Appl. Phys. B 83, 185–187 (2006)
DOI: 10.1007/s00340-006-2160-y

Applied Physics B
Lasers and Optics

D.A. AKIMOV[1]
T. SIEBERT[1]
A.M. ZHELTIKOV[2,✉]
W. KIEFER[1]

A double-pass optical parametric amplifier seeded by a blue-shifted output of a photonic-crystal fiber

[1] Institut für Physikalische Chemie, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
[2] Physics Department, International Laser Center, M.V. Lomonosov Moscow State University,
Vorob'evy gory, 119899 Moscow, Russia

Received: 6 February 2006

ABSTRACT A blue-shifted output of a photonic-crystal fiber, providing a frequency upconversion of femtosecond Ti:sapphire laser pulses, is used to seed a double-pass optical parametric oscillator (OPA). The OPA is based on a BBO crystal, pumped by 65-mW 150-fs second-harmonic pulses of a Ti:sapphire laser. Gain factors in excess of 10^3 are demonstrated for such an OPA, yielding tunable light pulses within the range of wavelengths from 420 to 650 nm, a peak power up to 250 kW, and a typical pulse width of about 200 fs at a repetition rate of 100 kHz.

PACS 42.81.Gs; 42.81.Qb

Photonic-crystal fibers (PCFs) [1, 2] offer a broad variety of novel strategies for ultrafast optics and short-pulse laser technologies. Tailored dispersion [3] and manageable nonlinearity [4] are the key factors behind the remarkable performance of recently developed PCF-based components in short-pulse laser sources [5], pulse compressors [6–8], fiber-optic elements for dispersion control [9, 10], and efficient frequency shifters [11]. PCFs for the nonlinear-optical spectral transformation of ultrashort pulses are currently extensively used in many areas of ultrafast science, giving an excess to the carrier–envelope phase [12], allowing the generation of stabilized frequency combs for optical metrology and femtosecond clockwork [13, 14], simplifying pump–seed synchronization in few-cycle optical parametric chirped-pulse amplification (OPCPA) [15], and facilitating the creation of novel optical coherence tomographs [16], nonlinear spectrographs [17], and microscopes [18].

Typical of any fiber-optic component, the laser-induced damage of fiber material is a natural limitation on the acceptable fluence of pump laser pulses in PCF frequency converters. The power of the frequency-converted or supercontinuum PCF output is thus also limited, restricting applications of PCF frequency shifters and supercontinuum generators to the domain where moderate field intensities are sufficient. Development of amplification techniques for the supercontinuum and frequency-shifted output of PCFs would thus offer the ways to substantially expand the area of applications for PCF-based nonlinear-optical components. Teisset et al. [15] have recently demonstrated that the Raman-shifted soliton output of a PCF pumped with few-cycle laser pulses can seed amplification in a Nd:YAG laser, enabling a novel synchronization scheme for OPCPA. In this work, we use a double-pass scheme of an optical parametric amplifier (OPA) based on a BBO crystal pumped by 65-mW 150-fs second-harmonic pulses of a Ti:sapphire laser to demonstrate parametric amplification of a frequency-upconverted PCF output. We will show that such an OPA scheme allows gain factors exceeding 10^3 to be achieved for the blue-shifted PCF output, delivering wavelength-tunable light pulses within the spectral range from 420 to 650 nm.

Fused silica PCFs used in our experiments consisted of a small core with a diameter of about 4.5 μm and a dual cladding, which, in its turn, included two sections with substantially different spatial scales of microstructure (the inset in Fig. 1). The inner part of the microstructure cladding, which is adjacent to the fiber core, includes air holes with a typical diameter of about 4 μm. The air holes in the outer part of the microstructure cladding are considerably larger, with their mean diameter estimated as 9 μm. For the fundamental guided mode of this PCF, the wavelength of zero group-velocity dispersion (GVD) is 985 nm. Fundamental-wavelength, 800-nm Ti:sapphire laser pulses can therefore sense only the normal dispersion when they are coupled into this mode of the PCF. For the second- and third-order modes, the zero-GVD wavelengths are 830 and 740 nm, respectively. Thus, for higher PCF modes starting with the third-order mode, the fundamental wavelength of Ti:sapphire laser pulses falls within the range of anomalous dispersion. Off the center of the PCF structure, laser radiation can be guided along small silica waveguide channels in the inner part of the microstructure cladding with a characteristic diameter of 1–1.8 μm. In these channels, 800-nm Ti:sapphire laser pulses are always guided in the regime of anomalous dispersion.

