuth-oxide fiber are used to generate smooth supercontinuum spanning from 1200 nm to 1800 nm, with sub-0.5 nJ pulse energies. The spectral broadening in a 2-cm length of this fiber was used to compress 150-fs pulses to 25 fs.

OCIS codes: (190.4370) Nonlinear optics, fiber; (320.7110) Ultrafast nonlinear optics; (320.5520) Pulse compression

---

References and Links

1. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, C. G. Jorgenson, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared," Opt. Lett. **29**, 250-252 (2004).
2. 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. **24**, 1221-1223 (1999).
3. J. Shah, "Ultrafast spectroscopy of semiconductors and semiconductor nanostructures," Springer Series in Solid-State Sciences **115,** (Springer, New York, New York, 1999).
4. 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," To be presented at LEOS (Lasers and Electro-Optic Society) Annual Meeting, Oct. 2004 (Puerto Rico).
5. 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. 83, 4598-4600 (2003).
6. R. Ell, U. Morgner, F. X. Kaertner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T .Tschudi, M. J. Lederer, A. Boiko, B Luther-Davies, "Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser," Opt. Lett. **26**, 373-375 (2001).
7. 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. **24,** 631-633 (1999).
8. 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. **28**, 643-645 (2003).
9. 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. **27**. 61-63 (2002).
10. 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. **23**, 630-632 (1998).
11. Y. Matsui, M. D. Pelusi, and A. Suzuki, "Generation of 20-fs optical pulses from a gain-switched laser diode by a four-stage soliton compression technique," IEEE Phot. Tech. Lett. **11**, 1217-1219 (1999).
12. 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 **77**, 269-277 (2003).
13. S. Taccheo and L. Boivin, "Investigation and design rules of supercontinuum sources for WDM applications," Optical Fiber Communication Conference 2000, ThA1.
14. K. Kikuchi, K. Taira, and N. Sugimoto, "Highly nonlinear bismuth oxide-based glass fibres for all-optical signal processing," Electron. Lett. **38**, 156-157 (2002).

Received 25 October 2004; revised 4 November 2004; accepted 5 November 2004

15. N. Sugimoto, T. Nagashima, T. Hasegawa, S. Ohara, K. Taira, and K. Kikuchi, "Bismuth-based optical fiber with nonlinear coefficient of 1360 $W^{-1}km^{-1}$," Optical Fiber Communication Conference Postdeadline 2004, PDP26.
16. G. P. Agrawal, *Nonlinear fiber optics*, (Academic Press: New York, 1995).
17. 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. **24**, 1774-1776 (1999).

1. Introduction

Broad spectra, spanning hundreds of nanometers, are useful for a variety of applications including frequency metrology [1], medical imaging [2], spectroscopy [3], characterization of broadband devices, such as photonic crystals [4,5], and communication systems. Such spectra can be generated either directly from ultrafast modelocked lasers [6,7] or in highly nonlinear fiber [8]. At 1550 nm, 20-fs pulses, with a spectral width of 190 nm, have been produced directly from a Cr:YAG laser [9]. At the same wavelength, 14.5-fs pulses have been generated from an optical parametric amplifier stretcher/compressor [10]. A semiconductor laser, producing 1-ps pulses, followed by four stages of soliton compression [11] was used to generate 20-fs pulses. More highly nonlinear, normally dispersive fiber can offer a less complex solution. In this paper, we report the generation of smooth, unstructured supercontinuum spectra spanning 1200 to 1800 nm with a highly nonlinear bismuth-oxide fiber. Pulses of 150 fs duration from an optical parametric oscillator (OPO) are also compressed to 25 fs with a 2-cm length of fiber and a grating pair compressor.

