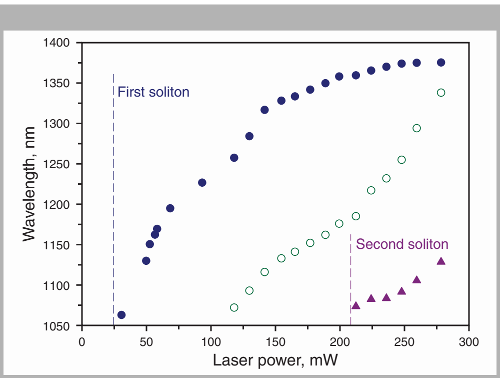
Abstract: Soliton self-frequency shift in a highly nonlinear photonic-crystal fiber is shown to enable an efficient wavelength conversion of 100-fs 70-MHz output of a solid-state ytterbium laser, allowing the generation of sub-100-fs laser pulses with a central wavelength tunable from 1060 to 1400 nm. In the single-soliton regime, laser pulses are efficiently converted into isolated wavelength-tunable bands, with a photon-number conversion efficiency of 82% achieved for ytterbium-laser pulses converted to a spectral band at 1125 nm supporting 35-fs transform-limited pulses. For high input powers, the ytterbium-laser pulses are coupled to multiple solitons inside the fiber, enabling efficient supercontinuum generation through involved soliton dynamics.



Central wavelengths of three frequency-shifted solitons at the output of a 30-cm piece of the 1.6-μm-core-diameter PCF measured as functions of the average laser power

Widely tunable 70-MHz near-infrared source of ultrashort pulses based on a mode-locked ytterbium laser and a photonic-crystal fiber

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Highly nonlinear photonic-crystal fibers (PCFs) [1,2] push the frontiers of ultrafast laser science and technologies. These fibers enable efficient spectral and temporal transformation of ultrashort light pulses [3], offering an attractive fiber-format alternative to conventional wavelength converters based on nonlinear-optical crystals. Supercontinuum generation in PCFs [4,5] has been intensely studied and used through the past decade as the key technology enabling the control of the carrier-envelope phase of few-cycle field waveforms [6] and the development of novel broadband sources [7,8] for spectroscopy, microscopy, bioimaging, and frequency-comb metrology. Soliton-self-frequency shift (SSFS) [9] in highly nonlinear PCFs allows an efficient, widely tunable wavelength conversion of ultrashort laser pulses [10,11] and helps to all-optically synchronize the pump and seed fields in optical parametric amplification of few-cycle light pulses [12–14]. Nonlinear-optical PCF components have been shown to be ideally suited to work in combination with Ti:Sapphire and Cr:Forsterite solid-state mode-locked sources [3–5,15], as well as with ytterbium fiber lasers [16–19].

Here, we show that SSFS in a highly nonlinear PCF can provide an efficient wavelength conversion of 100-fs 70-MHz output of a solid-state ytterbium laser, allowing

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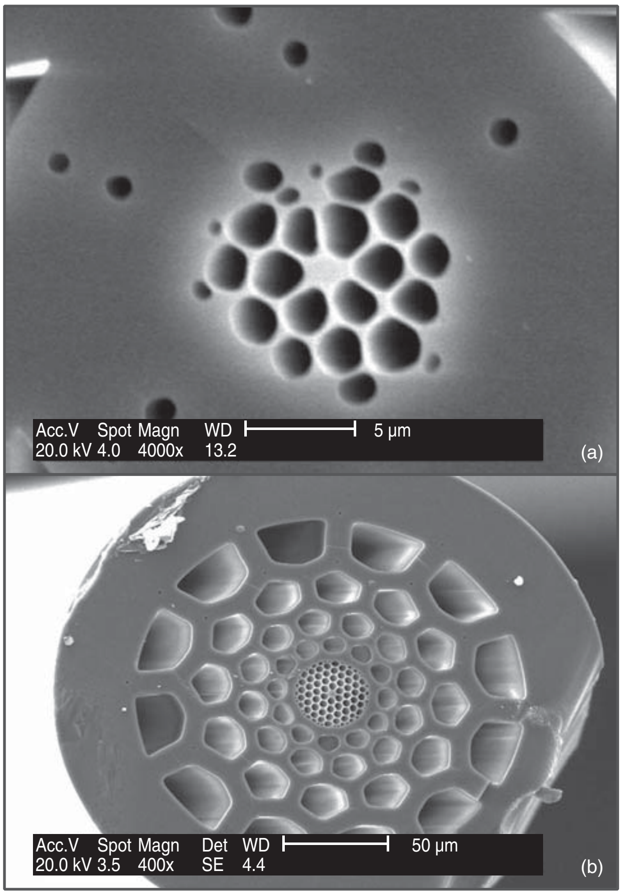

