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SOLID-STATE LASERS AND NONLINEAR FREQUENCY CONVERSION

Fiber Supercontinuum Generators with an Extended Set of Controlled Parameters in Real Time Scale

S. M. Kobtsev and S. V. Smirnov

Novosibirsk State University, Novosibirsk, 630090 Russia
e-mail: kobtsev@lab.nsu.ru

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Abstract—Different methods for controlling the radiation parameters of supercontinuum (SC) are analyzed. In particular, the possibility of varying the SC spectral power density due to variations in the pulse repetition rate and radiation wavelength of the pumping laser, the increase in the SC degree of coherence due to the choice of the optimal phase modulation of pumping pulses, and the variations in the SC pulse repetition rate in the two-wave pumping scheme due to the variations in the frequency difference are considered. A new method for controlling the spectrum width and the spectral power density level of the SC generated upon continuous excitation using an additional noise pumping component is proposed.

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INTRODUCTION

The necessity of broadband coherent radiation, i.e., a supercontinuum (SC), appears in the solution of numerous problems in the field of nanotechnologies, optical communications, metrology, biomedicine, spectroscopy, and other applications. However, different applications impose different, sometimes incompatible, requirements on SC properties. Thus, for example, for metrology of optical frequencies, an SC is required with a spectral width not smaller than one octave, whose amplitude and phase are highly stable, while, for multiwavelength sources in WDM technology, a relatively small SC spectral width is sufficient. In the latter case, the requirements to the homogeneity of the spectral power density and the regularity of the time structure of radiation, which should have the form of a periodic sequence of single pulses, are of the greatest importance. For optical coherent tomography, a broadband SC with a low noise level and rather arbitrary spectral power density profile is necessary, while, in ultrashort pulse generation schemes, an SC with a temporal distribution of the intensity in the form of a sequence of single pulses with quadratic and cubic phase modulation is used [1]. In counter pumping schemes for fiber Raman amplifiers [2], an SC with a special spectral power density profile that ensures a spectrally homogeneous amplification coefficient is required.

One of the approaches to creating a universal SC generator, which can be used to solve a wide number of problems for various applications, is the development of methods of dynamic variations in SC parameters in order for the radiation of this universal SC satisfied the requirements of a large number of problems, if not all of them. Moreover, the necessity of dynamic variations in SC generation parameters directly appears in spectroscopic, cytometric, biomedical, and other applications. Note that, as a rule, existing SC generators ensure the control of the total radiation power and the smooth tuning of one or several wavelengths separated by the external controlled spectral filter in a limited region of the wide SC spectrum. In this case, the total power is usually controlled based on changes in the power of pump radiation. Since the latter also determines the SC spectral width, this approach is inefficient from the point of view of controlling SC spectral power density.

In this paper, different methods for variations in the parameters of broadband radiation obtained using the most widespread SC generator scheme are analyzed. This scheme consists of a pump source, which can include the master oscillator and the amplifier; an nonlinear optical fiber, in which spectral broadening of pumping takes place; and a filter/converter. The latter can, for example, separate one or several spectral components from the wide SC spectrum and compensate for the frequency modulation of selected pulses. The dynamically variable parameters of the pump source are the radiation power and the wavelength; the duration, the phase modulation, the pulse repetition rate and shape (for pulsed pumping); the spectral composition (the line width and the power of different spectral components) for continuous pumping. The nonlinear optical fiber used for spectral broadening of pumping has less significant controlling capabilities, which include the possibility of tuning the refractive index written in fibers of Bragg gratings, thermal effects, the creation of induced anisotropy, and so on.

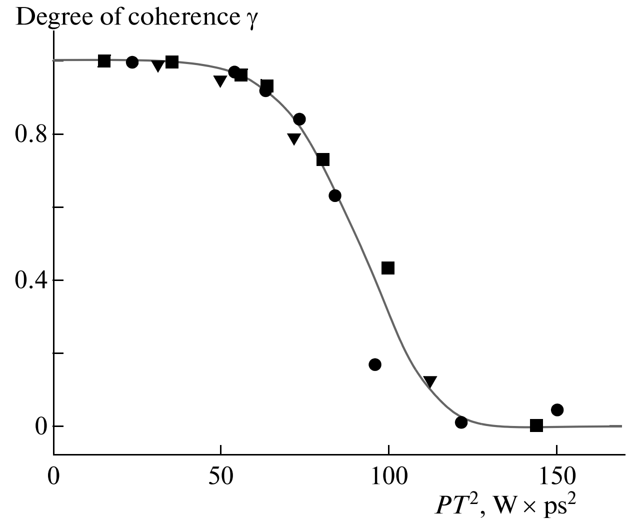

Fig. 1. SC degree of inter-pulse coherence as a function of the product of peak power P and squared duration T of pumping pulses for a power of (squares) 10, (circles) 15, and (triangles) 20 kW.

