Spectral shaping of supercontinuum in a cobweb photonic-crystal fiber with sub-20-fs pulses

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Multiple approaches to generate a smooth, powerful, and stable supercontinuum in cobweb photonic-crystal fibers were undertaken by use of 18-fs pulses. These approaches include utilization of incident pulses with various chirp, power, and polarization states, as well as fibers with different lengths and core sizes. For long fibers (tens of centimeters) the supercontinuum contains a finely modulated structure that can be smoothed when the oscillator is in a regime of relaxation oscillations. Short fibers provide a supercontinuum free of gaps. By optimization of these parameters supercontinua exceeding one octave with modulations of less than 10 dB have been generated. © 2002 Optical Society of America

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1. INTRODUCTION

A smooth supercontinuum (SC) is needed for many scientific applications. Among them are optical coherence tomography[1,2] (OCT), high-precision spectroscopy,[3] and generation of extremely short[4] and phase-stabilized short pulses.[5–9] For the first two applications a smooth rectangular or quasi-Gaussian spectrum is preferred. It was previously shown that photonic-crystal fibers (PCFs) permit the generation of a SC covering more than one octave,[10] but in many cases the spectral gaps are too deep (strong modulations of more than 10 dB and even gaps of 10–30 nm appear), limiting their direct application. Although OCT already utilizes a SC generated by PCF in the infrared,[1] it is essential to extend the spectral range to the visible down to 0.4 μm (Ref. 2) to further enhance the OCT axial resolution and provide access to a spectral region that is interesting for spectroscopic OCT of biological chromophores. Because gaps in the spectrum can affect the OCT image quality as well as the precision of the measurements, optical sources with spectral variations of less than 10 dB are desirable.

The SC generated by PCFs can be optimized by two different approaches: optimization of the conditions under which the SC is generated or utilization of spectral shapers. Because spectral shapers are restricted in their performance as a result of their limited spectral range and high losses, this paper focuses on the first approach.

As a result of the high nonlinearity of PCFs the generated SC is extremely sensitive to amplitude fluctuations of the incident radiation, inducing a complex phase distribution in the SC and additional noise. Indeed, PCFs show noisier behavior than conventional fibers[4,5,9] do and distort the spectral phase in such a way that the exiting pulse could not, until now, be properly compressed.[11] The additional noise can be explained by the increased number of nonlinear processes involved. Conventional fibers generate a SC mainly by self-phase modulation, resulting in a symmetrical, bell-shaped spectrum centered at the central pump wavelength.[4,5] In the case of PCFs, a number of effects such as self-phase modulation, high-order soliton formation,[12] group-velocity dispersion, third-order dispersion,[13] four-wave mixing, cross-phase modulation, birefringence, and self-steeping[14] contribute to the generation of a SC. The superpositioning of all these processes leads to its complex spectral shape. The best results to date in the attempts to produce a smooth SC spectrum rather were obtained by the utilization of 100-fs pulses[10] and a long PCF (in the range of meters), although there is no proof of coherence of such a broad SC covering 400–1600 nm.

Recent one-dimensional modeling based on the Maxwell equation[12] and the nonlinear envelope equation[13] demonstrated a qualitative agreement in the SC bandwidth with experiments in which 100-fs pulses were exploited.[10] The SC shape for different pulse durations, pulse energies, fiber structures, and fiber lengths was calculated numerically. Theory[15] predicts no birefringence for perfect PCFs, which means that polarization effects should be negligible. In specially prepared anisotropic PCFs, however, birefringence was observed.[16] Nevertheless, because of imperfections in the structure of real PCFs and a number of experimental conditions (fiber bending, stress, and the surface quality of the fiber ends) polarization effects are undoubtedly present. To our knowledge no systematic experimental results are currently available on this subject.

Predictions of the SC dependence on the pulse shape were demonstrated for picosecond pulses.[14] To date polarization issues have been investigated only for conventional fibers irradiated by 100-fs, low-peak-power pulses (some kilowatts).[17] In a recent publication[18] polarization effects were observed, although they were not as pronounced or utilized as in this study.

