Abstract: Fabrication and experimental demonstration of photonic-crystal fibers (PCFs) made of TF10 glass are reported. These fibers integrate a high material nonlinearity with dispersion and field-confinement nanomanagement. A specifically designed array of nanoholes in the fiber core is shown to provide the desired dispersion and nonlinearity properties of PCF modes, allowing efficient frequency upconversion of Cr:forsterite laser pulses through solitonic and four-wave mixing mechanisms.

An SEM image of the photonic-crystal fiber, close-up view

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Dispersion and nonlinearity nanomanagement of highly nonlinear photonic-crystal fibers for the spectral transformation of Cr:forsterite laser pulses

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Photonic-crystal fibers (PCFs) [1,2] have boosted optical technologies, allowing the creation of novel light sources, frequency-comb expanders, and frequency shifters for optical metrology [3–5], ultrafast science [6,7], coherent spectroscopy [8], nonlinear microscopy [9], quantum optics [10], and optical coherence tomography [11]. The remarkable performance of PCFs in various areas of optical science and technology is largely based on the unique dispersion tunability of these fibers, allowing dispersion properties unattainable and unthinkable for

standard optical fibers to be designed through fiber structure modifications [12].

For solid-core PCFs, the required dispersion profile is typically engineered [1,12] by choosing the appropriate geometry of the cladding, as well as by varying the size and the shape of the fiber core. In view of a rich diversity of possible cladding geometries, several useful and efficient algorithms have been proposed [13,14] to formalize dispersion engineering procedures in terms of the ratio of the airhole diameter d to the PCF pitch Λ and the ratio

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of Λ to the radiation wavelength λ . It has been demonstrated that the dispersion of PCFs is sensitive to even small, nanoscale variations in fiber geometry [15]. A small defect in the core of a structurally simple PCF has been shown [16] to offer an interesting solution for the control of chromatic dispersion of PCFs. Numerical simulations demonstrate that, with an appropriate adjustment of the defect size, PCFs with ultraflattened dispersion profiles can be created. As shown in [17], arrays of air nanoholes can noticeably modify the properties of guided modes in optical fibers, enabling a fine tuning of fiber dispersion, nonlinearity, and gain. Such fiber dispersion nanomanagement solutions can provide ultraflattened group-velocity dispersion profiles and control the fiber nonlinearity and gain. PCFs with guided modes modified by arrays of nanoholes have been experimentally demonstrated in [18].

In this work, we apply the concept of dispersion and field-confinement engineering to PCFs made of a highly nonlinear material. Such PCFs have been shown recently to offer much promise for efficient spectral transformation of laser pulses [19–22]. We report below a fabrication and experimental demonstration of PCFs made of TF10 glass. These fibers integrate a high material nonlinearity with dispersion and field-confinement nanomanagement. An array of nanoholes in the fiber core is shown to provide the desired dispersion and nonlinearity properties of PCF modes, allowing efficient frequency upconversion of Cr:forsterite laser pulses through solitonic and four-wave mixing mechanisms.

Photonic-crystal fibers used in our experiments were fabricated of TF10 glass using the standard PCF fabrication technology [1,2]. The nonlinear refractive index, n_2 , of TF10 glass is typically an order of magnitude higher than n_2 of fused silica, allowing the enhancement of optical nonlinearity relative to fused silica PCFs with a similar geometry. Material dispersion of TF10 glass also considerably differs from the dispersion of fused silica. In particular, the wavelength λ_z where the group-velocity dispersion (GVD) is zero in the bulk of TF10 glass, $\lambda_z \approx 2.0 \mu\text{m}$, is noticeably shifted toward longer wavelengths relative to the zero-GVD wavelength of fused silica.

The core-cladding geometry of our fiber (Fig. 1) is typical of an index-guiding PCF [1]. However, in addition to the standard structure of PCF, the core of our PCF features a hexagonal array of six additional submicron air holes, running along the fiber axis. These holes are designed in such a way as to achieve the required spatial field intensity profiles and the desired dispersion properties of waveguide modes. In the inset to Fig. 2, we present the field intensity profiles calculated with the use of the polynomial-expansion technique for the fundamental and several low-order modes of the fiber. As can be seen from these calculations, the light field in the fundamental and low-order modes of the PCF is confined within the circle bounded by the hexagonal array of air holes.

