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Fiber Supercontinuum Generators with Dynamically Controlled Parameters

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Abstract—Various methods to dynamically control the supercontinuum (SC) parameters are analyzed. The possibility of variations in the SC power spectral density due to variations in the wavelength and pulse repetition rate of the pumping laser is considered. An increase in the SC coherence owing to the optimization of the pump-pulse frequency modulation is discussed. A variation in the repetition rate of the SC pulses generated in the scheme with the two-wavelength pumping due to a variation in the frequency difference is studied.

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The supercontinuum (SC) [1] generation is widely used in various applications. Note that different applications impose different and, sometimes, incompatible requirements on the SC radiation. For example, the metrology of optical frequencies necessitates the application of the SC with a spectral width of no less than an octave at a relatively high stability of the amplitude and phase. One must use broadband radiation in the optical coherence tomography (OCT), whereas the multiwave sources in the WDM technology can employ a relatively narrow part of the SC spectrum, but must exhibit an uniform power spectral density and a regular time structure of radiation (a periodic pulse train). In an alternative telecommunications application of the SC radiation (backward-pumped fiber Raman amplifiers [2]), the profile of the SC power spectral density must provide a spectrally uniform gain in the absence of strict requirements on the time structure of the SC radiation. In various schemes for the ultrashort pulse (USP) generation, the SC intensity distribution represents a pulse train with a quadratic- and cubic-phase modulation [3]. The possibility of the compression of the SC wave packets with a relatively complicated time structure using spatial modulators has been recently demonstrated in [4].

Thus, the creation of versatile SC generators that can be used in various applications necessitates a dynamic variation in the radiation parameters that is needed for a particular system. In addition, the dynamic variation in the generation parameters is needed in spectroscopy, cytometry, biomedical applications, etc. Conventional SC generators only allow a variation in the total radiation power and a smooth tuning of one or several wavelengths selected from the broad SC spectrum by an externally controlled spectral filter. Note that a variation in the total power is normally based on a variation in the pump power. However, the latter also determines the SC spectral width, so that the variation appears ineffective with respect to the tuning of the SC power spectral density. The tuning range of the selected wavelengths is limited by the free-dispersion range of acoustooptical filters (no greater than an octave). However, several applications necessitate a wider variation in the SC radiation parameters. In this work, we analyze various methods that can be used to change the parameters of the broadband radiation generated using the most popular scheme of the SC generator. Such an SC generator consists of a pump source that can contain a master oscillator and an amplifier, a nonlinear optical fiber in which the pump radiation is spectrally broadened, and a filter (transformer). The last component is used to select a single or several spectral components from a broad SC spectrum, to compensate for the frequency modulation of the selected pulses, etc. The dynamically varied parameters of the pump source are the radiation power and wavelength; the pulse duration, phase modulation, repetition rate, and shape (for the pulsed pump); and the spectral structure (line width and the modulation frequency and depth) in the case of CW pumping. The nonlinear optical fiber that is used for the spectral broadening of the pump radiation offers poor tuning possibilities: one can only change the Bragg gratings of the refractive index recorded in the fibers, vary the thermal effects, and induce anisotropy. The output radiation transformer makes it possible to control the width and position of the selected spectral lines, the pulse duration and phase modulation, and the pulse repetition rate (in the presence of multiplexers). Variations in the above parameters of the generator can lead to variations in one or several parameters of the output radiation: the SC spectral width and shape, the total power, the power spectral density, the coherence, and the parameters of the time distribution. Below, we analyze the effect of the dynamically controlled pump parameters on the SC characteristics. The analysis is based on our experimental data and the results of the