The main objective of this paper is to investigate whether short intense pulses (20 fs) can be used to produce smoother spectra compared with those generated by 100-fs pulses. This study is especially interesting for applications such as the generation of extremely short and phase-stabilized pulses, which might be achieved by use of short pieces of PCF as the broadening device and a compressor. It is expected that the utilization of short pulses can reduce the input power required for generation of a SC, considering that a higher peak power could result in improved efficiency of SC generation.

Here we present and discuss experimental results with an aim to generating a smooth, coherent spectrum in the 500–1100-nm range by utilization of chirp, polarization, and power control of the incident pulse. We demonstrate that spectral modulations can significantly be suppressed by use of either a self-*Q*-switching mode (which is a regime of relaxation oscillations) of a Ti:sapphire oscillator or by use of short fibers in the range of millimeters. Furthermore, our results are compared with those achieved in conventional fibers and PCFs with a high-energy Ti:sapphire oscillator.[5]

2. EXPERIMENTAL SETUP

Cobweb PCFs[19] (see Fig. 1) with core sizes of 1.6, 1.9, 2.5, 3.0, and 4.0 μm were investigated. Because the fibers consist of the same material and have the same structure, the zero-dispersion points are distributed within 700 to 1000 nm. The dispersion for the 2.5-μm fiber at the center wavelength of the input pulses was close to zero. The fibers were mounted on a three-dimensional translational piezocontrolled stage.

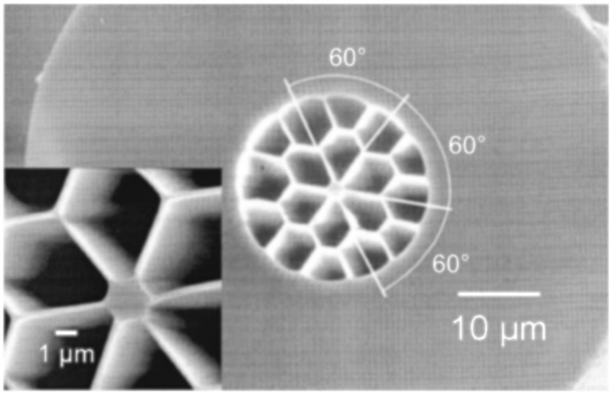

Fig. 1. Cobweb PCF structure.

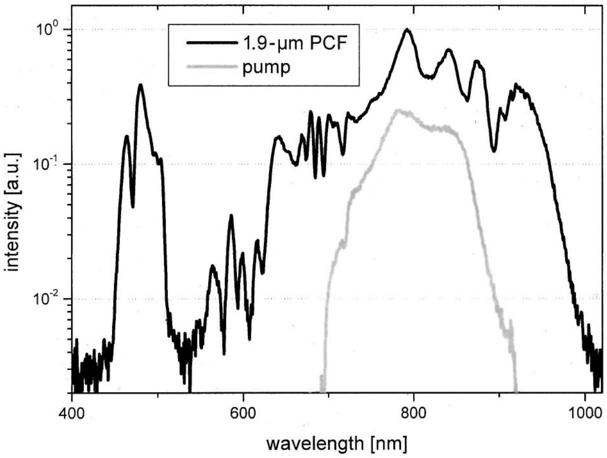

Fig. 2. SC without polarization or shape control, scaled to the maximum intensity, and with the pump source spectrum resized for better readability.

A Ti:sapphire oscillator (Femtolasers Produktions, GmbH) provided 18-fs linearly polarized pulses with an average power of as much as 600 mW at an 80-MHz repetition rate. The output spectrum centered at 790 nm is shown in Fig. 2 (gray line).

An achromatic objective with $f = 4$ mm and a numerical aperture of $\mathrm{NA} = 1.0$ was used for focusing, providing smooth dispersion with minimal chromatic aberration in the range of 700–900 nm. The intensity of the input beam was set to 0.1–5 TW/cm^2. The coupling efficiency was 10%–50%, depending on the core diameter of the fiber. Quarter- and half-wave plates designed for a central wavelength of 780 nm were used to vary the polarization properties of the incident beam. Fiber rotation about the axis is essentially equivalent to the application of a half-wave plate, but if we consider the fact that standard wave plates are designed for a single wavelength fiber rotation is preferable in the cases of spectrally broad (>70-nm) pulses. In the case of a broad initial spectrum (to 130 nm) wave plates introduce slightly different phase retardations for different wavelengths (as much as a 2% mismatch at the wings of the oscillator spectrum). As a result the polarization of the incident beam is slightly elliptically modified for some wavelengths.

