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# Temporal Structure of a Supercontinuum Generated under Pulsed and CW Pumping

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**Abstract**—The numerical simulation based on the solution to the generalized nonlinear Schrödinger equation is used to analyze various regimes of the supercontinuum generation in optical fibers under pulsed and CW excitation. The time dependences of the supercontinuum intensity are studied, and the optimal generation regimes are discussed with respect to various applications of the supercontinuum.

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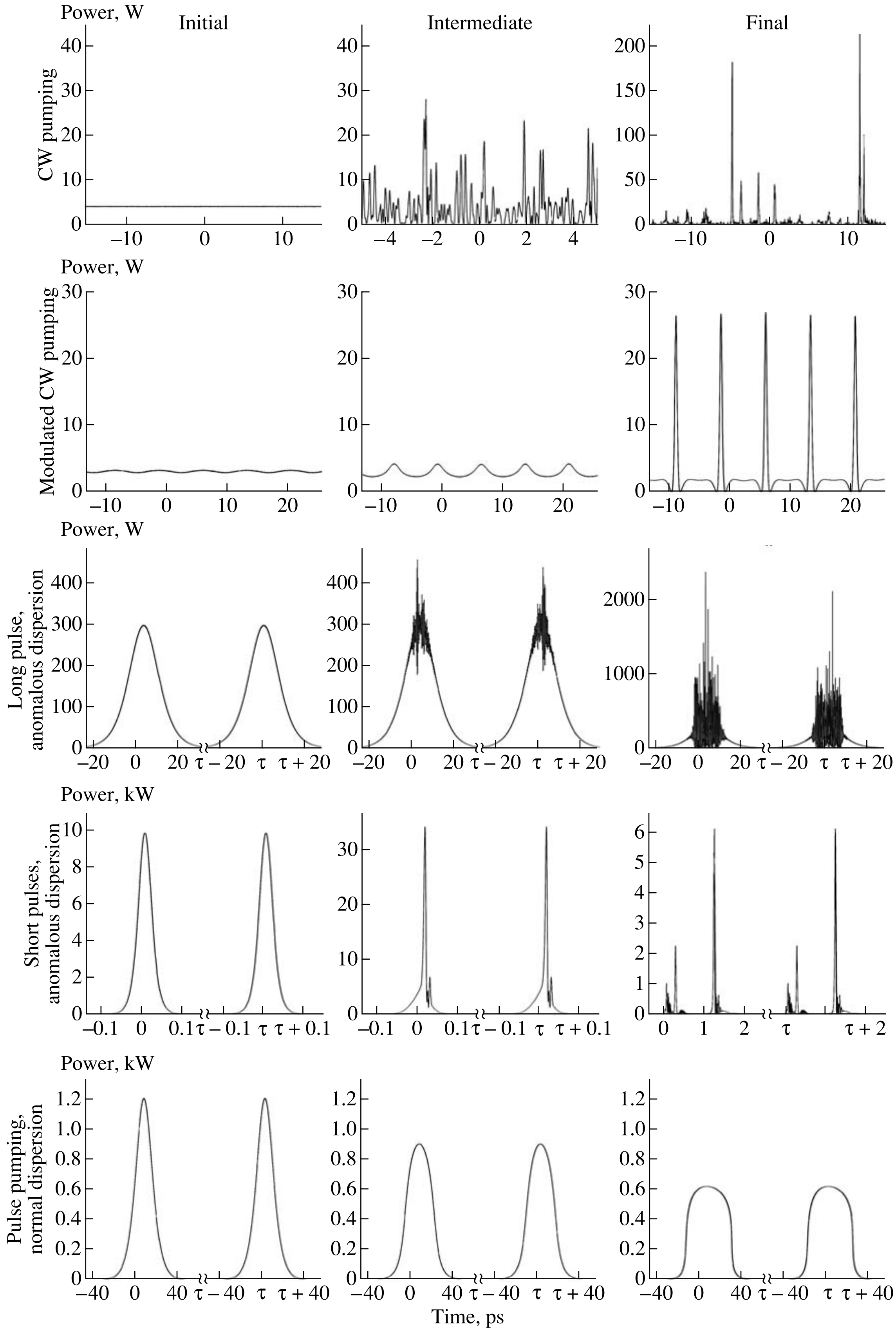
One of the topical trends in the study of the supercontinuum (SC) generation involves the search for optimal regimes of the spectral superbroadening of radiation with respect to various applications of this effect [1, 2]. Note that the requirements on the SC radiation can be significantly different in the analysis of different problems. For example, the optical coherence tomography (OCT) employs the most broadband SC to image biological tissues at the highest resolution. A similar requirement is imposed in confocal microscopy, whereas the backward-pumped broadband fiber Raman amplifiers can operate at a relatively narrow (no greater than 100 nm) spectral width. However, in the latter case, the predetermined profile of the SC power spectral density must be provided [3]. In several applications, primary attention is paid to the temporal structure of the SC radiation. One such application is the metrology of optical frequencies, which necessitates a relatively high pump pulse-to-pulse stability of the SC wave packets. In telecommunications wavelength-division multiplexing (WDM) systems, the SC time structure must represent a regular pulse train. Specific temporal structures are also needed for the ultrashort pulse (USP) generation, time-resolved spectroscopy, etc. In this work, we present the first analysis of various regimes of spectral broadening under both pulsed and CW excitation and the modulated CW pumping. Primary attention is paid to the temporal characteristics of the SC radiation. We consider the limitations on the application of various regimes of the SC generation that result from the temporal irregularity.