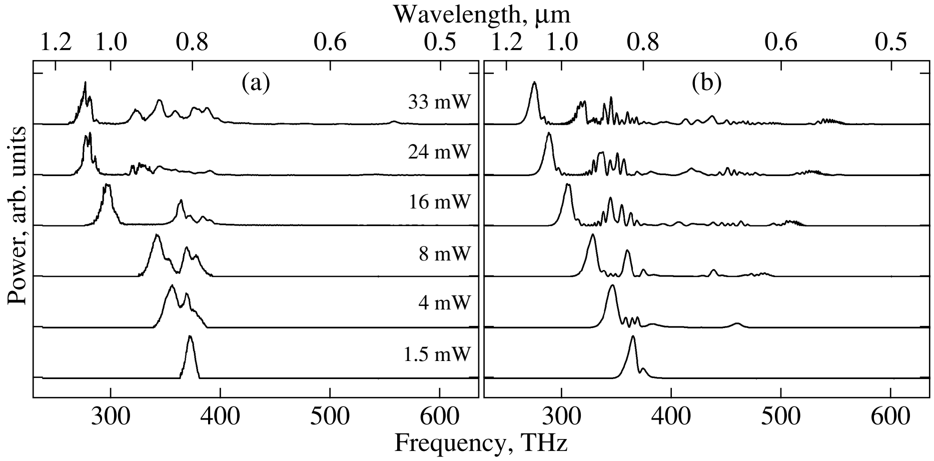

Fig. 1. (a) Experimental and (b) calculated SC spectra obtained for the biconical fiber with a waist of 2.3 µm and a length of 12 cm that is pumped by a 80-MHz train of the 50-fs pulses of the Ti:sapphire laser at a wavelength of 805 nm. The mean pump powers are shown on the curves.

computer simulation involving the numerical solution of the generalized nonlinear Schrödinger equation as well as the literature data.

We have demonstrated that an increase in the pump power normally results in an increase in the SC power and spectral width upon the pulsed [5] and CW [6] excitation. In the case of the pulsed pump, an increase in the power is additionally accompanied by an increase in the number of peaks in the spectra and the time structure of the SC radiation and a decrease in the degree of interpulse coherence [7]. This is seen from Fig. 1, where we present the experimental and calculated spectra of the SC generated in biconical fibers at various pump levels. The numerically simulated dependence of the degree of interpulse coherence on a product of duration T and power P of the pump pulses is shown in Fig. 2. Note that, at relatively high pump powers, we observe the saturation of the SC power [8] due to an increase in the energy loss related to the stimulated Raman scattering and the IR absorption in silicon fibers. This effect can limit the applicability of the method to control the SC parameters based on a variation in the pump power. Thus, alternative solutions must be elaborated.

One of the alternative techniques enabling one to control the SC spectral width and, hence, the power spectral density, is based on a variation in the wavelength of the pump pulses in the vicinity of the zero-dispersion wavelength of the fiber. We have demonstrated a possibility of such a control using 80-fs pump pulses of a Ti:sapphire laser tuned in the range 789–847 nm [9]. Our recent results that will be published separately indicate an even stronger dependence of the SC generation efficiency on the pump wavelength in the case of the picosecond excitation. Specifically, a variation in the wavelength of the 1-ps pump pulses by only 9 nm causes more than a threefold (fivefold) SC spectral broadening at a level of –15 (–10) dB (Fig. 3). Such a dependence is qualitatively reproduced in the numerical simulation. In Fig. 3, the differences between the slopes and absolute spectral widths on the experimental and calculated curves can be due to errors in the measurement of the input parameters for the simulation procedure (pump-pulse energy and duration and zero-dispersion wavelength).

Using a decrease in the duration of the bandwidth-limited pump pulses, one can increase the degree of the SC interpulse coherence (Fig. 2) and the SC spectral width. The evidence in favor of this statement can be found in our work [7] and in [10, 11].

The frequency modulation (chirp) of the pump pulses affects both the SC spectral width and coherence. Our experimental [7] and numerically calculated

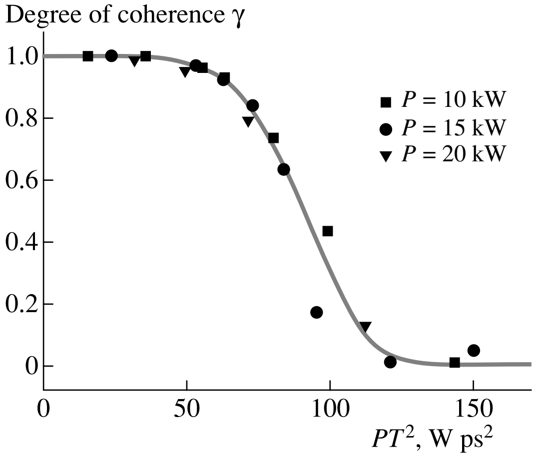

Fig. 2. Plot of the degree of SC interpulse coherence vs. the product of peak power P and square of duration T of pump pulses.