Figure 1 (online color at www.lphys.org) SEM images of photonic-crystal fibers. The fiber core diameter is (a) 1.6 μm and (b) 2.0 μm

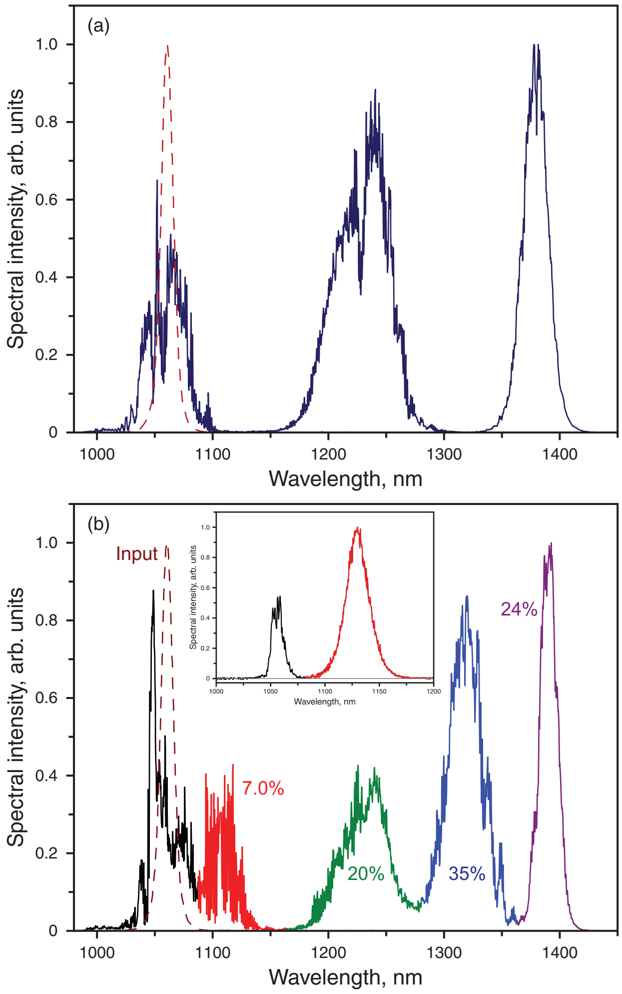

Figure 2 (online color at www.lphys.org) Typical spectra measured at the output of the PCF with a core diameter of 1.6 μm. The input laser power is (a) 247 W and (b) 260 W. The fiber length is 30 cm. The spectrum of input laser pulses is shown by the dashed line. The inset displays the PCF output spectrum PCF measured for an input pulse energy of 1 nJ

the generation of sub-100-fs laser pulses with a central wavelength tunable from 1060 to 1400 nm. We demonstrate that, by changing the power of input laser pulses, the regime of wavelength conversion in a PCF can be switched from efficient frequency shifting in isolated tunable spectral bands to supercontinuum generation.

In experiments, 100-fs pulses with a central wavelength of 1058 nm, delivered by a solid-state ytterbium laser at a repetition rate of 70 MHz, were launched into a PCF with a short-focal-length lens. Two types of PCF were used in experiments (Fig. 1a and Fig. 1b), both providing anomalous dispersion at 1058 nm. In the PCF of the first type (Fig. 1a), a 1.6-μm-diameter silica core is surrounded by two rings of air holes, which serve to confine the light field in the fiber core, thus enhancing optical nonlinearity. PCF of the second type (Fig. 1b) is a dual-cladding fiber with a core diameter of 2.0 μm. The inner part of the microstructure cladding in this fiber is designed toward providing the desired dispersion profile of the fundamental waveguide mode, minimizing temporal stretching of ultrashort laser pulses used in experiments. The strong confinement of light within a small fiber core (1.5 – 2.0 μm for the PCFs used in experiments) provides a high nonlinearity, allowing efficient spectral transformation of low-energy laser pulses. The maximum energy attainable with our laser source was 7 nJ. An attenuator consisting of a half-wave plate and a Glan prism was used to control the energy of laser pulses coupled into the fiber.

