Spectral narrowing of chirp-free light pulses in anomalously dispersive, highly nonlinear photonic-crystal fibers

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Abstract: Spectral narrowing of nearly chirp-free 50-fs pulses delivered by a diode-pumped ytterbium solid-state laser (Yb DPSSL) is experimentally demonstrated using an anomalously dispersive, highly nonlinear photonic-crystal fiber (PCF). The ratio of spectral narrowing and the accompanying temporal pulse broadening are controlled by the peak power of Yb DPSSL pulses at the input of the fiber.

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Self-phase modulation (SPM) is a basic mechanism behind the spectral broadening of laser pulses in nonlinear media [1]. In certain regimes, however, SPM can induce an opposite effect, resulting in a spectral narrowing of a laser pulse [2 – 5]. This type of spectral transformation, often referred to as spectral compression, is of particular interest for the creation of efficient fiber amplifiers of picosecond pulses [6] and design of telecommunication fiber links [7]. Unlike linear spectral filtering, which rejects frequency components falling outside the selected spectral region, spectral narrowing focuses radiation energy within the required frequency band through nonlinear-optical frequency conversion, thus substantially reducing energy loss. Highly nonlinear photonic-crystal fibers (PCFs) [8, 9] allow an enhancement of spectral narrowing [10], offering attractive solutions [11] for high-resolution multiplex microspectroscopy based on coherent anti-Stokes Raman scattering (CARS) and helping to develop single-fiber-oscillator CARS microscopes.

A standard technique for spectral narrowing involves using a negatively chirped input pulse [3 – 5, 10]. SPM in a positive-n_2 medium red-shifts the leading edge of the pulse and blue-shifts its trailing edge. For a pulse with an initial negative chirp, such an operation transfers the energy from the wings of the field spectrum toward its central part, thus narrowing the spectrum. Here, we demonstrate a spectral narrowing of nearly chirp-free 50-fs pulses delivered by a diode-pumped ytterbium solid-state laser (Yb DPSSL) using an anomalously dispersive, highly nonlinear PCF. We show that the ratio of spectral narrowing and the accompanying temporal pulse broadening are controlled, in agreement with the results of numerical simulations based on the generalized nonlinear Schrödinger equation (GNSE), by the peak power of Yb DPSSL pulses at the input of the fiber.

We start with the analysis of the evolution of an ultrashort light pulse propagating through a fused silica PCF with a core diameter of about 2.2 μm, provided by the University of Bath. The diameter of air holes in the cladding of this fiber slowly varied from the central part of the fiber to its periphery, as shown in inset 1 to Fig. 1, with its average value in the central part of the cladding estimated as 1.9 μm. For a numerical analysis of pulse evolution, we used the GNSE [1] for the field envelope $A = A(z, t)$ including high-order dispersion effects, fiber loss, the shock term, as well as both instantaneous and retarded parts of third-order optical nonlinearity (i.e., Kerr and Raman effects): $\frac{\partial A}{\partial \xi} = i\sum_{k=2}^{6}\frac{(i)^k}{k!}\,\beta^{(k)}\frac{\partial^k A}{\partial \tau^k} + P_{nl}(\xi,\tau)$, where z is the propagation coordinate, t is the time variable, τ is the retarded time, $\beta^{(k)} = \partial^k \beta / \partial \omega^k$ are the coefficients in the Taylor-series expansion of the propagation constant β, $P_{nl}(\xi,\tau) = i\hat{F}^{-1}\left[n_2 \omega c^{-1} S_{eff}^{-1}\tilde{p}_{nl}(\xi,\omega_0-\omega)\right]$ is the nonlinear polarization, n_2 is the nonlinear refractive index of the fiber material, ω is the current frequency, ω_0 is the central frequency of the input field, c is the speed of light, S_{eff} is the frequency-dependent effective mode area, the operator $\hat{F}^{-1}(\bullet)$ denotes the inverse Fourier transform, $\tilde{p}_{nl}(\xi,\omega-\omega_0) = \hat{F}\left[A(\xi,\tau)\int_{-\infty}^{\infty} R(t)\left|A(\xi,\tau-t)\right|^2 dt\right]$ is the frequency-domain nonlinear polarization, $\hat{F}(\bullet)$ is the Fourier transform operator, and $R(t)$ is the Raman response function.

