Quantum Electronics **37** (11) 1038 – 1042 (2007)

PACS numbers: 42.70.Qs; 42.65.Wi; 42.65.Tg
DOI: 10.1070/QE2007v037n11ABEH013655

Control of the spectral and coherent properties of a supercontinuum with pronounced soliton structures in the spectrum by using phase-modulated femtosecond pump pulses

S.M. Kobtsev, S.V. Kukarin, S.V. Smirnov, N.V. Fateev

***Abstract*. It is found experimentally for the first time that the initial phase modulation of femtosecond pump pulses considerably affects the degree of coherence of the short-wavelength radiation of a supercontinuum with pronounced soliton structures in the spectrum generated in a microstructure fibre. The long-wavelength soliton radiation preserves the complete coherence upon changing the phase modulation of the pump pulse despite considerable variations of the carrier frequency of solitons. The maximum width of the supercontinuum and the maximum degree of coherence of its short-wavelength radiation are achieved for small positive values of the phase modulation parameters.**

Keywords: *supercontinuum, microstructure fibre, soliton, femtosecond pulses, degree of radiation coherence*.

1. Introduction

The propagation of femtosecond pulses through a microstructured (MS) fibre can be accompanied by the generation of broadband radiation, the so-called supercontinuum (SC), which can cover the wavelength range exceeding an octave [1, 2]. The shape and width of the spectrum and other parameters of a supercontinuum are determined to a great extent by the parameters of pump pulses, in particular, by their phase modulation (chirp). By now a number of theoretical and experimental studies of the influence of the phase modulation (PM) of femtosecond pump pulses on the parameters of the SC generated in MS fibres [3 – 13] and other fibres [14, 15] and media [16] have been performed. It has been shown that the maximum SC width [3, 4] and the minimum level of amplitude [4, 7] and phase [7] noises of the SC for a fixed average power of femtosecond pump pulses are achieved for the PM close to zero. In these papers, SCs with relatively smooth spectral envelopes were investigated. However, for certain combinations of the MS fibre and pump pulse parameters, a SC with distinct soliton structures (self-frequency-shifted solitons [8, 9]) in the long-wavelength wing of the spectrum can be produced. This SC generation regime has a specific nature compared to the generation of a smooth SC. For example, as the PM of pump pulses is changed, not only the SC width changes but also its shape changes considerably, especially in the long-wavelength wing of the emission spectrum [10, 11].

We studied earlier the degree of coherence of different frequency components of the SC containing distinct peaks corresponding to optical solitons [17]. It was found that the degree of coherence of optical solitons in the SC (which, as the pump radiation, were completely coherent) noticeably differed from that of non-soliton SC radiation with a relatively low spectral power density in the short-wavelength wing (the degree of coherence for different components of this wing was 0.25 – 0.57).

In this paper, which continues our previous studies [17], we investigated for the first time the influence of the PM of femtosecond pump pulses on the degree of coherence of different spectral components of the SC, which contains several weakly overlapped soliton peaks in the long-wavelength spectral region and a broad short-wavelength wing covering the wavelength range of width a few hundreds nanometres.

2. Experimental

We used in experiments a MS silica fibre of length 30 cm with a nearly elliptical core with the ellipse axes 1.4 and 1.9 μm (Fig. 1). The calculated value of the wavelength λ_0 corresponding to the zero dispersion of the fibre is ~ 750 nm. The scheme of the experimental setup is shown in Fig. 2. A 350-mW Ti : sapphire laser emits 80-fs, 795-nm pulses at a pulse repetition rate of 100 MHz. The PM of the output pulses could be changed by using a controllable two-pass, two-prism compressor and plane – parallel plates of different thickness placed in the laser beam. A small part of radiation ($\sim 1\,\%$) transmitted through the compressor and a Faraday isolator was directed to an interference scanning autocorrelator, while the main part of radiation was coupled through a microobjective into the core of the MS fibre. The polarisation plane of the pump radiation was made coincident with the minor axis of the elliptic fibre core by using a half-wave phase plate located in front of the microobjective. The