Figure 1 An SEM image of the photonic-crystal fiber: (a) general and (b) close-up view

As a measure of optical nonlinearity, we use the standard definition of the nonlinearity coefficient $\gamma = (2\pi n_2)/(\lambda S_{eff})$, where λ is the wavelength and

$$S_{eff} = \frac{\left[\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F(x, y)|^2 dx dy \right]^2}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F(x, y)|^4 dx dy}$$

is the effective mode area, $F(x, y)$ being the transverse field profile in the PCF mode. By inspecting the expression for γ , we identify two factors providing the enhancement of optical nonlinearity for the considered type of PCF. The first factor is related to the material of the fiber, whose nonlinear refractive index n_2 is an order of magnitude higher than that of fused silica. A stronger confinement of the light field within the circle of nanoholes in the fiber core is the second factor of nonlinearity enhancement. In Fig. 2, we plot the wavelength dependence of the effective area S_{eff} for the fundamental mode doublet of the PCF (shown

Figure 2 (online color at www.lphys.org) The wavelength dependences of (1) the effective mode area S_{eff} and (2) the group-velocity dispersion for the fundamental mode doublet of the PCF. Field intensity profiles for the fundamental (1,2) and higher order (3–6) PCF modes are shown in the insets

in insets 1, 2 to Fig. 2). For longer wavelengths, diffraction is stronger, and the guided modes become less compact. Accordingly, the nonlinear coefficient γ decreases from $\approx 1300 \text{ W}^{-1}\text{km}^{-1}$ at the wavelength of 800 nm to approximately $700 \text{ W}^{-1}\text{km}^{-1}$ at $1.25 \mu\text{m}$. Fiber dispersion nanomanagement, implemented in the chosen PCF design, provides an anomalous dispersion for Cr:forsterite laser radiation, with the zero-GVD wavelength λ_z ($\lambda_z \approx 1.19 \mu\text{m}$ for the fundamental mode of our PCF, see curve 2 in Fig. 2) lying close to the central wavelength of Cr:forsterite laser pulses ($1.25 \mu\text{m}$). A fiber with such dispersion properties offers ideal conditions for efficient spectral transformation and frequency shifting of Cr:forsterite laser pulses.

The laser system used in our experiments was based on a two-arm long-cavity master oscillator consisting of

Figure 3 (online color at www.lphys.org) The spectra of radiation transmitted through a 20-cm section of PCF. The input pulse has an energy of 2 nJ and an initial pulse width of 70 fs. The laser beam is (1) aligned with the fiber axis and (2) tilted with respect to the fiber axis

Figure 4 (online color at www.lphys.org) The propagation-constant mismatch $\delta\beta$ between the soliton centered at $1.25 \mu\text{m}$ and dispersive waves guided by the fundamental mode of the PCF (1) and modes with intensity profiles 4 (2) and 6 (3), shown in Fig. 2, as a function of the wavelength of the dispersive wave

a 10-mm Cr^{4+} :forsterite crystal, a set of totally reflecting mirrors, an 8% output coupler, and a prism pair for dispersion compensation. The laser oscillator was pumped with a 7.5-W ytterbium fiber laser radiation. The laser cavity was adjusted to generate 70-fs pulses with an average power up to 150 mW and a central wavelength of $1.25 \mu\text{m}$ at a repetition rate of about 20 MHz [23]. The laser pulses were coupled into the PCF through a micro-objective, providing a coupling efficiency of 12%. The mode content of laser radiation in the fiber was modified by changing the

tilt angle of the input laser beam with respect to the fiber axis.