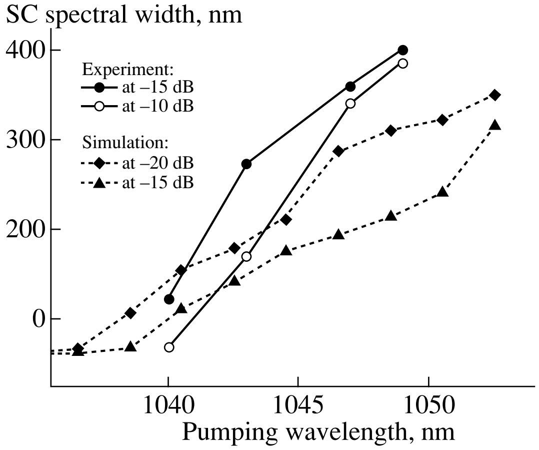

Fig. 3. Plots of the spectral width of the SC generated in the SC-5.0-1040 fiber with a length of 3 m vs. the pump wavelength at the pump pulse duration and energy of 250 fs and 1 nJ, respectively.

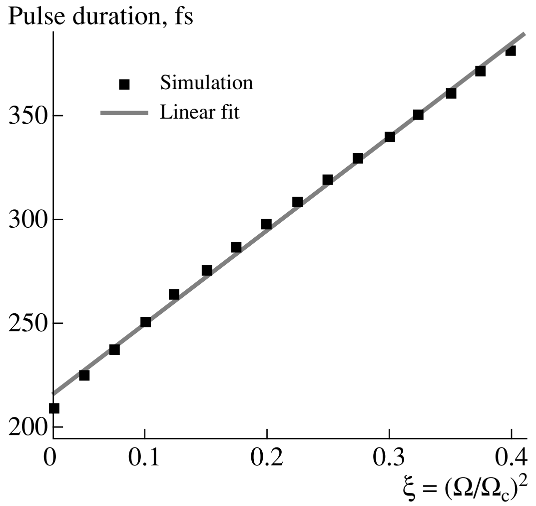

Fig. 4. Plot of the pulse duration vs. initial modulation frequency Ω for the modulated CW pumping (Ω_c is the characteristic frequency of the modulation instability [18]).

[12] results indicate that the maximum spectral broadening and the maximum degree of coherence are reached at an almost zero chirp of the pump pulses.

Evidently, a variation in the pump-pulse repetition rate at a fixed-pulse energy can lead to a variation in the SC mean power and power spectral density at a constant width of the generation spectrum.

In the case of the CW pumping, one of the methods to control the SC is based on a variation in the excitation spectral width. It was demonstrated in the experiments from [8] that an increase in the pump spectral width leads to an increase in the generation efficiency and the smoothing of the SC spectra. An important role of the finiteness of the pump time coherence in the SC generation is mentioned in [6, 13], where the numerical simulation was used to study the SC generation upon the CW excitation.

One of the distinctive features of the SC generation upon the CW pumping is the irregular time structure of radiation, which can substantially limit the applicability domain of the broadband radiation. The time distribution of the intensity of the spectrally broadened radiation can be regularized using the amplitude modulation of radiation delivered to the fiber [14, 15]. When the pump radiation propagates inside the fiber, the modulation depth increases owing to the induced-modulation instability and, consequently, a continuous wave is transformed into a pulse train. The repetition rate of the generated pulses is determined by the frequency of the amplitude modulation of the pump wave and can easily be tuned in the range from several gigahertz to 1 THz [16]. In addition, such a scheme for the generation of spectrally broadened radiation allows the duration of the generated pulses to be varied. The numerical simulation shows that the pulse duration at the fiber exit virtually linearly depends on the square of frequency Ω of the initial amplitude modulation (Fig. 4). Note also that the frequency and depth of the initial modulation govern the signal-to-noise ratio in the output signal [17].

Thus, several methods to dynamically control the parameters of the fiber SC generators are analyzed. The analysis shows that a minor portion of the means of controlling the SC parameters is implemented in the existing generators. The corresponding modernization of the SC generators will make it possible to create versatile sources of the broadband coherent radiation needed for multiple applications in physics, biology, biomedicine, etc.

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