In our experimental scheme (Fig. 1), amplified 100-fs pulses of 800-nm Ti:sapphire laser radiation with an average power of 1–10 mW were coupled into the PCF with a length of 4 cm. Solitons in the central PCF core, as well as in the off-center waveguiding channels undergo a continuous red shifting [19] due to the Raman effect (the inset in Fig. 2) and are forced to emit Cherenkov-phase-matched dispersive waves in the visible because of high-order dispersion effects [20, 21].

✉ Fax: 7 495 939 5174, E-mail: zheltikov@phys.msu.ru

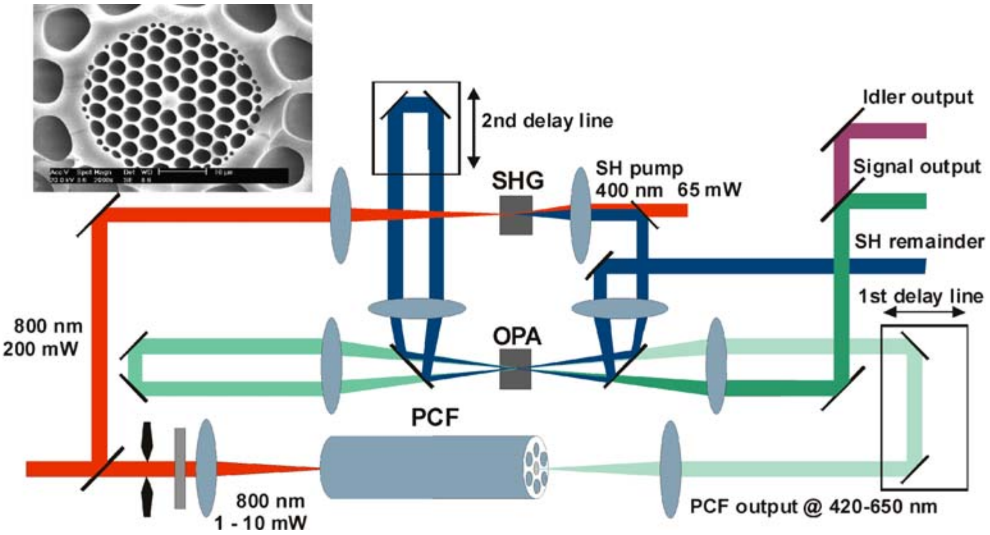

FIGURE 1 Diagram of optical parametric amplification of the frequency-shifted output of a photonic-crystal fiber. An SEM image of the photonic-crystal fiber is shown in the *inset*

These dispersive waves are observed as blue-shifted spectral components at the output of the PCF (Fig. 2). Off-center waveguiding channels with slightly different diameters (the inset in Fig. 1) are characterized by different dispersion profiles, allowing different frequency shifts to be achieved for the input field with the same central frequency and the same intensity, thus providing a wavelength tunability of PCF output [11]. The energy of Ti:sapphire laser pump pulses at the input of the fiber was adjusted by a variable attenuator shown in Fig. 1 and ranged from 5 to 35 nJ. We expect that, with a carefully optimized efficiency of pump coupling into the PCF, the same energies of the blue-shifted output can be achieved with pump energies at least an order of magnitude lower.