2. Design theory of supercontinuum

To generate supercontinuum, we use highly nonlinear normally dispersive bismuth oxide fiber. While supercontinuum has attracted much interest, the optimum method for generating it is still under discussion. The widest spectra are observed in anomalous dispersion fiber, but pulse break-up and the variety of subsequent nonlinear effects that occur under this condition generally produce structured and noisy spectra [12]. Spectral broadening obtained with normal dispersion fiber, on the other hand, results in less spectral structure and noise, and is better suited to pulse compression [12,13]. Bismuth-oxide-based glass fiber is a newly developed fiber [14,15] with sufficiently high nonlinearity to permit stable supercontinuum generation at low powers under conditions of normal dispersion.

In a normal dispersion fiber, the spectral broadening is proportional to $\sqrt{L_d / L_{nl}}$, where L_d is the dispersive length, and L_{nl}, the nonlinear length [13]. The nonlinear length can be written as, $L_{nl} = 1/\gamma P_o$, where P_o is the peak power of the input excitation, and γ, the nonlinear index coefficient. The dispersive length is defined as $L_d = \tau_o^2 / \beta_{av}$, where τ_o is the pulsewidth parameter and β_{av}, the average dispersion. Thus, $\sqrt{L_d / L_{nl}}$ can be written as $\sqrt{(\tau_o^2 P_o \gamma) / \beta_{av}}$. We can increase the spectral broadening by increasing the nonlinearity of the fiber and using pulses with high peak power. Dispersion limits the maximum amount of spectral broadening possible, but the supercontinuum generated is still smooth and controlled.

3. Bismuth-oxide fiber and experimental setup

The bismuth-oxide fiber we used has a core diameter of 1.7 μm and an effective area of 3.3 μm^2. The nonlinear coefficient is approximately 1100 +/- 15% $(W\text{-}km)^{-1}$, about 400 times larger than that of standard dispersion-shifted single mode fiber. The large normal dispersion of the fiber, –250 ps/nm/km, provides the ultimate limit on spectral broadening, but is responsible for the smooth unstructured supercontinuum produced. Calculations indicate that the dispersion of the fiber is relatively flat, within 20%, over a large wavelength range of 1200 to 1800 nm. The refractive index of the core is 2.22, and that of the cladding 2.13 at 1550 nm. The experiments reported in this paper were performed with two different lengths of the nonlinear fiber: 1 m and 2 cm. A standard fiber cleaver was used to prepare the ends of the 1-m length. The 2-cm piece of fiber was mounted in two connected ceramic ferrules with a thin coating of wax and the ends were polished.

An OPO, producing 150-fs pulses tunable between 1400 to 1600 nm, is used as the signal source. It is synchronously pumped by a Ti:Sapphire laser, at a repetition rate of 82 MHz. The output of the OPO is coupled into a 3-cm length of single-mode fiber, which serves as a spatial filter. Next, the light from the SMF is recollimated and focused into a length of highly nonlinear bismuth-oxide fiber, with an aspheric lens. After the fiber, either an aspheric lens or a reflecting objective (for compression experiments) is used to collimate the light. The output is sent to either an optical spectrum analyzer, an autocorrelator, or grating compressor.

4. Experimental results

In Fig. 1, typical spectra produced from a 2-cm piece of fiber are shown as a function of power. The input excitation was centered at 1540 nm and the coupling loss was 6 dB. For 32 mW of output average power, spectrum is generated from 1300 nm to >1700 nm, with a 3-dB spectral width of 170 nm. (The optical spectrum analyzer had a range limited to wavelengths less than 1700 nm.) The interference in the center of the spectra comes from insufficient attenuation of cladding modes. 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 shoulders apparent in the spectra are caused by optical wave breaking [16], which occurs when the effects of self-phase modulation (SPM) are much larger than that of group-velocity dispersion (GVD).

Spectra obtained with the 2-cm length of fiber for three different input wavelengths: 1450 nm, 1500 nm and 1540 nm, are shown in Fig. 2. The power is kept constant for the three measurements In order to obtain a more complete evaluation of the spectrum generated with 1540-nm input, we extended our measurements with a spectrometer to observe the actual roll-off of the spectrum at 1800 nm. The spectra generated at the three different wavelengths are nearly identical, indicative of the flat dispersion profile of the fiber. The fiber becomes multimode at ~1390 nm, and it is probable that this limits the short wavelength side of the spectrum.