S.M. Kobtsev, S.V. Kukarin, S.V. Smirnov, N.V. Fateev Novosibirsk State Univrsity, ul. Pirogova 2, 630090 Novosibirsk, Russia;
e-mail: kobtsev@lab.nsu.ru

Received 8 June 2007; revision received 20 July 2007
Kvantovaya Elektronika **37** (11) 1038 – 1042 (2007)
Translated by M.N. Sapozhnikov

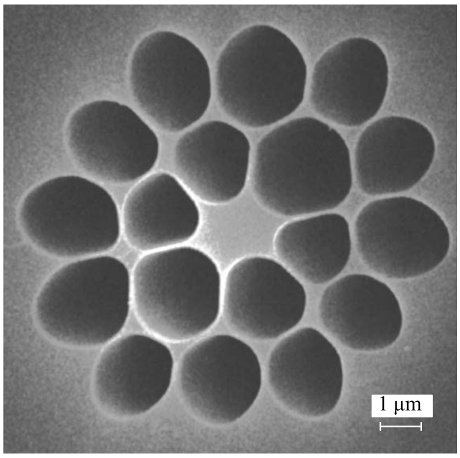

Figure 1. Photograph of the MS fibre end.

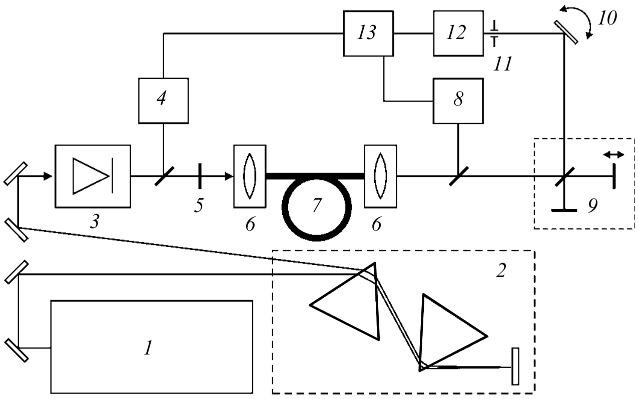

Figure 2. Scheme of the experimental setup: (*1*) femtosecond Ti : sapphire laser; (*2*) prism compressor; (*3*) Faraday isolator; (*4*) interferometric scanning autocorrelator; (*5*) half-wave phase plate; (*6*) microobjective; (*7*) MS fibre; (*8*) optical spectrum analyser; (*9*) Michelson interferometer; (*10*) diffraction grating; (*11*) aperture; (*12*) CCD camera; (*13*) computer.

coincidence was controlled by obtaining the maximum SC width by the method used in [18]. Radiation emerging from the MS fibre was collimated with a microobjective and directed to a Michelson interferometer with the arm length difference ~3 m to observe the interference of two successive SC pulses. The interference pattern of certain spectral components of the SC was selected with the help of a diffraction grating and detected with a CCD camera with the averaging time of a few milliseconds. The visibility of the detected interference pattern for a selected SC wavelength was defined as $V(\lambda) = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities of the interference signal. The degree of interpulse coherence of the first order $\gamma(\lambda, t_1 - t_2)$ was determined from the results of measurements [19].

The parameter C of the initial phase modulation and duration of pump pulses were determined by using a computer-controlled interference autocorrelator based on a scanning Michelson interferometer and a nonlinear photodetector.

3. Experimental results and discussion

Figure 3 presents the SC spectra generated in the MS fibre for different PM parameters of pump pulses and fixed average power (75 mW) at the MS fibre output. For the PM of pulses close to minimal, the SC has the broadest spectrum containing four solitons. As the modulus of the PM parameter is increased, the SC spectrum narrows down and the number of generated solitons decreases. Thus, the dependence of the SC spectrum on the PM of pump pulses (Fig. 4) is consistent as a whole with the results obtained in [8, 9]. However, it should be pointed out that the maximum width of the SC spectrum was achieved in our experiments for small positive values of the PM parameter $C = 0.2 - 0.3$, which can be explained by the optimal initial compression of pulses with such PM in the MS fibre having the anomalous dispersion at the pump wavelength.