Radiation coming out of the PCF is parametrically amplified (Fig. 1) in a 1-mm-thick BBO crystal in the presence of second-harmonic Ti:sapphire laser pulses, serving as a pump field. Upon the first pass through the nonlinear crystal, the amplified PCF output is reflected from a pair of mirrors, sending the beam back to the BBO crystal synchronously with the second-harmonic Ti:sapphire laser pulses, transmitted through a tunable optical delay line, for the second pass of optical parametric amplification.

The energy of blue-shifted pulses measured at the output of the PCF is estimated as 10 pJ (inset 1 in Fig. 3). The spectrum of these pulses stretches from 507 to 533 nm (curve 1 in Fig. 3). After the first pass through the OPA, the energy of the blue-shifted pulses increases up to a nanojoule level (inset 2). Since the blue-shifted pulses are chirped at the output of the PCF, their entire spectrum cannot be amplified in the OPA

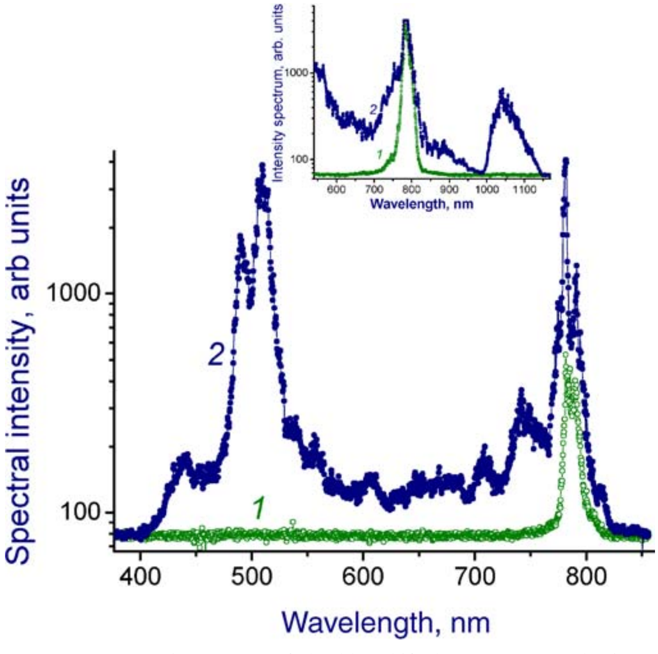

FIGURE 2 Intensity spectra of the blue-shifted PCF output. The input pump pulses (fundamental-wavelength radiation of a Ti:sapphire laser) have the pulse width of about 100 fs and an average power of (1) 0.3 mW and (2) 3 mW. The pump and the long-wavelength part of the output spectra are shown in the *inset*

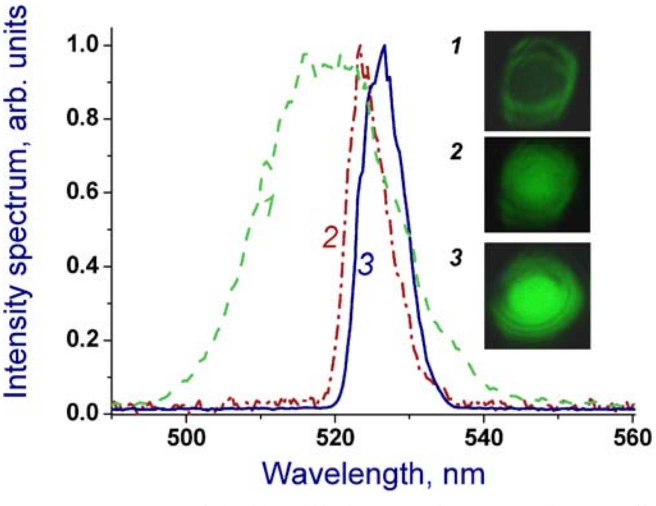

FIGURE 3 Spectra of the blue-shifted output of a 1.1-µm-diameter off-center waveguide channel in the PCF before amplification (1) and the spectra of amplified radiation after one (2) and two (3) passes along the OPA. The *insets* show transverse intensity profiles of frequency-shifted radiation before amplification (1) and after one (2) and two (3) passes along the OPA