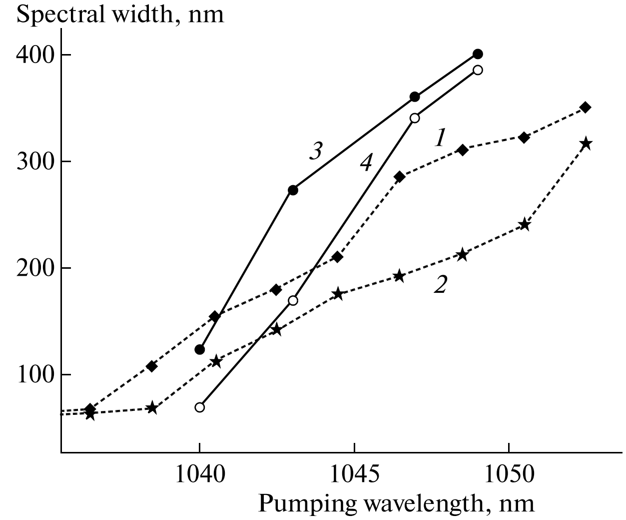

Fig. 2. Spectral width of SC generated in a SC-5.0-1040 fiber with a length of 3 m as a function of the wavelength of pumping pulse with a duration of 1 ps and a power of 1 nJ on a level of (*1*) 20, (*2*, *3*) 15, (*4*) 10 dB; (*1*, *2*) model, and (*3*, *4*) experiment.

A finite radiation converter can be used, e.g., to control the width and position of the selected spectral lines, the duration and phase modulation of pulses, and the repetition rate (if multiplexers are used). By varying the parameters of the generator scheme mentioned above, one can change one or several parameters of the output radiation, including the width and shape of the SC spectrum, the total power, spectral power density, and the coherence and temporal distribution parameters. Below, the influence of dynamically varied pump parameters on the characteristics of the generated SC will be analyzed. The analysis is based on the results of our experimental studies and computer simulation (numerical solution of the generalized nonlinear Schrödinger equation) and results obtained by other authors.

METHODS FOR CONTROLLING SUPERCONTINUUM PARAMETERS

Results of our previous studies show that, as a rule, an increase in the pump power results in the growth of the power of generated SC and the width of its spectrum both for pulsed [3] and continuous [4] excitation. In the case of pulsed pumping, the power growth is accompanied by the growth of the number of peaks in the spectrum and the temporal structure of the SC radiation, as well as a decrease in the degree of inter-pulse coherence. Figure 1 shows the dependence of the SC degree of inter-pulse coherence on the product of the squared duration T and power P of pump pulses obtained in numerical simulation [5]. Note that, for a rather high pump power level, the saturation of the generated SC power is observed [6], which is related to an increase in the energy losses for induced combination scattering and absorption in quartz fibers in the ultraviolet and infrared regions. This effect may limit the applicability of the method for controlling SC parameters based on the variations in the pump power, which stimulates the search of alternative solutions.

One of the alternative methods for controlling the SC spectral width and, therefore, the spectral power density level, is based on the variations in the wavelength of pumping pulses in the vicinity of the zero dispersion wavelength of the fiber. Previously, we demonstrated the fundamental possibility of this control using pump pulses of a Ti:Sapphire laser with a pulse length of 80 fs and a wavelength tuned in the range of 789–847 nm [7]. The results of our latest studies [8] testify to the even stronger dependence of the SC generation efficiency on the pump wavelength if picosecond excitation pulses are used. Thus, a change in the wavelength of pump pulses with a duration of 1 ps by only 9 nm results in a change in the width of the generated SC spectrum by more than a factor of three on a level of −15 dB and more than a factor of five on a level of −10 dB (Fig. 2). This dependence is qualitatively reproduced in numerical simulation. In this case, some differences in the slope and absolute values of the spectral width in experimental and numerical plots in Fig. 2 can be due to the errors of determination of the input parameters of simulation, the energy and duration of pump pulses, and the zero dispersion wavelength of the fiber. By reducing the duration of spectrally limited pump pulses and the degree of inter-pulse coherence in an SC (Fig. 1), its spectral width can be increased. These conclusions are proven by both the results of our previous studies [5] and other authors [9, 10].