The profile of the group velocity dispersion (GVD) of the considered type of PCF, defined by means of the spectral interferometry (SI) technique [12], is presented in inset 2 to Fig. 1. The results of these SI-based dispersion measurements agree well with the results of calculations performed with the use of the localized-function expansion technique and the finite-element method. Parameters of the input laser field (a central wavelength $\lambda \approx 1.04$ μm and an initial FWHM pulse width $\tau \approx 50$ fs) are chosen in such a way as to model experiments with an Yb DPSSL source presented below. The effective mode area was calculated from the

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PCF structure by using the localized-function expansion technique, yielding $S_{\text{eff}} \approx 3.8\ \mu\text{m}^2$ at 1040 nm, which corresponds to a nonlinear coefficient $\gamma = \omega c^{-1} n_2 S_{eff}^{-1} \approx 50\ \text{W}^{-1}\text{km}^{-1}$.

As can be seen from the GVD profile shown in inset 2 to Fig. 1, the PCF provides an anomalous dispersion for 1.04-μm laser pulses. For the implementation of the studied spectral narrowing regime, the initial peak power P of an input laser pulse is chosen in such a way that the condition $N < 1$ is satisfied for the soliton number $N = (l_d / l_{nl})^{1/2}$, where $l_d = T^2 / |\beta_2|$ and $l_{nl} = (\gamma P)^{-1}$ are the dispersion and nonlinear lengths, T is the characteristic pulse width, related to the FWHM pulse width τ by $T \approx \tau / 1.763$, and $\beta_2 = \partial^2 \beta / \partial \omega^2$, with β being the propagation constant of the relevant waveguide mode and ω being the eradiation frequency. For the PCF used in our experiments (see inset 1 in Fig. 1), $\gamma \approx 50\ \text{W}^{-1}\text{km}^{-1}$ and $\beta_2 \approx -900\ \text{fs}^2/\text{cm}$ at $\lambda \approx 1.04\ \mu\text{m}$, yielding $N \approx 0.8$ for the maximum pulse energy of 70 pJ used in spectral-narrowing experiments presented below.

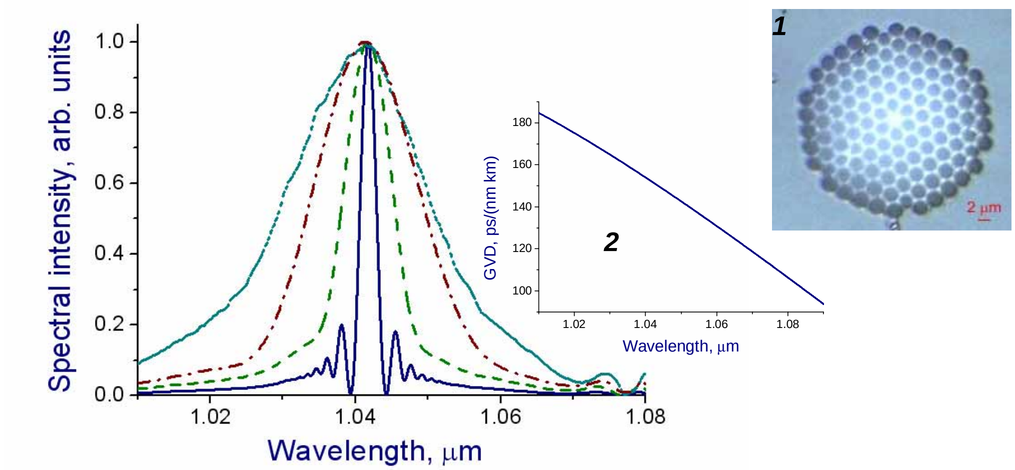

Fig. 1. Spectra of an ultrashort laser pulse with an initial spectrum shown by the dotted line transmitted through a PCF with a length of 10 cm (dash--dotted line), 50 cm (dashed line), and 250 cm (solid line). Cross section image and dispersion profile of the PCF, provided by the University of Bath, are presented in insets 1 and 2, respectively. The input peak power of the laser pulse is 1 kW.