Since the central wavelength of Cr:forsterite laser pulses falls within the range of anomalous dispersion, these pulses can form solitons in the fundamental and higher order modes of the PCF. High-order dispersion induces wave-matching resonances between solitons and dispersive waves [24,25], giving rise to intense blue-shifted emission, observed as prominent features in the PCF output spectra (Fig. 3). The central wavelength of this blue-shifted emission is controlled by phase matching between the parent soliton and the emitted dispersive wave. In Fig. 4, we plot the mismatch $\delta\beta = \beta_s(\lambda_0) - \beta(\lambda_d)$ of the propagation constant $\beta(\lambda_d)$ of dispersive-wave emission at the wavelength λ_d in one of the PCF modes and the propagation constant of the soliton $\beta_s(\lambda_0)$ centered at the pump wavelength $\lambda_0 = 1.25 \mu\text{m}$. As can be seen from the comparison of Figs. 3 and 4, the central wavelengths of blue-shifted emission bands observed at the output of the PCF correlate well with the wavelengths where dispersive waves guided in the fundamental and higher order PCF modes are phase-matched with the soliton produced by Cr:forsterite laser pulses. In particular, the $1.25\text{-}\mu\text{m}$ soliton in the fundamental PCF mode is phase-matched with a dispersive wave at 888 nm (curve 1 in Fig. 4). In experimental spectra, this corresponds to the blue-shifted emission band centered around 880–890 nm (curve 1 in Fig. 3). For the higher order PCF mode labeled as mode 4 in Fig. 2, the soliton-dispersive-wave phase matching is achieved at 768 nm, where another intense emission band is observed in the PCF output (curve 2 in Fig. 3). Finally, the spectral peak centered at 680 nm in the experimental spectra in Fig. 3 is attributed to a wave-matching resonance between the soliton at $1.25 \mu\text{m}$ and mode 6 of the PCF (see Fig. 4).

Interestingly and quite importantly, the energy of laser pulses required for the efficient generation of the blue-shifted emission band centered at 880–890 nm is much lower than the energy necessary for the generation of the emission bands centered at 680 and 770–780 nm. This tendency agrees well with the dispersion profiles of these modes. The emission band centered at 880–890 nm is identified as a dispersive-wave emission of the soliton in the fundamental mode. The GVD provided by our PCF for this mode is much lower than the GVD for the higher order modes. This implies the lower radiation energy required for the formation of the fundamental soliton. Indeed, emission bands in higher order modes show up as the input energy increases or the fiber is tilted with respect to the input beam, providing the higher energy input for higher order modes.

The shortest wavelength emission band in the PCF output is centered at 540 nm. This band is observed only in the presence of spectral peaks at 680 and 880–890 nm (Fig. 3). Radiation with frequencies ω_a corresponding to the 540-nm emission band can be generated through four-wave mixing (FWM) $\omega_1 + \omega_2 = \omega_a + \omega_s$, involving Stokes photons (ω_s) from the 880–890-nm emission band and a pair of pump photons (ω_1 and ω_2) from the 680-nm band.

Figure 5 (online color at www.lphys.org) Photonic-crystal fiber frequency converter

A complex beam-pattern structure of 540-nm emission in the PCF output is indicative of multimode phase matching [26] as a mechanism leading to efficient FWM.

We have demonstrated in this work the nonlinear-optical performance of novel PCFs made of high- n_2 TF10 glass. These fibers integrate a high material nonlinearity with dispersion and field-confinement nanomanagement. The desired dispersion and nonlinearity properties of guided modes in our PCFs have been achieved with a specifically designed array of nanoholes in the fiber core, allowing efficient frequency upconversion of femtosecond pulses of $1.2\text{--}1.3\text{-}\mu\text{m}$ Cr:forsterite laser radiation (Fig. 5). Because of a special importance of this wavelength range for a microscopy and imaging of biological objects [27–29], PCFs demonstrated in this work may allow the creation of compact devices and handpieces for the wavelength-selective imaging of biological tissues, including optical coherence tomographs, nonlinear-optical microscopes, and fiber endoscopes.

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References

- [1] P.St.J. Russell, *Science* **299**, 358 (2003).
- [2] J.C. Knight, *Nature* **424**, 847 (2003).
- [3] D.J. Jones, S.A. Diddams, J.K. Ranka, A. Stentz, R.S. Windeler, J.L. Hall, and S.T. Cundiff, *Science* **288**, 635 (2000).