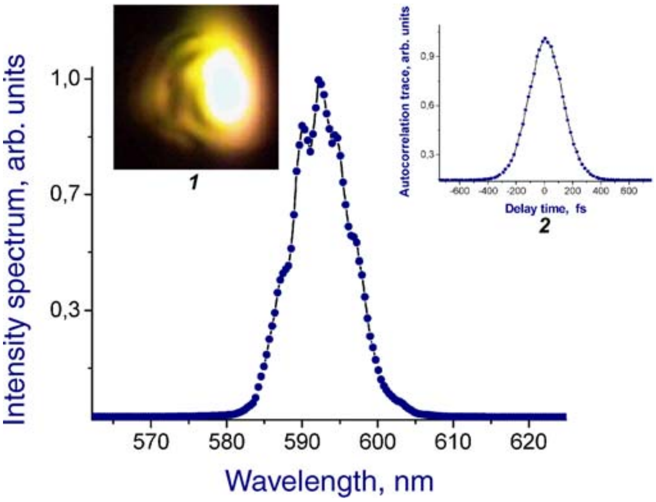

FIGURE 4 Intensity spectrum of the output of the double-pass OPA seeded by the blue-shifted pulses from the central core of the PCF. *Insets* 1 and 2 show the transverse intensity profile and the autocorrelation trace of this double-pass OPA output

without a careful compensation for the group delay. Curve 2 in Fig. 3 displays a typical spectrum of blue-shifted radiation after the first pass through the OPA, showing that only spectral components lying within the range of wavelengths from 522 to 532 nm have been efficiently amplified. The spectrum of the amplified pulse can be smoothly tuned within the spectrum of the unamplified frequency-shifted PCF output (curve 1) by adjusting the delay line and rotating the nonlinear crystal. The second pass through the OPA allows the energy of the blue-shifted PCF output to be increased up to 25 nJ. The spectrum of the amplified pulses at the output of the double-pass OPA is further narrowed (curve 3) unless special measures are taken to compensate for group-delay effects.

When Ti:sapphire laser pulses are coupled into the central core of the PCF, solitons can be excited only in higher order modes, with the blue-shifted signal generated only in high-order guided modes. Because of natural limitations dictated by the geometry of nonlinear interaction between the blue-shifted PCF output and the second-harmonic pump field in a nonlinear crystal, parametric amplification is efficient in this regime only for a certain sector of the blue-shifted beam. This geometry of OPA can yield an output beam with a reasonably smooth intensity profile (inset 1 in Fig. 4) and a typical energy of 50 nJ, corresponding to the average power of 5 mW. As the chirp of the blue-shifted pulses generated in the central core of the PCF is less than the chirp of the blue-shifted output of the small-diameter off-center waveguide channel, a high efficiency of optical parametric amplification of the frequency-shifted pulses from the central core of the PCF can be achieved within a broader spectral range. Indeed, the spectrum of the output of the double-pass OPA seeded by the blue-shifted pulses from the central core of the PCF (Fig. 4) is typically noticeably broader than the spectra of the amplified output of the off-center waveguides (Fig. 3). The autocorrelation function measured for the amplified blue-shifted output of the central PCF core (inset 2 in Fig. 4) allows the temporal width of the OPA output to be estimated as 180 fs. From the measured spectra of the OPA output, we expect that even shorter pulses can be produced by careful chirp compensation.

We have experimentally demonstrated an efficient optical parametric amplification of light pulses frequency-upshifted in a PCF. A double-pass OPA based on a BBO crystal pumped by 65-mW 150-fs second-harmonic pulses of a Ti:sapphire laser is shown to provide gain factors exceeding 10^3 for the blue-shifted PCF output tunable within the range of wavelengths from 420 to 650 nm. Such an OPA can generate light pulses with energies as high as 50 nJ and a pulse width of about 200 fs at a repetition rate of 100 kHz, providing average powers up to 5 mW, thus offering the ways for the creation of high-average power PCF-based light sources.