For this regime, numerical simulations (Fig. 1) reveal a clear tendency toward a spectral narrowing of the laser field propagating through the fiber. Physically, this spectral narrowing phenomenon is a result of the joint action of SPM and dispersion. Given the temporal profile of the field intensity $I(t)$, SPM gives rise to a frequency shift $\delta\omega(t) \propto -\partial[I(t)]/\partial t$, which is negative on the leading edge of the pulse and positive on its trailing edge. With input pulse parameters matched with those of the fiber, the SPM-induced chirp can thus cancel the chirp resulting from the negative dispersion of the fiber. It is instructive to consider this SPM-induced spectral barrowing as a four-wave mixing process, where the parameters of SPM and pulse chirp are set in such a way that the central part of the field spectrum is amplified at the expense of a depletion of spectral wings. Although physically, this scenario of spectral narrowing is similar to the scenarios studied in the earlier work on spectral compression, we emphasize that, unlike spectral narrowing techniques demonstrated in Refs. 3 – 5, 10, the approach considered here does not require negatively chirped input pulses, but is also applicable to transform-limited, chirp-free fields.

As long as the input pulse parameters are chosen in such a way as to satisfy the condition $N < 1$, higher ratios of spectral narrowing can be achieved for pulses with lower input energies (Fig. 2(a)). This more efficient spectral narrowing of pulses with lower input energies, however, requires larger propagation lengths (Figs. 2(a), 2(b)). For fibers with a finite loss, the attenuation length defines an upper bound for the length of nonlinear interaction, which effectively limits the maximum attainable ratio of spectral narrowing. For input pulse parameters corresponding to $N > 1$, on the other hand, the ratio of spectral narrowing is limited because the pulse propagation dynamics is dominated by solitonic phenomena, and high ratios of spectral narrowing, occurring as a part of soliton dynamics, come into a conflict with a high efficiency of energy transfer from the input field to a spectrally compressible soliton.

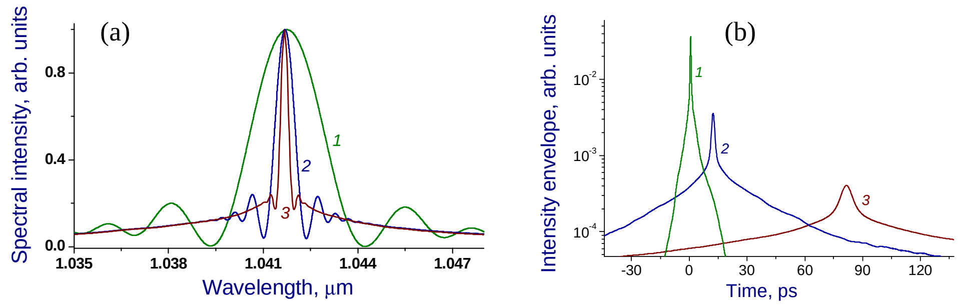

Fig. 2. The spectral intensity (a) and temporal envelope (b) of a light pulse undergoing a spectral narrowing in the PCF. The input pulse energy is 45 pJ (*1*), 38 pJ (*2*), and 35 pJ (*3*). The fiber length is 2.5 m (*1*), 33 m (*2*), and 100 m (*3*).

For an experimental demonstration of spectral narrowing, we used a diode-pumped ytterbium solid-state laser oscillator, delivering laser pulses with a spectrum centered around 1040 nm (Fig. 3(a)) at a pulse repetition rate of 75 MHz. From second-harmonic generation FROG measurements, the FWHM pulse width of the Yb DPSSL output was estimated as 50 fs (the solid line in Fig. 3(b)), with the pulse chirp not exceeding 10^{-4} fs^{-2} (the dashed line in Fig. 3(b)). Some of the spiky features in the reconstructed pulse shape may be a FROG artifact, as the entirety of experimental data indicated that the mode-locked Yb DPSSL used in experiments produced pulses with a very clean temporal envelope.

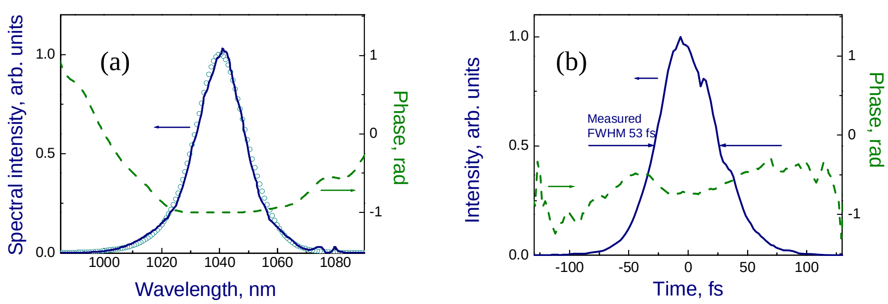

Fig. 3. Characterization of the Yb DPSSL output: (a) directly measured spectral intensity (solid line), the spectral intensity (open circles) and the spectral phase (dashed line) reconstructed from the FROG trace; (b) the temporal envelope (solid line) and chirp (dashed line).