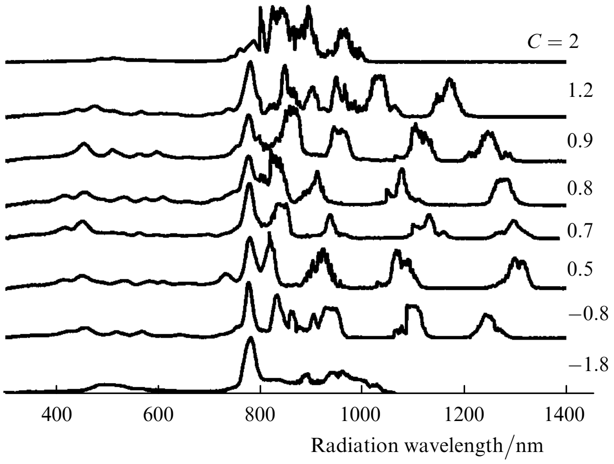

Figure 3. Emission spectra generated in the MS fibre at different parameters C of the pump pulse chirp and the average output power 75 mW.

To measure the degree of coherence of SC radiation, we selected the SC generation regime when one component dominated in the short-wavelength part of the spectrum (the SC radiation had a certain colour), while in the long-wavelength region the distinct peaks corresponding to optical solitons were observed. This regime was achieved

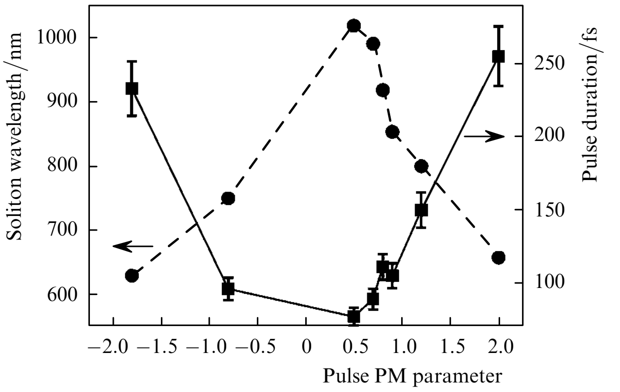

Figure 4. Dependences of the spectral position of the long-wavelength soliton peak and the pump pulse duration on the PM parameter of the pump pulse for the average SC radiation power 75 mW.

by reducing the pump power down to the value at which the average SC power at the MS fibre output was 30 mW. The maximum of the spectral power in the short-wavelength part of the spectrum was observed at 510 nm and was separated almost by an octave from the longest-wavelength soliton. This SC generation regime is of interest for using in metrology, in particular, in an optical clock [20]. However, to understand the outlook for its application, it is necessary to elucidate the possibility of increasing the degree of coherence of short-wavelength radiation by varying the PM of pump pulses and to analyse the influence of this variation on the coherence of the longest-wavelength soliton.

Our experiments revealed a strong dependence of the degree of coherence of SC radiation at 510 nm on the PM parameter of pump pulses (Fig. 5). The degree of coherence changed from 0.3 to 0.65 when the PM parameter was changed from -1.8 to 2. The obtained dependence has an asymmetric shape, the degree of coherence in the region of negative PM parameters decreasing faster than in the region of positive PM parameters. The maximum degree of coherence (0.65) was obtained for pump pulses with the small positive PM parameter equal to 0.1.

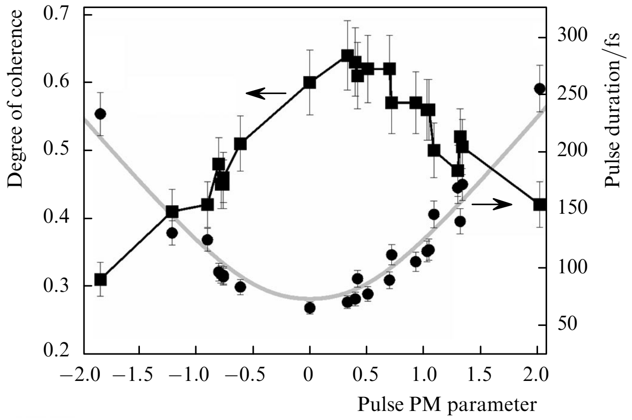

Figure 5. Dependences of the degree of coherence of SC radiation at a wavelength of 510 nm and the pump pulse duration on the PM parameter for the average SC radiation power 30 mW; the grey curve is the calculated dependence.