One of the promising methods for the SC generation that makes it possible to reach record-high radiation powers [4] is the spectral broadening of the CW pumping. The study of the SC generation under the CW pumping has been recently started [5]. It is demonstrated in [6, 7] that, at the initial stage of the CW-radiation propagation along the fiber, the principal effect involves the modulation instability (MI). This effect leads to the noise amplification in two spectral bands that are symmetrically located on both sides of the pump line and, hence, to a modulation of the CW radiation. When the radiation propagates along the fiber, the oscillation amplitude increases. This causes a decay in the CW radiation to a series of pulses (upper plots in the figure). For a part of such pulses, the pulse energy is sufficient for the formation of optical solitons that propagate along the fiber in the absence of the dispersion broadening, but with an increase in the wavelength due to the stimulated Raman self-scattering. Note the simultaneous transfer of a part of their energy to the short-wavelength part of the spectrum owing to the parametric processes. The soliton parameters (energy and wavelength) appear to be random quantities, since the solitons emerge from the amplified noise. Broad and smooth SC spectra observed in experiments (see, for example, [8]) can be obtained in simulations upon averaging with respect to a large number of solitons at the fiber exit [7].

The noise amplification plays the key role at the initial stage of the spectral broadening of the CW pumping. Therefore, the SC temporal distribution is aperiodic in the case of the CW pumping. The SC temporal distribution represents an irregular series of pulses with different wavelengths, energies, and durations that follow each other at different (random) time intervals. Due to the irregularity of the temporal structure, this regime of the SC generation cannot be employed in several applications: telecommunications, metrology of optical frequencies, time-resolved spectroscopy, etc. Practical interest in the SC under the CW pumping is related to applications that are insensitive to the irregularities of the temporal structure: OCT, confocal microscopy, backward-pumped Raman amplifiers, and steady-state spectroscopy. However, the CW pumping can cause difficulties even in these applications, due to the need in very long (with a length of no less than 1 km) highly




Evolution of the temporal structure of the pumping radiation upon the SC generation in five regimes.

Applicability of the SC generated under pulsed and CW pumping

| | CW pump | Modulated CW pump | Pump by long pulses ($\beta_2 < 0$) | Pump by short pulses ($\beta_2 < 0$) | Pulses pump ($\beta_2 > 0$) |
|---|---|---|---|---|---|
| Metrology | – | – | – | + | – |
| OCT | + | + | + | + | + |
| WDM | – | + | – | – | + |
| Raman-amplifiers | + | + | + | + | + |
| USP generation | – | + | – | + | + |
| Time-domain spectroscopy | – | + | – | – | + |

nonlinear fibers and the relatively high price or the absence of the fibers whose zero-dispersion wavelength lies outside the telecommunications spectral range.