Light pulses propagating in an anomalously dispersive fiber tend to generate optical solitons, with the number of these solitons N and their parameters controlled by the peak power and the pulse width of the input pulses, as well as dispersion and nonlinearity of the fiber. Because of the Raman effect, the central wavelengths of the soliton pulses are red-shifted (Fig. 2a and Fig. 2b), enabling tunable wavelength conversion of the Yb-laser output. For

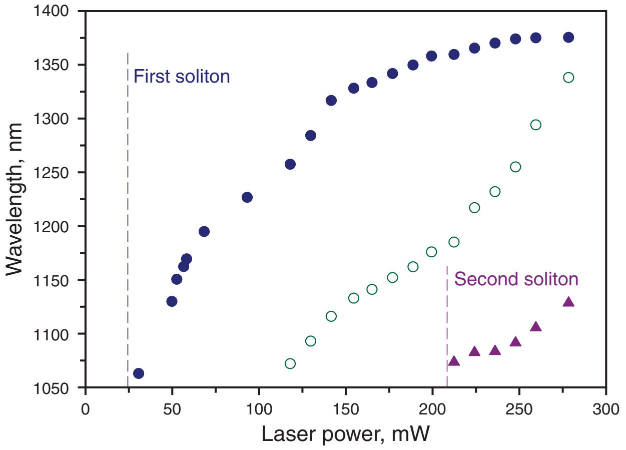

Figure 3 (online color at www.lphys.org) Central wavelengths of three frequency-shifted solitons at the output of a 30-cm piece of the 1.6-μm-core-diameter PCF measured as functions of the average laser power. The vertical dashed lines show the thresholds for the excitation of the j=1 and j=2 solitons

ideal solitons defined as solutions to the canonic nonlinear Schrödinger equation, the energy carried by the j-th soliton ($j = 1, \dots, N$) and expressed in soliton units [20] is $E_j = 4\xi_j$, where $\xi_j = W - j + 0.5$ is the soliton eigenvalue, controlled by the input pulse energy $E_0 = 2W^2$ (also measured in soliton units [9,20]). For a highly nonlinear PCF with a core diameter of 1.6 μm (shown in Fig. 1a), the second-order dispersion coefficient for the waveguide mode with the largest propagation constant β is $\beta_2 = \partial^2\beta/\partial\omega^2 \approx 0.1$ ps^2/m. The coefficient of nonlinearity for this mode is $\gamma \approx 90$ W^{-1}km^{-1}. The peak power of the lowest-order soliton supported by such a fiber at a central wavelength of 1058 nm is $P_1 \approx 0.33$ kW. With a soliton pulse width $\tau_1 \approx \tau_{FWHM}/1.67 \approx 60$ fs and a repetition rate of 70 MHz, this translates into a pulse energy of about 40 pJ and an average laser power of $\tilde{p}_1 \approx 2.8$ mW.

In experiments, the lowest-order solitons become visible in the spectra measured at the output of the PCF (filled circles in Fig. 3) for laser average powers above $p_l \approx 23$ mW, which correlates well with a laser-beam incoupling efficiency for this type of fiber. The pulse width of an ideal soliton decreases with the growth in its energy in accordance with $\tau_1 = \tau_0/2\xi_1$, where τ_0 is the input pulse width. Although high-order dispersion and Raman effects give rise to deviations from this scaling, a noticeable spectral broadening of solitons with respect to the input pulse observed in our experiments (Fig. 2a and Fig. 2b) indicates efficient pulse compression, occurring as a part of soliton dynamics in the highly nonlinear fiber. The bandwidth of the soliton feature centered at 1125 nm in the inset to Fig. 2b is approximately 40 nm, corresponding to a transform-limited pulse with a pulse width of about 35 fs. The photon-number conversion efficiency from the input laser field for this soliton is estimated as 82%. Four soliton pulses whose spectral signatures are presented in Fig. 2b carry different fractions of the overall PCF output energy, ranging from 7% for the soliton pulse centered at 1100 nm to 35% for the 1320-nm soliton. As a general tendency, the frequency shift of optical solitons first rapidly increases with the growth in the energy of input laser pulses, but then saturates due to high-order dispersion, diffraction, self-steepening, and waveguide loss [21–23].