For the case of the 1540-nm input, we compressed the output pulse using a grating pair. The gratings had 75 lines/mm and were separated by 8.5 cm. The average power exiting the compressor was roughly 6 mW, with 20 mW entering (this also takes into account the 30% loss of the reflecting objective). The pulses were then sent into a broadband autocorrelator, utilizing metallized beamsplitters, a speaker to dither the delay, a parabolic mirror, rather than a lens, to focus onto a detector, and a GaAs LED as the two-photon absorption detector. We were able to compress the pulses to 25 fs, as shown in Fig. 3. The autocorrelation was fitted with the PICASO phase retrieval algorithm [17]. The transform limit of the spectrum was ~16 fs. The time-bandwidth product of our compressed pulses, assuming a sech pulse envelope, is ~0.49. The pulsewidth is likely limited by incomplete higher-order chirp compensation as well as the roll-off in spectral efficiency of the gratings at wavelengths shorter than 1500 nm.

#5559 - $15.00 US   Received 25 October 2004; revised 4 November 2004; accepted 5 November 2004

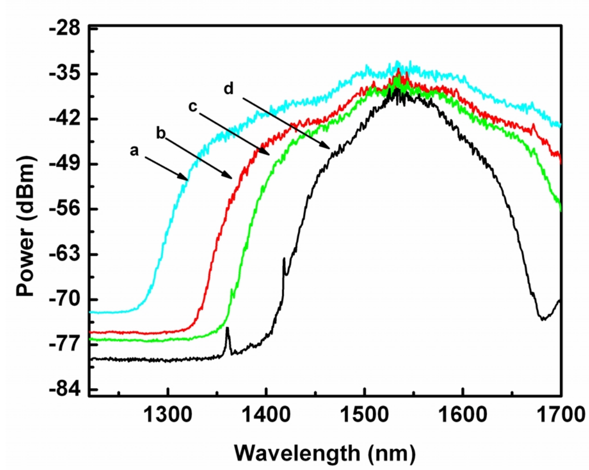

Fig. 1. Spectra from a 2-cm piece of fiber generated by 1540-nm excitation at average powers exiting the fiber of: a) 32 mW b) 21.4 mW c) 14 mW d) 7 mW. The interference at the center of the spectra is due to insufficient attenuation of cladding modes.

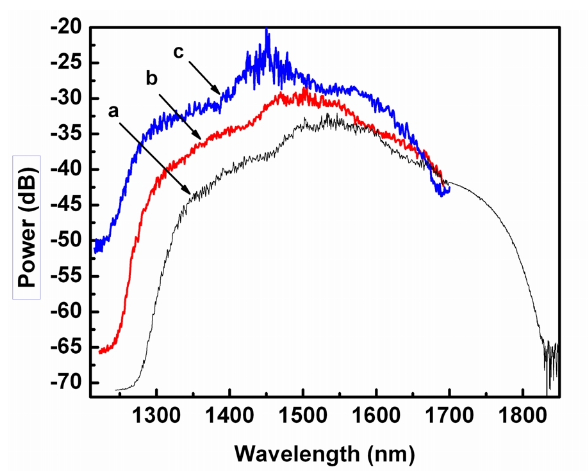

Fig. 2. Spectra from a 2-cm length of fiber of input wavelengths of: a) 1540 nm b) 1500 nm c) 1450 nm. The spectra were taken up to 1700 nm with an optical spectrum analyzer, and the measurement from 1700 – 1900 nm was taken with a spectrometer. The spectra were all taken for comparable powers and are vertically offset for ease of viewing.