The MI-induced noise amplification plays an important role in the SC generation in the case of the long-pulse pumping (picosecond- and nanosecond-pump pulses) at the pump wavelength belonging to the anomalous dispersion region. At the initial stage of the propagation of such pulses along the fiber (the third row in the figure), the MI build-up gives rise to the amplitude modulation. The modulation depth increases and results in the decay of long excitation pulses to a large number of femtosecond subpulses. In this case, the SC temporal structure represents a regular series of wave packets that follow each other at a repetition rate of the pump pulses. Each of the wave packets exhibits a stochastic internal structure comprising a large number of subpulses with different durations, energies, and wavelengths. This is similar to the above scenario of the CW pumping. Thus, the limitations on the applications of the CW-pumped SC are valid for this regime.

One of the methods to regularize the temporal distribution of the CW-pumped SC involves a weak amplitude modulation of the CW radiation at the entrance to the fiber [9, 10]. When the frequency of the initial modulation falls in the MI amplification band, the modulation amplitude increases and, finally, the CW radiation decays to a regular pulse train (the second row in the figure). Two competing processes (noise amplification and the initial amplitude modulation of the CW radiation due to MI) yield a limitation on the repetition rate of the pulses generated due to the decay of the modulated CW pumping [11]. In the experiments, the typical repetition rates range from tens to hundreds of gigahertz [10, 12–14]. Our calculations from [11] show that a pulse train with a repetition rate of no greater than 1 GHz can be generated at the optimal parameters of the fiber and pumping. This regime can be used when the spectrally broadened radiation is employed in metrology, time-resolved spectroscopy, telecommunications, and other applications. The limitations on this generation regime are primarily due to a relatively weak spectral broadening of the modulated CW pumping (normally, no greater than 100–200 nm in the telecommunications spectral range).

The SC temporal distribution with substantially different properties can be obtained using short (femtosecond)-pulse pumping with the wavelength lying in the anomalous dispersion region of the fiber. The calculations show that the propagation of such pulses along the fiber is accompanied by a significant pulse compression that is followed by the pulse decay. However, in contrast to the case of the long-pulse pumping, the generation of new spectral components results from the phase modulation rather than the MI-induced pump-noise amplification. Consequently, the nonrandom phase of the generated SC spectral components is locked to the phase of the pump pulse [15]. Hence, in this regime, the SC temporal distribution represents a regular series of wave packets whose repetition rate is equal to the pump-pulse repetition rate. The internal structure of each wave packet can be relatively complicated and can contain a significant number of pulses with different energies and wavelengths. However, this structure is not stochastic and is reproduced from one packet to another (the fourth row in the figure). The spectrum of such a train can be relatively broad (more than two optical octaves [16]) and can represent a frequency comb. Therefore, this regime can be used in the metrology of optical frequencies as well as in OCT, cytometry, confocal microscopy, USP generation, etc. The limitations on the application of this regime are primarily related to the complicated temporal structure consisting of a large number of pulses. Thus, the SC generation under the femtosecond pumping is not an optimal solution for the time-resolved spectroscopy and the WDM technology in telecommunications.

Finally, note the SC generation regime related to the application of the pulsed pumping in the normal dispersion region of the fiber. It is seen from the last row in the figure that a regular pulse train is observed at the fiber exit in this regime. The main effect that leads to the spectral broadening is the self-phase modulation, which imposes limitations on the spectral width and the applicability domain of this regime of the SC generation similarly to the case of the modulated CW pumping.

Thus, five main regimes of the SC generation are analyzed. These regimes are characterized by different scenarios of the spectral broadening, the properties of the time distributions of intensity, and the spectral broadenings. It is expedient to use the SC generation under short-pulse pumping in the anomalous dispersion region, modulated CW pumping, and the pulsed pumping in the normal dispersion region in the applications that employ the spectrally broadened radiation with a regular temporal structure. The last two regimes are interesting for such applications as WDM and time-resolved spectroscopy, where regular series of identical pulses are needed. However, these regimes are characterized by a relatively weak spectral broadening. The generation regime with the femtosecond pumping is the most appropriate one in the applications that employ superbroadband SC and are insensitive to the time distribution of the intensity. The conclusions regarding the applicability of various regimes of the SC generation are summarized in the table.

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