- [4] R. Holzwarth, T. Udem, T.W. Hänsch, J.C. Knight, W.J. Wadsworth, and P.St.J. Russell, *Phys. Rev. Lett.* **85**, 2264 (2000).
- [5] Th. Udem, R. Holzwarth, and T.W. Hänsch, *Nature* **416**, 233 (2002).
- [6] A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V.S. Yakovlev, A. Scrinzi, T.W. Hänsch, and F. Krausz, *Nature* **421**, 611 (2003).
- [7] C.Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuska, A.M. Zheltikov, and F. Krausz, *Opt. Express* **13**, 6550 (2005).
- [8] S.O. Konorov, D.A. Akimov, E.E. Serebryannikov, A.A. Ivanov, M.V. Alfimov, and A.M. Zheltikov, *Phys. Rev. E* **70**, 057601 (2004).
- [9] H.N. Paulsen, K.M. Hilligsøe, J. Thøgersen, S.R. Keiding, and J.J. Larsen, *Opt. Lett.* **28**, 1123 (2003).
- [10] J.G. Rarity, J. Fulconis, J. Duligall, W.J. Wadsworth, and P.S.J. Russell, *Opt. Express* **13**, 534 (2005).
- [11] I. Hartl, X.D. Li, C. Chudoba, R.K. Rhanta, T.H. Ko, J.G. Fujimoto, J.K. Ranka, and R.S. Windeler, *Opt. Lett.* **26**, 608 (2001).
- [12] W.H. Reeves, D.V. Skryabin, F. Biancalana, J.C. Knight, P.St.J. Russell, F.G. Omenetto, A. Efimov, and A.J. Taylor, *Nature* **424**, 511 (2003).
- [13] A. Ferrando, E. Silvestre, P. Andres, J.J. Miret, and M.V. Andres, *Opt. Express* **9**, 687 (2001).
- [14] A. Ferrando, E. Silvestre, J.J. Miret, and P. Andres, *Opt. Lett.* **25**, 790 (2000).
- [15] W.H. Reeves, J.C. Knight, P.St.J. Russell, and P.J. Roberts, *Opt. Express* **10**, 609 (2002).
- [16] K. Saitoh, N. Florous, and M. Koshiba, *Opt. Express* **13**, 8365 (2005).
- [17] A.M. Zheltikov, submitted.
- [18] S.O. Konorov, D.A. Akimov, A.A. Ivanov, M.V. Alfimov, A.B. Fedotov, D.A. Sidorov-Biryukov, L.A. Mel'nikov, A.V. Shcherbakov, I. Bugar, D. Chorvat Jr., F. Uherek, D. Chorvat, and A.M. Zheltikov, *Laser Phys. Lett.* **1**, 402 (2004).
- [19] V.R.K. Kumar, A.K. George, W.H. Reeves, J.C. Knight, P.S.J. Russell, F.G. Omenetto, and A.J. Taylor, *Opt. Express* **10**, 1520 (2002).
- [20] H. Hundertmark, D. Kracht, D. Wandt, C. Fallnich, V.V. Ravi Kanth Kumar, A.K. George, J.C. Knight, and P.S.J. Russell, *Opt. Express* **11**, 3196 (2003).
- [21] P. Petropoulos, H. Ebendorff-Heidepriem, V. Finazzi, R.C. Moore, K. Frampton, D.J. Richardson, and T.M. Monro, *Opt. Express* **11**, 3568 (2003).
- [22] A.N. Naumov, A.B. Fedotov, A.M. Zheltikov, V.V. Yakovlev, L.A. Mel'nikov, V.I. Beloglazov, N.B. Skibina, and A.V. Shcherbakov, *J. Opt. Soc. Am. B* **19**, 2183 (2002).
- [23] A.B. Fedotov, A.A. Ivanov, and A.M. Zheltikov, in preparation.
- [24] P.A. Wai, H.H. Chen, and Y.C. Lee, *Phys. Rev. A* **41**, 426 (1990).
- [25] N. Akhmediev and M. Karlsson, *Phys. Rev. A* **51**, 2602 (1995).
- [26] G.P. Agrawal, *Nonlinear Fiber Optics* (Academic, San Diego, 2001).
- [27] B. Bouma, G. Tearney, I. Bilinsky, B. Golubovic, and J. Fujimoto, *Opt. Lett.* **21**, 1839 (1996).
- [28] S. Chu, I. Chen, T. Liu, P. Chen, C. Sun, and B. Lin, *Opt. Lett.* **26**, 1909 (2001).
- [29] A.A. Ivanov, M.V. Alfimov, and A.M. Zheltikov, *Phys. Uspekhi* **47**, 687 (2004).