Multiple pairs of chirp mirrors were used mainly to precompensate the positive dispersion of the focusing objective, so the chirp was varied by alteration of the number of reflections. The mirrors provide a change of the group-delay dispersion with only a small effect on the third-order dispersion. The total losses caused by the chirp mirrors did not exceed 15% for up to 30 bounces. Each bounce introduced approximately 40 fs^2 of negative group-delay dispersion. Spectra were measured by use of a spectrometer with an operating range of 350–1100 nm and a 3-nm resolution. The pulse properties were monitored with a fast photodiode and an autocorrelator.

3. RESULTS

Because of the limitations of the spectrometer, the observed SC ranged from 400 to 1100 nm, depending on the core diameter of the fiber. Two different approaches were undertaken to smooth the SC.

First, fibers with various lengths and core diameters were investigated. In fibers with core diameters of less than 2 μm, the blue part of the SC was more pronounced, but a gap at approximately 530 nm appeared (see Fig. 2). In PCFs with larger cores the modulation of the SC spectra was smaller, whereas spectral broadening was weaker. The dependence of the SC on the fiber length (50–1000 mm) was not strong; however, with longer fibers, the spectra became broader and more stable, and new peaks appeared within the gaps. As shown in Fig. 3, curve b, for these long fibers, on the other hand, fine fluctuations in the temporal SC structure were unavoidable (qualitatively the same behavior has been obtained for the SC with and without polarization and chirp control).

The period of the fine structure is 6.5 ± 1 THz, which in the time domain corresponds to two simultaneously propagating pulses in the fiber with a separation of 150 fs at the output. Operating the mode-locked oscillator in a so-called self-*Q*-switched (or relaxation oscillation) mode,[20] where a pulse-train envelope modulation appears at 500 kHz (see the inset in Fig. 3), resulted in the fluctuating structure's being washed out (Fig. 3, curve a). The self-*Q* switching leads to modulations of the average pulse energy, spectrum, and duration. This regime is stable (see the inset) and was obtained by variation of the pump level of the oscillator or by movement of one of the focusing mirrors of the cavity. The average pulse duration was comparable in the case of pure mode locking with that of self-*Q*-switched mode locking.

Because we had limited success in generating a smooth SC by varying only the PCF's core diameter and its length, polarization and chirp control of the incident pulse were added to our approach. An analyzer placed behind the fiber selected the linear polarization state of the exiting radiation. In Fig. 4 the spectral dependence on fiber orientation along the azimuthal axis is shown for a 2.5-μm fiber (for other PCFs a similar sensitivity was observed). A dip at 720 nm can be shifted to 660 nm just by rotation of the fiber in addition to an increase of the SC bandwidth. The spectral structure reproduces itself approximately every 60°, in agreement with the symmetry of the PCF structure shown in Fig. 1. At some fiber orientations along the azimuthal axis additional modulation (to as much as 30%) of the output intensity appeared. The temporal stability of the SC was high in the infrared, but fluctuations were strong on the blue side of the spectrum.

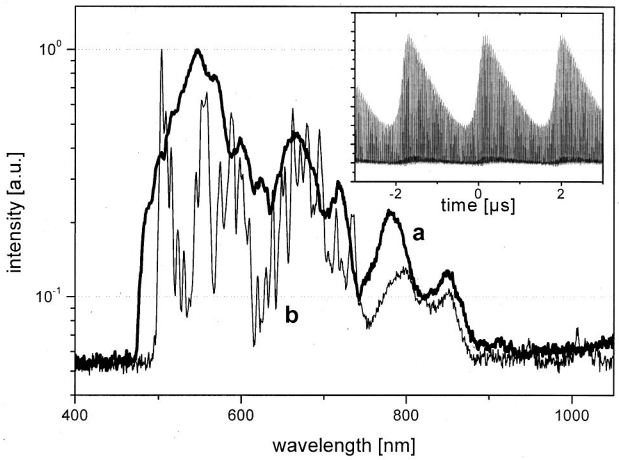

Fig. 3. SC (2.5-μm core diameter, 90 cm long) in two regimes: Curve a shows relaxation oscillations (self-*Q* switching), and curve b shows stable pulses of equal amplitude. Inset: The pulse train for curve a with polarization and chirp control enabled.