ACKNOWLEDGEMENTS We are grateful to K.V. Dukel'skii, A.V. Khokhlov, Yu.N. Kondrat'ev, and V.S. Shevandin for fabricating fiber samples. This study was supported in part by the Russian Foundation for Basic Research (projects 04-02-39002-GFEN2004 and 05-02-90566-NNS), the Russian Federal Research and Technology Program (contract no. 02.434.11.2010), and INTAS (projects nos. 03-51-5037 and 03-51-5288). The research described in this publication was made possible in part by Award no. RUP2-2695 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF).

REFERENCES

1 P.S.J. Russell, Science **299**, 358 (2003)
2 J.C. Knight, Nature **424**, 847 (2003)
3 W.H. Reeves, D.V. Skryabin, F. Biancalana, J.C. Knight, P.S.J. Russell, F.G. Omenetto, A. Efimov, A.J. Taylor, Nature **424**, 511 (2003)
4 A.B. Fedotov, A.M. Zheltikov, A.P. Tarasevitch, D. von der Linde, Appl. Phys. B **73**, 181 (2001)
5 K. Furusawa, A. Malinowski, J.H.V. Price, T.M. Monro, J.K. Sahu, J. Nilsson, D.J. Richardson, Opt. Express **9**, 714 (2001)
6 T. Südmeyer, F. Brunner, E. Innerhofer, R. Paschotta, K. Furusawa, J.C. Baggett, T.M. Monro, D.J. Richardson, U. Keller, Opt. Lett. **28**, 1951 (2003)
7 J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, Opt. Express **11**, 3332 (2003)
8 C.J.S. de Matos, S.V. Popov, A.B. Rulkov, J.R. Taylor, J. Broeng, T.P. Hansen, V.P. Gapontsev, Phys. Rev. Lett. **93**, 103901 (2004)
9 H. Lim, F. Ilday, F. Wise, Opt. Express **10**, 1497 (2002)
10 H. Lim, F. Wise, Opt. Express **12**, 2231 (2004)
11 S.O. Konorov, A.M. Zheltikov, Opt. Express **11**, 2440 (2003)
12 D.J. Jones, S.A. Diddams, J.K. Ranka, A. Stentz, R.S. Windeler, J.L. Hall, S.T. Cundiff, Science **288**, 635 (2000)
13 R. Holzwarth, T. Udem, T.W. Hänsch, J.C. Knight, W.J. Wadsworth, P.S.J. Russell, Phys. Rev. Lett. **85**, 2264 (2000)
14 T. Udem, R. Holzwarth, T.W. Hänsch, Nature **416**, 233 (2002)
15 C.Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuška, A.M. Zheltikov, F. Krausz, Opt. Express **13**, 6550 (2005)
16 I. Hartl, X.D. Li, C. Chudoba, R.K. Rhanta, T.H. Ko, J.G. Fujimoto, J.K. Ranka, R.S. Windeler, Opt. Lett. **26**, 608 (2001)
17 S.O. Konorov, D.A. Akimov, E.E. Serebryannikov, A.A. Ivanov, M.V. Alfimov, A.M. Zheltikov, Phys. Rev. E **70**, 057601 (2004)
18 H.N. Paulsen, K.M. Hilligsøe, J. Thøgersen, S.R. Keiding, J.J. Larsen, Opt. Lett. **28**, 1123 (2003)
19 G.P. Agrawal, *Nonlinear Fiber Optics* (Academic, San Diego, 2001)
20 N. Akhmediev, M. Karlsson, Phys. Rev. A **51**, 2602 (1995)
21 J. Herrmann, U. Griebner, N. Zhavoronkov, A. Husakou, D. Nickel, J.C. Knight, W.J. Wadsworth, P.St.J. Russell, G. Korn, Phys. Rev. Lett. **88**, 173901 (2002)