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Supercontinuum Fiber Sources under Pulsed and CW Pumping

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Abstract—Supercontinuum generation in optical fibers under pulsed and CW excitation is considered. The optimal generation regimes are discussed with regard to various applications of the effect.

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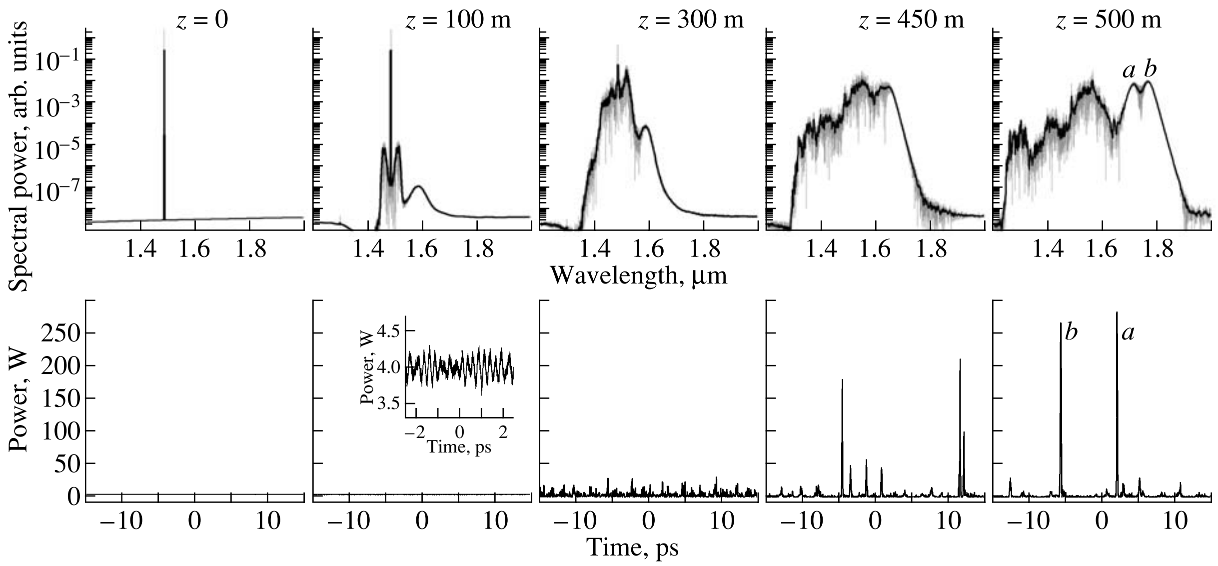
A search for the optimal regimes of the spectral superbroadening of radiation with regard to various applications is a topical problem in the study of the supercontinuum (SC) generation. The difficulties are related to the fact that the contributions of various nonlinear-optical effects to the spectral broadening of the pump radiation and, hence, the SC radiation properties can be significantly different for different optical fibers and different parameters of the pumping radiation. In particular, the generation mechanisms and several SC properties are substantially different for systems with CW and pulsed excitation. In addition, different applications impose different and, sometimes, opposite requirements on SC radiation. This excludes the possibility of the creation of an all-purpose scheme for SC generation, which can satisfy the requirements of all of the applications. For example, high-resolution OCT imaging of biological tissues necessitates the application of broadband SC. In contrast, the SC bandwidth used for telecommunications [1] with wavelength-division multiplexing (WDM) can be relatively narrow to span the conventional telecommunications spectral range (1500–1600 nm). However, in this case, the spectral power uniformity and the time dependence of intensity are important characteristics. A regular time structure is needed for the reliable modulation of radiation in time and for the prevention of the overlapping of neighboring pulses in the course of their propagation along the communications line. The uniformity of the SC spectral power enables one to eliminate the additional correcting spectral filters. A flat SC spectrum and a single-pulse distribution of the SC intensity in time are optimal for the time-resolved spectroscopy. However, in real systems, single pulses are only generated when the self-phase modulation serves as the main mechanism for the SC generation. In this case, the spectral width is relatively small (no greater than several tens of terahertz). A relatively large spectral broadening can be realized when the SC generation involves various nonlinear-optical effects including stimulated Raman scattering (SRS), stimulated self-scattering, and parametric processes. However, the corresponding distribution of the SC intensity in time is extremely complicated and corresponds to multiple single pulses. For SC applications in time-resolved spectroscopy, all of these pulses must be matched in time. This can be realized if the SC exhibits a stable spectral phase and a monotonic time dependence of the frequency modulation. Similar requirements on the SC are met in the problem of pulse compression. Note that, in the development of backward-pumping schemes for broadband-fiber SRS amplifiers in telecommunications systems, the time distribution of intensity appears insignificant and the spectral power and its wavelength dependence play the key role. In contrast to the WDM systems with the Π-shaped wavelength dependence, systems with a maximum uniformity of the gain must employ complicated profiles of the spectral power. The problem of the SC intensity profile with respect to the radiation wavelength also emerges in metrology in the development of an optical clock. In this case, the optimal SC spectral power profile represents two developed peaks at frequencies that differ from each other by a factor of two [2]. This makes it possible to increase the spectral power in the SC spectral ranges that are used for phase locking. In addition, a relatively high pulse-to-pulse phase and amplitude stability of the SC is a key parameter as in the case of pulse compression.