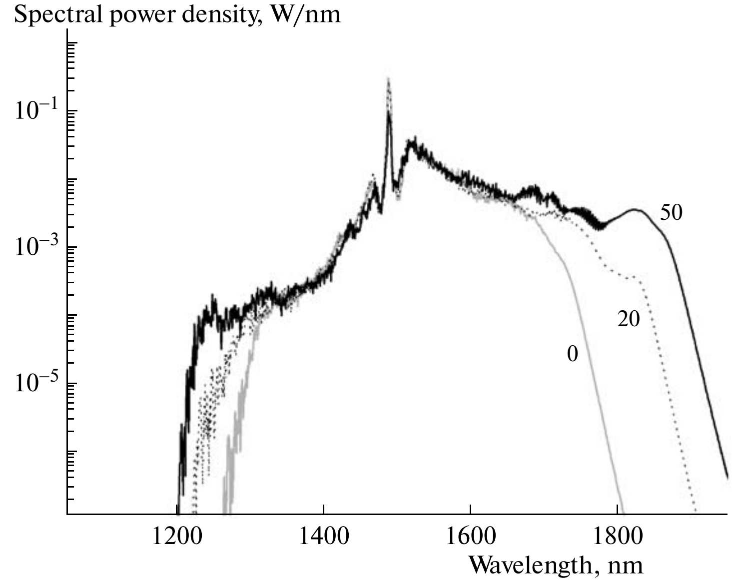

Fig. 3. SC spectra generated in highly nonlinear fiber [13] for seed noise power in pumping of 0, 20, and 50 dB.

The phase modulation (chirp) of pump pulses influences both the SC spectral width and the coherence. The results of our experimental studies [11] and the numerical simulation [5] are evidence that the largest spectral broadening and the maximal degree of coherence are achieved for values of phase modulation of pump pulses close to zero.

By varying the repetition rate of pump pulses at fixed pulse energy, the average power of SC power and its spectral power density level can obviously be varied at a constant width of the generation spectrum.

One of the possible methods for controlling the SC generated at continuous pumping is based on the change in the excitation spectral width. Thus, it was experimentally shown previously [6] that an increase in the pump line width results in an increase in the generation efficiency and in smoothing the SC spectrum. An important role played by the finite character of temporal coherence of pumping for the SC generation was also pointed out in [4, 12]. There, the SC generation under continuous excitation was studied numerically. Note, however, that the typical experiment [6] is based on the application of different pumping sources and spectral filters with different transmission bandwidths, which involves the introduction of changes into the generator scheme, which in turn makes this method inapplicable for the real-time control of the SC parameters. An alternative method that allows for the smooth real-time tuning of the spectral width and the spectral power density level of the supercontinuum at continuous excitation can be based on the introduction of an additional (noise) spectral component into pumping and the smooth variations in its power. Indeed, we showed previously [4] that the SC generation at continuous pumping is initiated by the development of a modulation instability resulting in the decay of continuous pumping into a stochastic pulse sequence. Numerical simulation shows [4] that, for typical experimental parameters [13], for modulation instability to develop, the initial fiber segment with a length of up to several hundred meters is required, while the main spectral broadening takes place on the remaining fiber length and is connected with the formation of solitons self-shifted with respect to frequency (the stimulated Raman self-scattering effect). The basis of the proposed new method for controlling the SC spectral width is the introduction into the fiber of a weak noise-like signal in the spectral region of the amplification of modulation instability along with the continuous pumping. The introduction of the seed noise results in the reduction of the fiber length necessary for the development of modulation instability and the formation of solitons, and, as a consequence, an increase in the fiber length on which the soliton frequency self-shift and the SC spectral width growth take place. Thus, by increasing the power of the additional noise pump component, the SC spectral width can be increased. The performance of this mechanism is proven by numerical simulation (Fig. 3). The calculations were performed using the parameters of a highly nonlinear fiber with a length of 200 m taken from experiment [13] and the continuous pumping power $P = 4$ W. The excess of the seed noise power over the quantum noise level is shown in Fig. 3; in this case, the ratio of the noise component and the pump power does not exceed 0.5%.