A spectral-interferometry technique [13] was used for a full characterization of the laser field transmitted through the highly nonlinear PCF [12]. For SI measurements, the Yb DPSSL output was divided into two beams with a beam splitter. The first of these beams was launched into the highly nonlinear PCF, placed in one of the arms of a Mach--Zehnder interferometer. The second beam, transmitted through a tunable delay line in the second arm of the interferometer, provided a reference signal for the measurement of a spectral

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interferogram. Spectral interferograms measured with a resolution better than 0.1 nm were employed to extract the spectral phase of the light field at the output of PCF by using a standard SI phase-retrieval algorithm [14]. The temporal envelope of the PCF output was then calculated by taking the Fourier transform of the spectrum measured at the output of the fiber with the spectral phase defined from SI measurements.

Figures 4 and 5 present the results of SI measurements performed on Yb DPSSL pulses transmitted through a 30-cm piece of PCF. Results of GNSE-based simulations, as can be seen from Fig. 4, provide an excellent fit for the experimental data. Both experimental and theoretical results indicate a substantial narrowing of laser pulses transmitted through the highly nonlinear PCF. We quantify this effect in terms of the spectral narrowing ratio, defined as $\psi = (\Delta\omega)_{in}/(\Delta\omega)_{out}$, where $(\Delta\omega)_{in}$ and $(\Delta\omega)_{out}$ are the root-mean-square spectral widths of the input and output fields, respectively. With an input pulse energy of 70 pJ, a spectral narrowing ratio $\psi \approx 2.6$ was achieved using a 30-cm PCF. The central peak of the compressed spectrum in this regime carries 83% of the total energy of the field. Notably, the sinc-type spectral structure of the spectrally compressed PCF output shown in the bottom panel of Fig. 4 is ideally suited, as highlighted by Pestov et al. [15], for the suppression of coherent background in CARS microspectroscopy.