At the same time, as follows from our experiments, solitons remain completely coherent for any variations of the PM of pump pulses.

The grey curve in Fig. 5 shows the calculated dependence of the duration of pump pulses with the envelope $\mathrm{sech}^2 x$ on their PM parameter. The duration of transform-limited pulses used in the calculation of the theoretical curve and providing the best fit of the experimental data was 90 fs. A small discrepancy between the calculated curve and experiment apparently suggests that it is necessary to use a more accurate theoretical model for determining the pulse duration and PM parameter from the experimental autocorrelation function.

4. Application of partially coherent radiation

As mentioned above, the generation of a broad SC (of the order of an octave) containing high-power density solitons can be of interest for using in metrology. Because one of the key parameters of radiation is the signal-to-noise ratio, the question of the applicability of SC radiation with the degree of coherence different from unity in an optical clock reasonably appears. Note that, aside from the PM of pump pulses considered here, a number of other parameters exist which considerably affect the degree of coherence of SC radiation. As shown in paper [21], the coherence of SC radiation increases upon pumping a MS fibre by radiation at a wavelength falling into the normal dispersion region of the fibre and also when shorter pump pulses are used. However, the SC width proves to be smaller in this case and can be insufficient for metrological measurements. In the anomalous dispersion regime, the SC width is considerably greater and can achieve two octaves [1], while the coherence of radiation can be increased at a fixed width of the spectrum by reducing the pump pulse duration and increasing its energy [20].

The degree of coherence of SC radiation in the vicinity of the specified wavelength is determined by the amplitude noise and phase fluctuations of radiation frequencies of SC pulses in the specified spectral region. We studied the influence of noise and fluctuations on the equidistant set of spectral lines (the so-called spectral comb) by considering a train of N pulses, whose field E can be represented in the form

$$E(t) = \sum_{n=1}^{N} f_n(t - nT), \tag{1}$$

where t is time and T is the average pulse repetition period. The Fourier transform of expression (1) gives

$$E(\omega) = \sum_{n=1}^{N} f_n(\omega) \exp(\mathrm{i}n\omega T)$$

$$\equiv \sum_{n=1}^{N} a_n(\omega) \exp[\mathrm{i}\phi_n(\omega) + \mathrm{i}n\omega T]. \tag{2}$$

By assuming that the amplitude a_n and phase ϕ_n of the spectral function of each pulse are random quantities, which depend neither on each other* nor the amplitude and phase of other pulses in the train, and also that the distribution functions of a_n and ϕ_n are independent of n, we obtain the degree of coherence in the form

$$\gamma(\omega) = \frac{|\langle f_i(\omega) f_j(\omega)\rangle_{i,j}|}{[\langle |f_i(\omega)|^2\rangle \langle |f_j(\omega)|^2\rangle]^{1/2}} = \frac{|\zeta|^2}{1 - \sigma_{\mathrm{a}}^2/\langle a\rangle^2}, \quad i \neq j. \tag{3}$$

Hereafter, the angle brackets mean averaging over the ensemble; $\sigma_{\mathrm{a}}^2 = \langle (a - \langle a\rangle)^2\rangle$ is the dispersion of fluctuations of the spectral amplitude of pulses; and $\zeta = \langle \exp(\mathrm{i}\phi)\rangle$. By using the assumptions made above, we can obtain the expression for the spectral radiation power

$$\langle |E(\omega)|^2\rangle = \langle a\rangle^2 |\zeta|^2 \left\{ \left[\frac{\sin(\omega TN/2)}{\sin(\omega T/2)}\right]^2 + N\left[\frac{1}{\gamma(\omega)} - 1\right]\right\}. \tag{4}$$

---

*This simplifying assumption is based on the fact that the model used here neglects the amplitude fluctuations of pulses at the fibre input (stable pumping is assumed) so that fluctuations of SC radiation are caused exclusively by the amplified noise: spontaneous photons with a random phase.

