Supercontinuum generators with CW and pulsed pump: temporal structure and dynamic control of parameters

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ABSTRACT

The present paper analyzes different methods for dynamic control of parameters of super-continuum generated in fibres both under pulse and CW pumping as well as peculiarities of temporal structure of different super-continua. In particular we show experimentally and numerically a sensitivity of supercontinuum spectral power density to wavelength and repetition rate of pump pulses. We find also that chirp variation of pump pulses results in change of super-continuum coherence for short-wavelength wing. A novel method for control of SC generation under CW pumping is proposed. We discuss the method for control of repetition rate and duration of pulses generated with the help of dual-wavelength pumping by means of adjusting input power and frequency difference. Developed super-continuum generators with enhanced set of controlled parameters are essential for cytometry, tomography, spectroscopy, communications and for other applications.

Keywords: super-continuum, nonlinear optics.

1 INTRODUCTION

The need for broad-band coherent radiation, super-continuum (SC), arises in solving a plethora of problems related to optical communications, metrology, bio-medical industry, spectroscopy, nano-technologies, and many other applications. However, different problems pose dissimilar, and often mutually exclusive requirements to the SC properties. Thus, for instance, metrology of optical frequencies needs SC with spectrum width of at least one octave and high stability of phase and amplitude, whereas multi-wavelength sources for WDM technology can be satisfied with relatively narrow SC spectrum, but high uniformity of spectral power density is necessary in this latter case as well as highly regular temporal structure of the radiation, which has to take form of periodic train of isolated pulses. Applications of optical coherence tomography (OCT) dictate broad-band SC with low noise level and relatively arbitrary distribution of spectral power density, while ultra-short pulse generators use SC with temporal intensity distribution in the form of trains of isolated pulses with quadratic and cubic phase modulation[1]. In Raman amplifiers with backward pumping[2] a special profile of SC spectral power density is important that leads to spectrally uniform Raman gain.

One of approaches to create a universal SC generator, which is applicable to solving a broad range of problems, may be development of techniques for dynamic control over SC parameters, so that the output of such generator would satisfy the requirements of most, if not all applications. Moreover, such SC generators are in demand for spectroscopy, cytometry, other bio-medical and broader applications where an immediate need exists for broad-band radiation with dynamically adjustable parameters. It is pertinent to note that SC generators available currently feature, as a rule, only control of the total output radiation power and continuous detuning (in a limited range) of a single or several wavelengths selected by an external tuneable filter from the broad SC spectrum. The output power adjustment is usually performed by controlling the pumping radiation input. Since this latter also determines the spectrum width of SC, such an approach does not allow, for example, adjustment of SC spectral power density.

The present work analyses methods of SC parameter control based on dynamic changes in pumping characteristics in different generation modes. In addition, applicability limitations of different SC generation modes are discussed in relation to features of temporal radiation structure. The conducted analysis is based on the results of our own

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previous experimental studies and computer modelling (numerical solution of the generalised non-linear Schrödinger equation) as well as on data reported by other authors.

2 PULSE-PUMPED SUPER-CONTINUUM

Investigations into different modes of SC generation with pulsed excitation originated in the end of 1960-s when Alfano and Shapiro observed spectral broadening of picosecond laser pulses passed through different glasses and crystals[3]. Subsequently, SC generation was achieved in a large number of various media, including liquids and gases, and also in different types of optical fibres. In these experiments, pumping pulses with durations ranging from femto- to nano-second domains[4] were used. Because of such broad range of pumping pulse duration and because of diversity in optical fibre types used for spectral broadening of pump radiation relative and absolute contribution of various non-linear optical effects into SC generation may be substantially different, thereby giving rise to diversity of parameters of the generated SC. The many operating mechanisms of SC generation under different parameters of the optical fibre and pumping pulses can be tentatively divided into three basic modes: SC generation in a fibre with normal dispersion, spectral broadening of relatively short (normally in the range of tens to hundreds of femtoseconds), and of long pulses in fibres with anomalous dispersion.