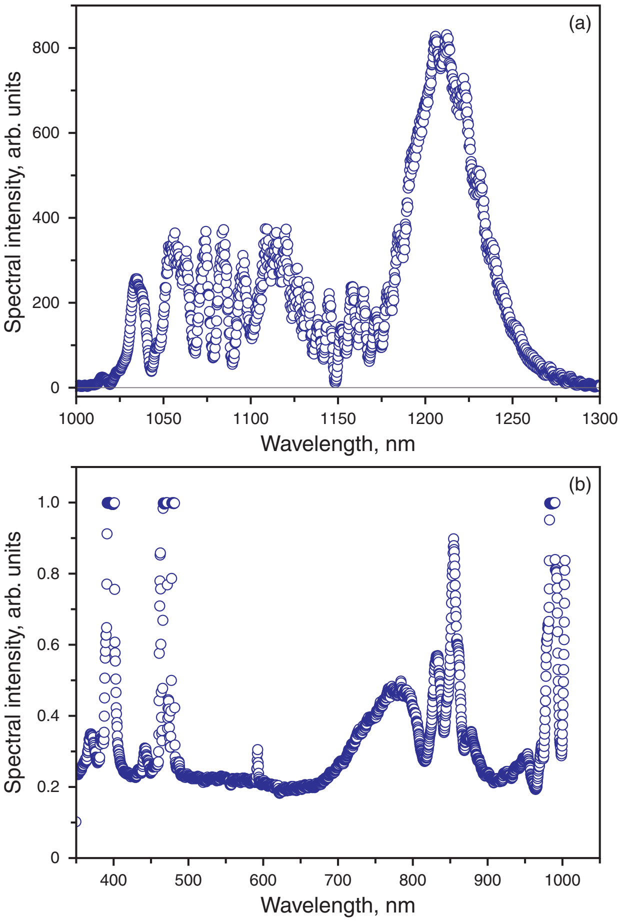

Figure 4 (online color at www.lphys.org) Infrared (a) and visible (b) parts of the spectrum measured at the output of a 9.5-cm piece of the 2.0-μm-core-diameter PCF

The next-order (j=2) soliton is generated in the same polarization mode when a peak power

$$P_2 = \left[\frac{W(\xi_2 = 0)}{W(\xi_1 = 0)}\right]^2 P_1 = 9P_1$$

is launched into the fiber. Indeed, features indicating the generation of such solitons become visible in PCF output spectra for average laser powers above $p_2 \approx 210$ mW (triangles in Fig. 3), which is approximately nine times higher than the average power needed for the generation of the lowest-order soliton. Solitons of different orders give rise to stable interference fringes in PCF output spectra (Fig. 4a), indicating the mutual coherence of solitons, which can be employed to synthesize few-cycle pulses in the infrared.

Solitonic features observed in PCF output spectra for laser powers exceeding 110 mW (open circles in Fig. 3) are attributed to the orthogonal polarization mode. The vectorial, multimode nature of solitons generated in a PCF is confirmed by intense dispersive waves, generated in the visible part of PCF output spectra (Fig. 4b) as a result of soliton instabilities induced by high-order dispersion. The spectrum of dispersive waves suggests that a manifold of polarization and/or spatial modes of the PCF contribute to the nonlinear-optical transformation of laser pulses in the fiber. In the regime of high input energies, the spectral lines related to wavelength-shifted solitons and dispersive radiation lines tend to merge into a broadband continuum spectrum (Fig. 4a and Fig. 4b).

We have shown in this work that soliton self-frequency shift in a highly nonlinear PCF enables efficient wavelength conversion of 100-fs 70-MHz output of a solid-state ytterbium laser, allowing the generation of sub-100-fs laser pulses with a central wavelength tunable from 1060 to 1400 nm. The regime of PCF-based wavelength conversion can be switched by varying the input laser power. In the single-soliton regime, laser pulses are efficiently converted into isolated wavelength-tunable bands, with a photon-number conversion efficiency as high as 82% attainable for ytterbium-laser pulses converted to a spectral band at 1125 nm supporting 35-fs transform-limited pulses. For high input powers, the ytterbium-laser pulses are coupled to multiple solitons inside the fiber, enabling efficient supercontinuum generation through involved soliton dynamics.

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