A specific feature of the SC generation regime at continuous pumping is an irregular temporal structure of its radiation, which may considerably limit the area of applicability of broadband radiation. To regularize

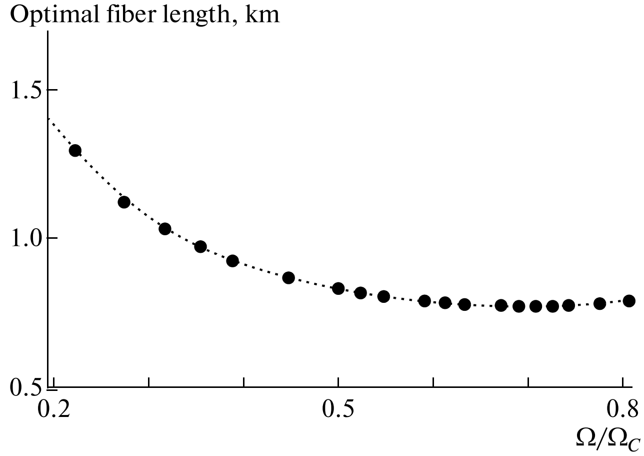

Fig. 4. Optimal fiber length as a function of initial modulation frequency Ω (Ω_C is the characteristic frequency of modulation instability [19]).

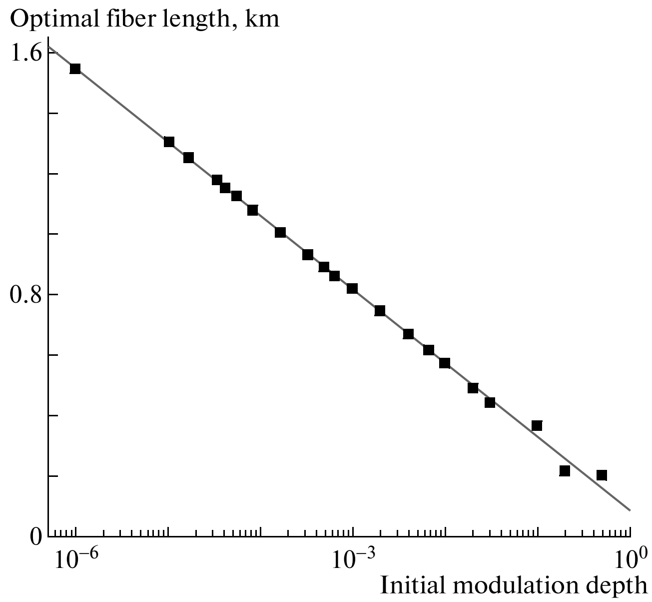

Fig. 5. Optimal fiber length as a function of the initial modulation depth of pumping radiation. Points show simulation results, and straight line is the linear approximation.

the temporal intensity distribution of the spectrally broadened radiation, the amplitude modulation of radiation at the input of the fiber can be used [14, 15]. In the course of the propagation of the pump radiation in the fiber, the modulation depth increases due to the effect of induced modulation instability, which results in the decay of the continuous wave into the sequence of pulses. The repetition rate of generated pulses is determined by the frequency of amplitude modulation of the pump wave and admits tuning from several dozen GHz to 1 THz [16]. For real-time pulse frequency tuning, it is necessary to take into account the dependence of the fiber length on which pulses are formed on the initial modulation frequency (Fig. 4). Since the real fiber length of an SC generator is constant, the initial modulation frequency tuning should be accompanied by the change of the modulation depth, thus compensating for the dependence shown in Fig. 4. The length of the effective pulse formation as a function of the initial intensity modulation depth of the pump radiation obtained in the numerical simulation is shown in Fig. 5. Along with the pulse repetition rate, the variations in the frequency of the initial amplitude modulation in this scheme allow one to vary the pulse duration at the output of the fiber. Our numerical simulation [17] shows that the dependence of the pulse duration at the output of the fiber on the frequency Ω of initial amplitude modulation is close to quadratic. Moreover, the initial modulation frequency and depth determine the signal-to-noise ratio at the output of the fiber [18].

CONCLUSIONS

We analyzed a number of methods for dynamic control of the parameters of fiber supercontinuum generators. In particular, a new method for controlling the SC spectral width based on changing the seed noise power at continuous pumping was considered. Our studies allowed us to conclude that existing generators use only a small fraction of their capabilities to control SC parameters. The improvement of SC generators in this direction would allow one to create universal sources of broadband coherent optical radiation necessary in the solution of a wide range of problems in physics, biology, chemistry, medicine, and other fields.

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