Spectral broadening of pumping pulses in the normal dispersion range is caused mainly by the effect of self-phase modulation (SPM). Temporal radiation profile at the output from the optical fibre usually has the form of a train of isolated pulses with repetition rate equal that of the pumping pulse repetition rate (see Fig. 1, upper row). Limitations to applications of this generation mode are related, first of all, to comparatively narrow spectrum width, normally not exceeding 100–200 nm in the 1.5-µm range.

Considerably greater spectral broadening can be induced when pulsed pumping is applied in the anomalous dispersion domain of the optical fibre since the SC generation efficiency is much higher due to soliton effects. In case of relatively short pumping pulses SPM is the principal mechanism of spectral broadening during the initial phase of generation, leading to broadening of the pulse spectrum and its temporal decomposition into a train of sub-pulses (see Fig. 1, second row). This process can be regarded as decay of an entangled state of a large number of solitons into a sequence of fundamental solitons. As they propagate further along the fibre, these fundamental solitons undergo a self-shift of their carrier frequency caused by the effect of stimulated Raman self-scattering, thus leading to the widening of the SC spectrum. Since the multi-soliton pumping pulse decays into a train of fundamental solitons mostly because of SPM within a comparatively short stretch of fibre, noise amplification does not noticeably affect this process. As a result, the temporal profile of SC intensity in this case appears as a regular sequence of wave packets, each of them, in its turn, consisting of a complicated non-periodic train of soliton sub-pulses with different intensity, energy, and wavelength.

A fundamentally dissimilar case is observed under pumping with comparatively long (dozens of picoseconds and longer) pulses in the anomalous dispersion domain of the fibre (see Fig. 1, third row). Because the spectrum broadening rate caused by SPM is inversely proportional to the pulse duration, SPM in this case does not play a key role in SC generation. Instead, modulation instability (MI) becomes the principal factor leading to noise amplification within two spectral bands located symmetrically with respect to the pumping line. By the time when the magnitude of amplified noise becomes comparable to the pumping pulse magnitude the pulse decays into a stochastic train of sub-pulses whose mean repetition rate is governed by the position of MI gain lines. Some of these sub-pulses form optical solitons experiencing self-shift of carrier frequency, thus giving rise to significant broadening of the SC spectrum. However, in contrast to the case of short pumping pulses discussed above, the energy and wavelength of these solitons are random values and exhibit considerable fluctuations from one pumping pulse to another. Consequently, experimental SC spectra are much smoother and devoid of isolated soliton peaks, which happens because of averaging during data acquisition over a large number of solitons with random parameters. The temporal structure of SC radiation is formed by a train of wave packets following one another with the pump pulse repetition rate, each of them consisting of a large number (several hundred or more) sub-pulses with essentially random parameters.

In an intermediate case of pulses with sub-picosecond and picosecond durations, partially coherent pulse trains (wave packets) are formed in the optical fibre. As we have shown in our calculations[5], the degree of inter-pulse coherence in the SC can be approximated by a function of product of peak pumping pulse power P and squared pumping pulse duration T^2 (see Fig. 2). In the limit of short pumping pulses the inter-pulse coherence degree of SC reaches maximum and in the limit of very long pulses it approaches zero, accordingly corresponding to generation of a regular or a stochastic wave packet sequence.