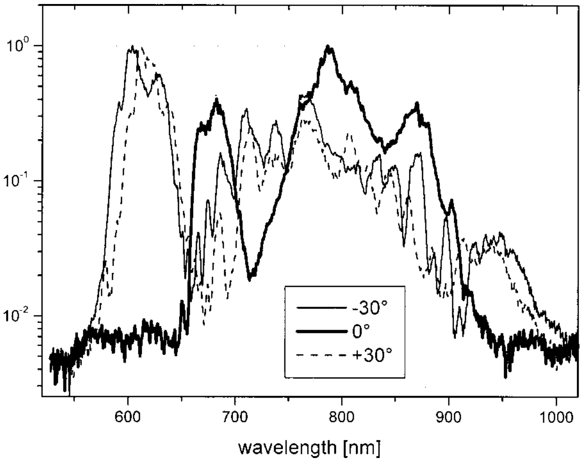

Fig. 4. SC (core diameter of 2.5 μm, 41-mm length) for different fiber orientations along the azimuthal axis.

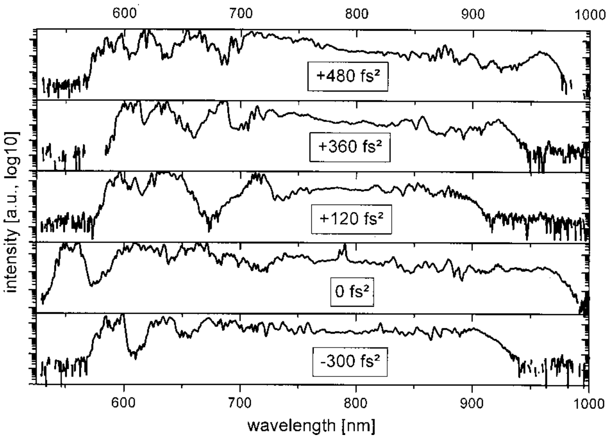

Fig. 5. SC (PCF with a 2.5-μm core) for different prechirps of the incident 18-fs pulse. The input average power was 400 mW.

Without wave plates in front of the fiber, the exiting radiation was mainly linearly polarized, but the orthogonal components were significantly stronger than at the input. The spectral components in the range of 500–600 nm differed in their polarization states. Using the wave plates caused the signal behind the analyzer to show an even more complex state of polarization, which allowed smoothing of the whole spectrum. The polarization dependence of the SC spectra can be observed with short and long, as well as bent, fibers. Figure 5 shows the spectral dependence on the chirp of the incident pulse. One can see a distinct variation in the spectral shape in the range of 530–750 nm and 870–1000 nm. The output spectrum is broader for the transform-limited pulses.

By use of polarization control the SC was investigated further with respect to pump-power (Fig. 6) and core-diameter (Fig. 7) dependences. These spectra already show significant improvement but are still limited by gaps of 20 dB. Reducing the fiber length to 4 mm not only allowed us to suppress fluctuations to less than 10 dB but also smoothed the SC substantially. The output power from the fiber was 30 mW in all three cases (Fig. 8).

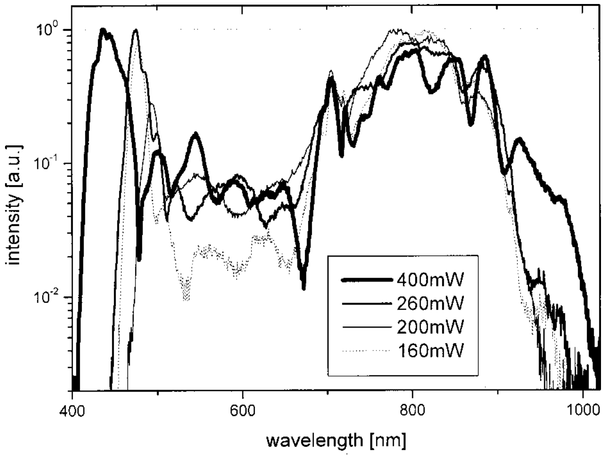

Fig. 6. Power dependence of the SC spectra for the PCF with a 1.9-μm core. Polarization and chirp control were used.