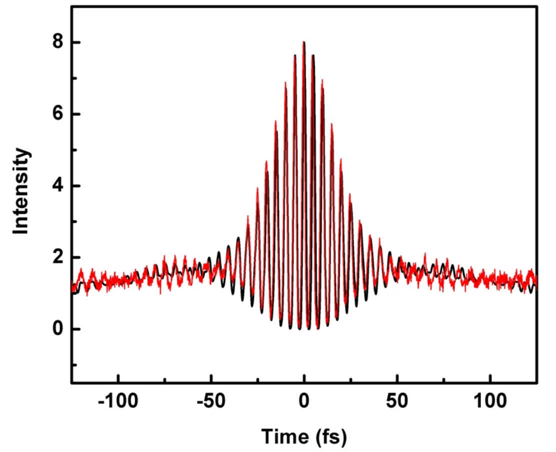

Fig. 3. Fringe resolved autocorrelation of 25-fs pulses generated from 2 cm of fiber with 150-fs input pulses at 1540 nm. The pulse is fitted with the Picaso phase retrieval algorithm.

Some applications of supercontinuum require only broad spectrum, and not short pulses. If short pulses are not required, a longer length of highly nonlinear bismuth-oxide fiber may be more suitable. Figure 4 shows some typical spectra versus power produced with a 1-m length of the fiber, with an input at 1540 nm. For 34 mW of output average power, spectrum is generated from 1300 nm to > 1700 nm, similar to that of the 2-cm length. We estimate that the output pulse in this case is approximately 80 ps. However, one will notice that the longer piece of fiber suppresses the cladding modes more effectively than the 2-cm length. After 2 cm, the pulse is already broadened to 800 fs, and the effect of SPM becomes greatly reduced. Nevertheless, some additional spectral smoothing is evidenced by the reduction of the shoulders due to wave breaking.

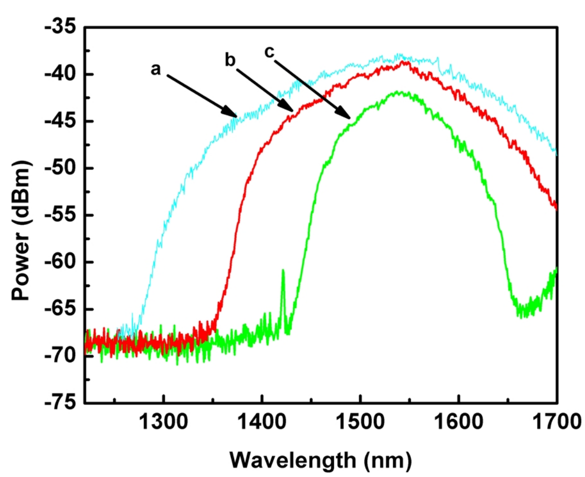

Fig. 4. Supercontinuum spectra from 1 m of highly nonlinear bismuth oxide fiber generated by 1540-nm excitation at average powers exiting the fiber of: a) 34 mW b) 20 mW c) 10 mW.

5. Conclusion

In conclusion, highly nonlinear small-core bismuth oxide fiber with normal dispersion has been used to generate smooth, unstructured continuum at telecommunication wavelengths, spanning from 1200 to 1800 nm. Compression experiments produced 25-fs pulses. It is

#5559 - $15.00 US Received 25 October 2004; revised 4 November 2004; accepted 5 November 2004

important to note that the pulses were produced with a commercially available source as well as grating compressor. Such pulses have many applications including nonlinear optics, spectroscopy, and frequency metrology. Broad, Gaussian-shaped spectra could be particularly useful for medical imaging techniques such as optical coherence tomography.

Acknowledgments

The authors gratefully acknowledge valuable advice and technical contributions from P. Rakich, J. W. Sickler, K. Taira, F. O. Ilday, T. E. Murphy, and K. S. Abedin.

#5559 - $15.00 US Received 25 October 2004; revised 4 November 2004; accepted 5 November 2004