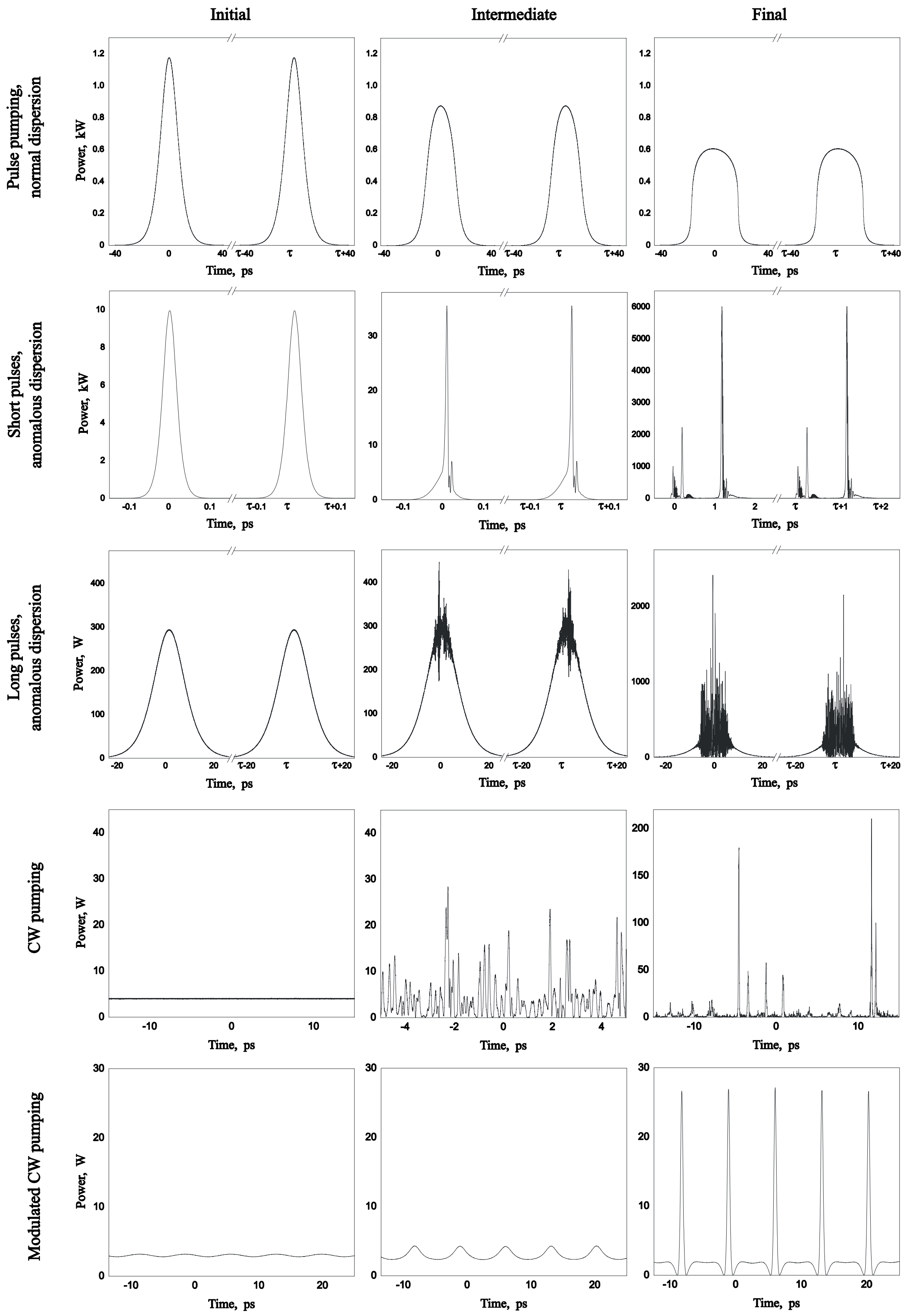

Fig 1 Evolution of temporal structure of pumping radiation during SC generation in five different modes.

One should include into fundamental methods of dynamic control over SC parameters those based on adjusting power, wavelength, duration, chirp, and repetition rate of pumping pulses. According to the results of our earlier studies[6], higher pump power usually leads to broader spectrum, more peaks in the spectrum and in the temporal distribution of SC intensity, as well as to reduction in the SC inter-pulse coherence (see Fig. 2). It is worth taking note that at sufficiently high pumping power levels a saturation of output power of the generated SC is observed[7] because of growth in energy losses to stimulated Raman scattering and absorption of quartz fibres in UV and IR ranges. This effect may potentially limit applicability of the SC parameter control methods based on the adjustment of the pumping power, thus necessitating search for alternative solutions.

One of alternative techniques to control the SC spectrum width and, consequently, its spectral power density is based on adjustment of pump wavelength in the vicinity of zero dispersion wavelength of the optical fibre. Earlier we demonstrated the fundamental possibility of such control with the use of 80-fs pumping pulses from a Ti:Sa laser tuned within the range of 789 to 847 nm[8]. Our latest research[9] demonstrates even stronger dependence of SC generation efficiency on the pumping wavelength when picosecond pulses are used for excitation. For instance, shifting the wavelength of 1-ps pumping pulses only by 9 nm produces a change in the generated SC spectrum width by a factor of more than 3 (at –15 dB level) and more than 5 (at –10 dB level), see Fig. 3.