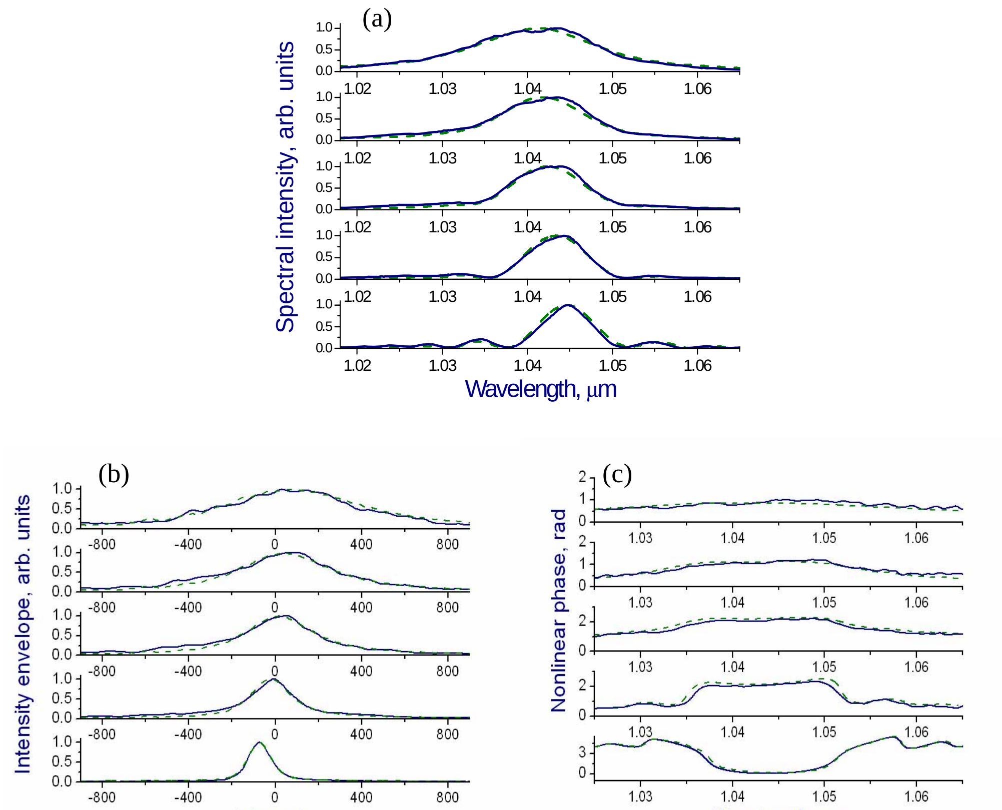

Fig. 4. Experimental (solid lines) and theoretical (dashed line) spectra (a), intensity envelope (b), and the nonlinear part of the spectral phase (c) of Yb DPSSL laser pulses transmitted through a 30-cm piece of PCF. The input laser pulse peak power is (from top to bottom) 0.4, 0.8, 0.9, 1.1, and 1.3 kW. The input pulse width is about 50 fs.

A unique feature of spectral narrowing in the regime of anomalous dispersion implemented in our experiments is associated with the possibility of maintaining a short pulse

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width of a laser field simultaneously with the narrowing of its spectrum. This regime of spectral transformation, illustrated in Fig. 5(a), requires a careful matching between the parameters of the input laser field and those of the PCF for the generation of pulses with a minimum chirp at the output of the fiber. In our experiments, for an input peak power of 1.4 kW, the spectrally compressed PCF output (filled circles in Fig. 5(a)) had a pulse width of about 130 fs in the time domain (filled circles in Fig. 5(b)). Although this pulse width was a factor of 2.6 larger than the input pulse width, it still suggested a pulse-width reduction by a factor of 7.7 relative to the PCF output measured for an input laser pulse with the same initial pulse width, but a peak power of 0.35 kW (open circles in Fig. 5(b)). This substantial reduction in the pulse width with the increase in the input laser peak power becomes possible, as can be seen from Fig. 5(a), through a generation of PCF output with a much flatter spectral phase. The possibility of maintaining a short pulse width of a spectrally compressed PCF output offers an interesting option for time-resolved measurements in nonlinear microspectroscopy, as well as for the spectral matching of a broadband output of mode-locked femtosecond laser sources, including fiber oscillators and laser sources of few-cycle pulses, to a narrower gain band of an amplifier stage [16].

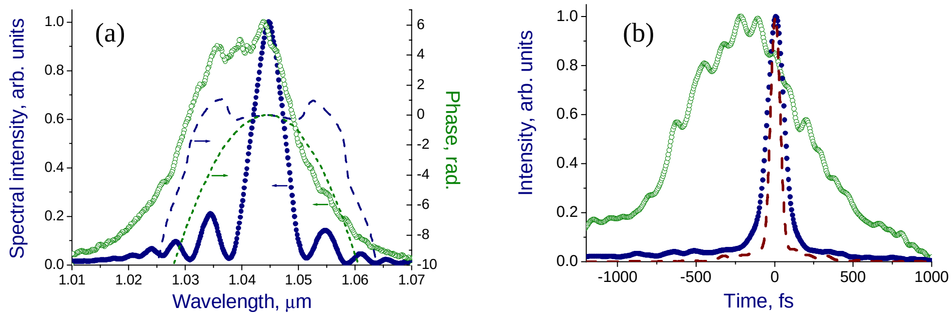

Fig. 5. Results of experiments demonstrating spectral narrowing of chirp-free pulses in a highly nonlinear PCF. (a) The spectrum (circles) and the spectral phase (dashed and dotted lines) of Yb DPSSL pulses transmitted through a 30-cm piece of PCF. The peak power launched into the fiber is 0.35 kW (open circles and the dotted curve) and 1.4 kW (filled circles and the dashed curve). The input pulse width is 50 fs. (b) Temporal envelope of the PCF output for laser pulses with a peak power of 0.35 kW (open circles) and 1.4 kW (filled circles). The dashed line shows a transform limited pulse corresponding to the measured spectrum at the output of the 30-cm PCF.

We have thus demonstrated a spectral narrowing of nearly chirp-free 50-fs pulses delivered by a diode-pumped ytterbium solid-state laser using an anomalously dispersive, highly nonlinear silica PCF. This regime of spectral narrowing is shown to allow a short pulse width of a laser field to be sustained simultaneously with the narrowing of its spectrum. The ratio of spectral narrowing and the accompanying temporal pulse broadening are controlled by the peak power of Yb DPSSL pulses at the input of the fiber.

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