Figure 6 presents the envelopes of spectra of a train of $N = 1000$ pulses normalised to unity. The curves are constructed by using expression (4) for different degrees of coherence γ. One can see that the decrease in the degree of coherence leads to the increase in noise between the lines of the comb. According to (4), the ratio of the noise intensity between lines to the intensity at the line centre is described by the expression

$$\left\langle \frac{I_{\text{noise}}}{I_{\text{sign}}} \right\rangle = \frac{1}{N}\left(\frac{1}{\gamma} - 1\right). \tag{5}$$

An important feature of expression (5) is that the noise-to-siganal ratio depends not only the degree of coherence γ but also on the number N of pulses in the train (on the averaging time τ_{av} of a detecting system). Figure 7 presents three curves for $N = 10^3$, 10^4, and 10^5 (for a pulse repetition rate of 100 MHz, the corresponding averaging times are 10^{-5}, 10^{-4}, and 10^{-3} s). Although the relative noise level can be reduced by increasing the averaging time, in applications related to the optical frequency stabilisation, τ_{av} should remain much smaller than the inverse maximum frequency of the technical noise, which is typically $10^3 - 10^4$ s^{-1}. For the maximum degree of coherence of short-wavelength radiation $\gamma \sim 0.6$ obtained in our paper, this corresponds to the noise-to-signal ratio $-30 \ldots -40$ dB, which is quite sufficient for applications.

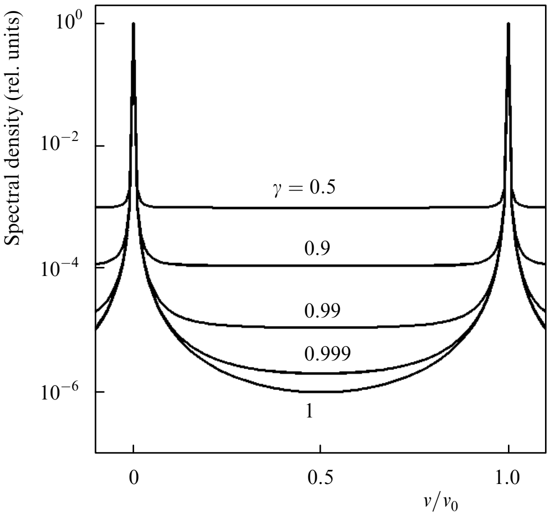

Figure 6. Ensemble-averaged envelopes of the spectra of pulse trains emitted at a pulse repetition rate $\nu_0 = 1/T$, plotted by using expression (4) for different degrees of coherence.

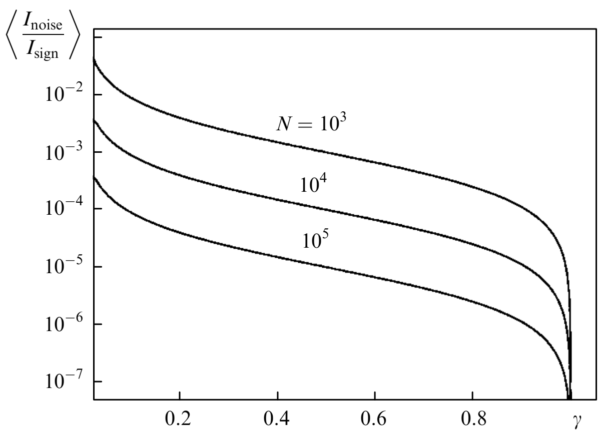

Figure 7. Dependence of the noise-to-signal ratio on the degree of coherence γ for different numbers N of pulses in the train.

5. Conclusions

Our experiments have demonstrated the possibility of controlling the degree of coherence of the short-wavelength radiation of a SC containing solitons by using the PM of femtosecond pump pulses. In this case, the long-wavelength soliton radiation preserves its total coherence upon varying the PM of pump pulses despite considerable accompanying variations in the carrier frequency of solitons. The maximum width of the SC and the maximum degree of coherence of the short-wavelength SC radiation are achieved at small positive values of the PM parameter. Note that numerical calculations performed in [5] for a SC with the smooth envelope of the spectrum also predict an increase in the average phase noise of SC radiation when the PM parameter of pump pulses differs from its optimal small positive value.