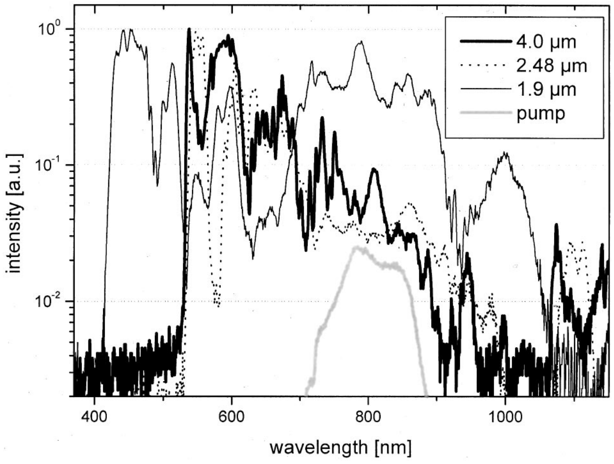

Fig. 7. SC for PCFs with different core diameters at an input power of 300 mW. The throughput is 10%–50%, depending on core diameter.

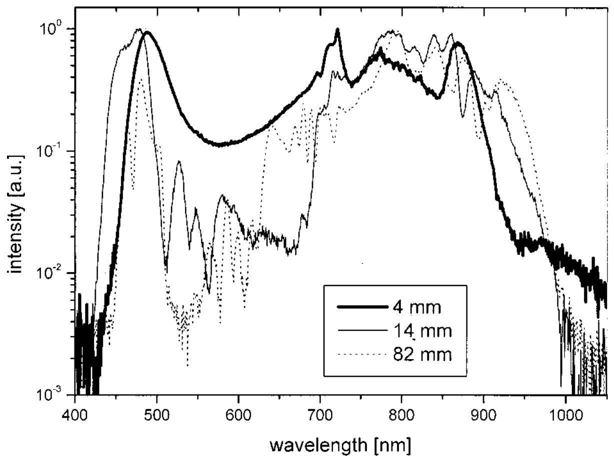

Fig. 8. SC for different-length PCFs with a 1.9-μm core. The output power is 25–28 mW.

4. DISCUSSION

As was mentioned in the introduction, a number of nonlinear processes lead to the formation of a SC. An oversimplified expression for normalized broadening caused by self-phase modulation, $\Delta\omega/\omega = n_2PL/cS\tau$ (Ref. 21), where n_2 is the nonlinear refractive index, P is the peak power, L is the fiber (effective) length, S is the effective mode area, c is the speed of light, and τ is the pulse duration, can be used as only a guideline. The other broadening mechanisms cannot be expressed in a similarly simple way because of their complexity. The experimental fiber-length dependence of the SC was clearly obtained for weak long pulses[22,23] for different types of fibers. This dependence is not pronounced in the case of short intense pulses (at more than 1 TW/cm^2). The dependence of the SC width with respect to changes of the average power is weak for both PCF and conventional fibers, especially at higher powers. Broadening in conventional fibers provides a smoother, bell-shaped-like spectrum in experiments[4,5] and theory.[24]

For short 9-fs pulses (intensity level, 10 TW/cm^2), the broadening in PCFs was not stronger than that in conventional fibers of similar core diameter,[25] but such pulses allow one to use relatively short conventional fibers of either type (as short as 1 mm) that can provide one-octave spectra for generating extremely short pulses or for stabilizing the absolute phase of the pulse.[4,5] It is worth noting that, in the only publication devoted to the compression of the SC behind the PCF,[11] the authors used a fiber of 16 cm in length but were unable to compress these pulses. The present paper suggests that the spectral phase is smoother in the case of a 4-mm fiber (see Fig. 8) that might allow the proper compression of the exiting pulse. Comparing the results presented in this paper and those in Refs. 6 and 22, we can conclude that the use of weak (some kilowatts of peak power) long pulses (100 fs) in long PCFs (of the order of 1 m) provide a SC of higher quality. On the other hand, shorter pulses allow one to reduce the average power of the incident pump that is desirable for several commercial applications, such as OCT.