The most widely spread realizations of SC generation yield bell-shaped and quasi-Π-type spectral distributions of radiation intensity. In the special generation regimes, the SC spectrum exhibits developed soliton peaks, which can be used separately. In particular, the SC soliton peaks that contain more than 40% of the pump energy [3] can be used for the creation of effective tunable short-pulse sources. The wavelength of such a soliton can be varied in wide ranges (by 200–400 nm) with a variation in the pump power. This regime of SC generation becomes even more promising due to the fact that the degree of coherence of such solitons is close to the maximum level [4]. A relatively high-phase stability of the soliton radiation contained



Numerical simulation of the propagation of CW radiation along a highly nonlinear fiber for the calculation parameters $P_0 = 4$ W, $\lambda_0 = 1486$ nm, $\beta_2 = -0.17$ ps^2/km, and $\beta_3 = 0.0393$ ps^3/km, which correspond to the experiment from [8].

in the SC spectrum enables one to analyze variants of the simultaneous application of soliton and nonsoliton SC radiation as the optimal variants in several applications, in particular, metrology [2].

Pulsed excitation is employed in the majority of publications devoted to SC generation and its applications. Recently, the study of SC generation under CW pumping was initiated [5]. It is demonstrated in [6, 7] that the main effect realized at the initial stage of CW-radiation propagation along the fiber involves modulation instability. It leads to noise amplification in two spectral bands that are symmetric relative to the pump line. This results in an increasing modulation amplitude of CW radiation ($z = 100$ m in figure). The energy of a part of these pulses is sufficiently high for soliton generation. These solitons propagate along the fiber in the absence of dispersion broadening with an increase in the wavelength due to the SRS. A part of their energy is simultaneously transferred to the short-wavelength spectral range owing to parametric processes. When $z = 500$ m, the wave packet in figure exhibits two optical solitons (*a* and *b*), which are temporally and spectrally separated from each other. The soliton parameters (energy and wavelength) represent random quantities, since the solitons are formed by the amplified noise. Experimentally observed broad and smooth SC spectra [8] result from averaging over a large number of solitons at the fiber exit.

Thus, the main significant difference between the mechanisms for the spectral broadening of CW radiation from the SC generation under pulsed pumping is related to the modulation instability, which causes the noise amplification at the initial stage of the CW-radiation propagation and the decay of this radiation to a series of pulses whose parameters exhibit substantial fluctuations. An alternative approach to SC generation under CW excitation that makes it possible to significantly weaken the effect of the amplified noise on the properties of the output radiation is as follows. A signal wave whose frequency falls into the gain band of the modulation instability is delivered to the optical fiber together with the pump wave [9, 10]. The study of such a generation regime is beyond the scope of this work and we plan to perform the analysis in the future. In the classical scheme (a single (pump) wave is delivered to the fiber), the time structure of SC radiation is irregular, so that this generation regime cannot be used in several applications (telecommunications, metrology of optical frequencies, time-resolved spectroscopy, etc.). In general, SC generation under CW pumping can only be interesting for applications that are insensitive to fluctuations in the time distribution of the intensity. OCT, SRS fiber amplifiers with backward pumping, spectroscopy in the absence of time resolution (see table), and, possibly, several other applications serve as examples. However, even in these cases, the application of CW excitation for SC generation can be impeded due to the need in extremely long (about one kilometer) highly nonlinear fibers and the absence or a relatively high price of highly nonlinear fibers for SC generation under CW excitation at wavelengths lying outside the telecommunications spectral range (about 1.5 μm). Note that, in the case of pulsed pumping, the fiber length normally ranges from several millimeters to several tens of centimeters.

Another disadvantage of the schemes for SC generation with CW excitation, which can serve as an additional obstacle for these applications, is the presence of relatively high (20–30%) energy fluctuations of the SC pulses.

Applicability of the CW- and pulse-pumped SC sources

	Pulsed pumping	CW pumping
Measurement of optical frequencies	$\beta_2 < 0$	–
Optical clock	$\beta_2 < 0$	–
Tomography	+	+
WDM	$\beta_2 > 0$	–
SRS amplifiers	+	+
Generation of ultrashort pulses	+	–
Steady-state spectroscopy	+	+
Time-resolved spectroscopy	+	–

However, a relatively high spatial and spectral density of radiation is an advantage of the CW-pumped SC generators. For a significant spectral broadening of the CW pump radiation, its power must reach a level of several or several tens of watts. The corresponding mean SC power will be on the same order of magnitude. For systems with pulsed pumping, a mean SC power of 10 W is quite rare: the typical SC powers range from hundreds of milliwatts to one watt. Moreover, calculations show that an increase in the input power for microstructured and tapered fibers that are commonly used for SC generation does not lead to a significant increase in the power spectral density. Such an increase leads to further SC spectral broadening accompanied by an increase in loss upon the propagation of broadband SC radiation along the fiber.

Thus, the existing schemes for SC generation with CW pumping are inferior to the pulsed-SC generators with respect to many parameters. However, the CW-pumped systems can be promising due to the relatively high spectral and spatial density of the SC radiation.

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