We have analysed the possibility of application of SC radiation with the degree of coherence different from unity in an optical clock. It has been shown that for the degree of coherence $\gamma \sim 0.6$ and small averaging times ($10^{-5} - 10^{-4}$ s), the noise-to-signal ratio does not exceed $-30 \ldots -40$ dB, which is acceptable for metrological applications.

Acknowledgements. This work was partially supported by a Grant 'Research and Development in Priority Directions of the Development of the Scientific and Technological Complex of Russia in 2007–2012' and INTAS (Grant No. 03-51-5288).

References

1. Ranka J.K., Windeler R.S., Stentz A.J. *Opt. Lett.*, **25**, 25 (2000).
2. Zheltikov A.M. *Usp. Fiz. Nauk*, **174**, 73 (2004).
3. Apolonsky A., Povazay B., Unterhuber A., Drexler W., Wadsworth W.J., Knight J.C., Russell P.St.J. *J. Opt. Soc. Am. B*, **19**, 2165 (2002).
4. Corwin K.L., Newbury N.R., Dudley J.M., Coen S., Diddams S.A., Weber K., Windeler R.S. *Phys. Rev. Lett.*, **90**, 113904 (2003).
5. Fedotov A.B., Zhou P., Kondrat'ev Yu.N., Konorov S.O., Vlasova E.A., Sidorov-Biryukov D.A., Shevandin V.S., Dukel'skii K.V., Khokhlov A.V., Bagayev S.N., Smirnov V.B., Tarasevitch A.P., Linde D., Zheltikov A.M. *Laser Phys.*, **13**, 816 (2003).
6. Konorov S.O., Bugar I., Sidorov-Biryukov D.A., Chorvat D., Kondrat'ev Yu.N., Shevandin V.S., Dukel'skii K.V., Khokhlov A.V., Fedotov A.B., Uherek F., Morozov V.B., Makarov V.A., Chorvat D., Zheltikov A.M. *Laser Phys.*, **14**, 772 (2004).
7. Washburn B.R., Newbury N.R. *Opt. Express*, **12**, 2166 (2004).
8. Golovchenko E.A., Dianov E.M., Prokhorov A.M., Serkin V.N. *Pis'ma Zh. Eksp. Teor. Fiz.*, **42**, 74 (1985).
9. Mitschke F.M., Mollenauer L.F. *Opt. Lett.*, **11**, 659 (1986).
10. Cormack I.G., Reid D.T., Wadsworth W.J., Knight J.C., Russel P.St.J. *Electron. Lett.*, **38**, 167 (2002).
11. Zhu Z., Brown T.G. *Opt. Express*, **12**, 689 (2004).
12. Tianprateep M., Tada J., Yamazaki T., Kannari F. *Jap. J. Appl. Phys.*, **43**, 8059 (2004).
13. Gui L., Fu X., Wen S., Qian L. *Proc. SPIE Int. Soc. Opt. Eng.*, **5627**, 442 (2005).

14. Wu Y., Lou C.Y., Han M., Wang T., Gao Y.Z. *Chinese Phys.*, **11**, 578 (2002).
15. Türke D., Wohlleben W., Teipel J., Motzkus M., Kibler B., Dudley J., Giessen H. *Appl. Phys. B*, **83**, 37 (2006).
16. Golubtsov I.S., Kandidov V.P., Kosareva O.G. *Kvantovaya Elektron.*, **33**, 525 (2003) [*Quantum Electron.*, **33**, 525 (2003)].
17. Kobtsev S.M., Kukarin S.V., Fateev N.V., Smirnov S.V. *Appl. Phys. B*, **81**, 263 (2005).
18. Kobtsev S.M., Kukarin S.V., Fateev N.V. *Kvantovaya Elektron.*, **33**, 1085 (2003) [*Quantum Electron.*, **33**, 1085 (2003)].
19. Mandel L., Wolf E. *Optical Coherence and Quantum Optics* (Cambridge, UK: Cambridge University Press, 1995).
20. Kobtsev S.M., Smirnov S.V. *Opt. Express*, **14**, 3968 (2006).
21. Dudley J.M., Coen S. *Opt. Lett.*, **27**, 1180 (2002).