By shortening the duration of spectrally limited pumping pulses it is possible to improve the SC inter-pulse coherence (see Fig. 2) and to broaden its spectrum. These conclusions are corroborated by the results of our earlier research[5] as well as by reports of other authors[10,11]. Phase modulation (chirp) of pumping pulses affects both SC spectrum width and its coherence. Our experimental investigations[12] and numerical modelling indicate that both the largest spectral broadening and the highest degree of coherence are achieved at phase modulation values of pumping pulses close to zero. Controlling the pump pulse repetition rate at fixed pulse energy will evidently achieve changing of the mean SC radiation power and its spectral power density at a constant width of the generation spectrum.

3 CW-PUMPED SUPER-CONTINUUM

Studies of SC generation with continuous-wave (CW) excitation began relatively recently. First reports on experimental demonstration of this generation mode date back to 2000[13, 14]. Compared to pulsed SC generation, CW pumping uses longer non-linear fibre and allows reaching record-high values of mean output power and spectral power density of SC[15]. The mechanism of spectral broadening is fully analogous to the SC generation in the limit of infinitely long pulses explained in the previous section. Temporal distribution of SC intensity in this case takes shape of a stochastic train of pulses (solitons) having different (random) parameters and propagating along the fibre with different velocities (see Fig. 1, next to the bottom row). When recording spectra of such SC in the experiment an average over enormous number of "random" solitons is taken, giving, as a result, smooth spectrum without any peaks corresponding to individual solitons.

In order to dynamically control the output parameters of SC generators with CW pump, it is possible, for example, to use adjustment of the power and line width of the pump. Similarly to the case of pulsed pumping, as the input power increases a broadening of the SC spectrum is observed, brought about by higher efficiency of non-linear optical processes leading to the spectrum broadening. According to experimental research[7], broadening of the pumping line also results in higher generation efficiency and smoothing of SC spectra. The important role played by finitude of temporal coherence of the pumping radiation in SC generation was also pointed out in Ref. [16, 17] where CW-pumped SC generation was studied by numerical modelling. Let us note, however, that a typical experimental implementation[7] is based on use of different pump sources and spectral filters with different band-widths, which means introduction of changes into the generator layout and makes this method inapplicable for real-time control over SC parameters. An alternative method allowing real-time continuous adjustment of the SC spectrum width and of its spectral power density with CW excitation may rest on introduction into the pumping radiation of an additional (noise) spectral component and on continuous adjustment of its power. Indeed, as we showed earlier on[16], SC generation under CW pumping is initiated by the development of MI which further leads to decay of continuous pump radiation into stochastic pulse train. Numerical modelling indicates[16] that for development of MI under typical experimental parameters[18] an initial stretch of fibre is necessary with the length of up to several hundred metres, whereas the majority of spectral broadening occurs along the remaining fibre length and is related to formation of frequency self-shifted solitons (effect of stimulated Raman self-scattering). At the base of the new method for control of the SC spectrum width that we here propose lies introduction into the optical fibre, along with the continuous pump radiation, of a weak noise-like signal that falls within the spectral range of MI gain. Adding seed noise will shorten the fibre length necessary for development of MI and soliton formation and, as a consequence, will leave a longer fibre section for self frequency shift of solitons and broadening of the SC spectrum. In this manner by raising the power of the additional noisy pump component a larger SC spectrum width may be achieved. Efficiency of this mechanism is confirmed by numerical modelling we carried out (see Fig. 4). Calculations were conducted on the basis of 200-m highly non-linear fibre with parameters taken from the experiment in Ref [18] at the CW pump power $P = 4$ W. The seed noise overshoot over the level of quantum noise in dB is given in the plot of Fig. 4, the ratio of the noise component power to the pumping power not exceeding 0.5%.