The results presented here on the subject of the broadening factor and of the noise at the output are not in complete agreement with those obtained from numerical modeling.[12,13] Let us formulate some relevant statements of Ref. 12 because our experimental conditions are close to those ones treated there: (i) There should be a pronounced difference in the SC shape for long (100-fs) and short (10–20-fs) pulses. Because of different mechanisms, the SC in the case of short pulses is not expected to be comparably wide as a result of the low number of solitons. The solitons created in the fiber have different frequencies, and, after fission within the fiber, they form the blue-shifted continuum. The more solitons that are involved, the broader is the SC expected. (ii) The SC is predicted to contain more noise in case of long pulses and long fibers.

In terms of statement (i), as can be seen from the experimental part above and comparison with the results of Ref. 10, short pulses do not provide significantly less broadening. In opposition to theory the SC spectra are noisier in the case of short pulses (for the same fiber length). From a physical point of view short pulses should provide more channels for spectral broadening that could lead to extra noise. This noise can prevent or limit some physical applications, such as stabilization of the pulse phase.[5–9] Note that in the model[13] the inherent SC noise is dependent on the pulse parameters. It increases with the input power and depends on the pulse stability and the integration time of the detector. The model predicts a slight frequency shift in the fine structure of the SC caused by energy fluctuations. The latter conclusions are in qualitative agreement with our results for a smooth SC in a self-*Q*-switching mode (see Fig. 3; the averaging time is longer than the period of the relaxation oscillations). In terms of statement (ii) long fibers indeed produce noisier output. An explanation for that could be that during the propagation along the fiber a competition of different nonlinear processes takes place.

As can be seen from Fig. 1, a real PCF is not perfect in the outer part of the web structure, and the core is not round but hexagonal (see inset of Fig. 1), which results in the observed effects of 60° azimuthal symmetry that were used for smoothing the spectrum. The PCF's azimuthal rotation is important in terms of experimental operation: Intuitively, the fiber must be adjusted in such a way that its photonic-crystal web coincides with the polarization plane of the incident beam. Tilting the polarization plane makes the beam sensitive to a slightly different core diameter (because of its hexagonal shape), which changes the dispersion seen by the pulse. Note that theory[15] does not take the noncylindrical core shape into account. Elliptical polarization would then lead to a continuous change of the dispersion, while the pulses (solitons that are generated at the entrance) are propagating differently, thus generating different spectra that can interfere at the output. This statement is supported by the experimental results that demonstrate that equally spaced modulations with a period of approximately 30 nm appear when the quarter-wave retarder is rotated. The polarization dependence of the SC is pronounced but seems difficult to model (time-consuming three-dimensional simulations are needed). Commonly, the PCF provides an additional degree of freedom for researchers to adjust the spectral shape of the SC resulting from its broken azimuthal symmetry. The large number of nonlinear processes occurring in the PCF under femtosecond-pulse irradiation can be utilized for smooth SC spectra generation if the number of knobs for controlling the broadening is also reasonable. Polarization and dispersion (chirp) control are examples of knobs that can be used for any type of PCF, providing higher efficiency and easy operating conditions.

5. CONCLUSION

In conclusion, we have presented results of experimental investigations of the spectral properties of SCs generated by cobweb PCFs. By means of fiber adjustment, chirp manipulation, polarization, and power properties of the incident 18-fs pulses, we were able to smooth the output spectra for fibers with different core diameters, ranging from 1.6 to 4 μm. Experimental results have demonstrated that long fibers (tens of centimeters) tend to introduce fine gaps into the SC spectrum, whereas short ones can lead to smoother spectra. The proposed simple technique has several advantages, such as higher throughput, lower costs, and higher sensitivity. It is applicable independently of a specific PCF structure and size as well as of the pulse parameters. Three-dimensional numerical simulations may be able to explain the observed polarization dependency in the generated spectra. Short pulses at high energy do not provide broader or overall smoother SC that are comparable with what was demonstrated before for long weak pulses but can generate similar spectra at lower average input power and in shorter fibers.

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