The peculiarity of CW-pumped SC generation manifesting itself in irregular temporal structure of its radiation may substantially limit the application area of such broad-band sources. To regularise the temporal distribution of the spectrally broadened radiation amplitude modulation of the input radiation may be applied[19, 20]. As the modulated pump radiation propagates along the fibre the modulation depth grows because of induced modulation instability effect that leads to decay of the continuous wave into a pulse train (see Fig. 1, bottom row). The repetition rate of generated pulses is given by the amplitude modulation frequency of the pump wave and allows detuning in the range of several tens of GHz to 1 THz[21]. Aside from the pulse repetition rate, the detuning of the frequency of the initial amplitude modulation in this layout may be used to control pulse duration at the exit from the fibre. Numerical modelling that we carried out[22] demonstrates that the dependence of pulse duration at the fibre exit upon the frequency Ω of the initial amplitude modulation is close to quadratic. The frequency and depth of the initial amplitude modulation determines additionally the signal/noise ratio at the fibre exit[23].

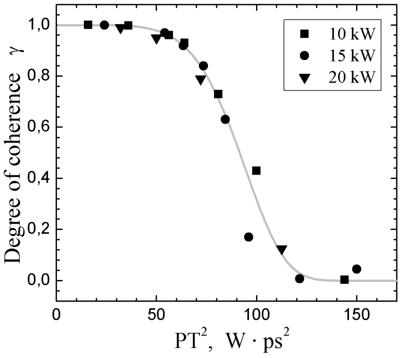

Fig 2 Dependence of SC coherence on pump pulse peak power P and duration T.

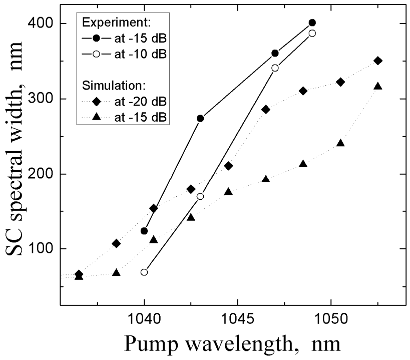

Fig 3 Dependence of SC spectrum width on pump wavelength

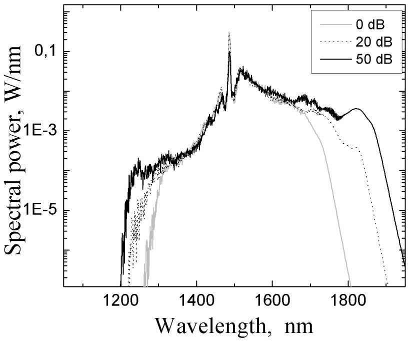

Fig 4 SC spectra obtained with different pump noise level.

5 CONCLUSIONS

In the view of the foregoing discussion, various modes of spectral broadening permit SC generation with different properties of temporal radiation structure. Specifically, pulsed pumping in the normal dispersion domain of the optical fibre or modulated CW pumping provides means for generation of SC shaped as periodic trains of isolated pulses necessary in multi-wavelength WDM sources, in ultra-short pulse generators, and in time-resolved spectroscopy. Limitation of practical application of these generation modes comes mainly from relatively small amount of spectral broadening. Super-continuum generated under CW excitation as well as from long pumping pulses in the range of anomalous fibre dispersion features stochastic temporal structure, which constrains its applicability in such fields as optical frequency metrology, WDM sources, etc. On the other hand, broad and smooth spectra of such SC may be used in medical and other areas where neither regular temporal structure nor phase stability of radiation is required. Finally, SC generation from short (femtosecond) pulses in the anomalous dispersion range combines a number of advantages of other modes allowing generation of broad SC spectra with stable spectral phase. This mode of generation is of particular interest from the viewpoints of metrology and optical coherence tomography. Its relative demerit is a complex temporal structure of radiation limiting its application in WDM light sources and time-resolved spectroscopy.

Furthermore, in the present report several methods of dynamic control over parameters of fibre generators of super-continuum are analysed and, in particular, a new technique for controlling the SC spectrum width is proposed, based on adjustment of seed noise power in the CW pump radiation. The conducted investigations lead to the conclusion that currently existing commercial SC sources use only a small portion of possibilities to control SC parameters.

Improvement of SC generators in this direction will pave the way to universal sources of broad-band coherent optical radiation, which are crucial in solving a wide range of problems in physics, biology, chemistry, medicine, and other areas.

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