PACS numbers: 42.65.Re
DOI: 10.1070/QE2010v040n10ABEH014195

Generation of transform-limited rectangular pulses in a spectral compressor

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***Abstract*. The generation of 100-fs transform-limited pulses with a rectangular envelope in a spectral compressor is demonstrated experimentally. The pulses are characterised by spectral interferometry.**

Keywords: *rectangular pulse, femtosecond pulse, chirp, spectral compression, spectral interferometry*

1. Introduction

Interest in the formation of ultrashort pulses (USPs) with a rectangular envelope is caused by their wide application, in particular, in optical communication for calibrating devices for USP-formation [1], in control of light-induced quantum states [2, 3], and so on. Such picosecond USPs are formed by splitting the initial USP into multiple replicas and delaying them in a set of birefringent crystals [4 – 7] or fibre optic couplers [8]. In an alternative approach, rectangular USPs are formed using spectral amplitude-phase masks placed into a femtosecond laser system [5, 6] or in waveguides with a sinc transfer function [7]. It should be noted that USPs formed by these methods have a super-Gaussian or trapezoid temporal profile, but, in the literature, they are usually called rectangular due to a flat peak and steep fronts [9].

The need for special devices [4 – 7] for formation of such rectangular pulses stimulates the development of new approaches to the problem. From the viewpoint of simplicity, it seems attractive to form rectangular USPs in a waveguide due to nonlinear-dispersion self-action. However, the pulse formed as a result of the mutual effect of the Kerr nonlinearity and the group velocity dispersion is positively chirped [1, 9]. Chirp-free rectangular USPs can be achieved by negative chirping of USPs at the entrance to the waveguide. Such a system is actually a spectral compressor consisting of a dispersive delay line (DDL) and a single-mode fibre (SMF) [10 – 12]. Indeed, the analysis of the role played by the group velocity dispersion in the spectral compression [13] showed the possibility of formation of transform-limited USPs with a rectangular envelope.

This work is aimed at experimental investigations of the formation of transform-limited rectangular USPs in a spectral compressor according to the numerical analysis [13]. The experiments were performed using spectral interferometry, which allows total characterisation of the complex radiation field [14].

2. Experimental technique

The experimental setup (Fig. 1) consisted of a Coherent Verdi 10 Mira 900F Ti : sapphire femtosecond laser (wavelength 800 nm, pulse duration at full width at half-maximum (FWHM) 100 fs, bandwidth 10.5 nm, pulse repetition rate 76 MHz, average power 1.5 W, peak power 2×10^5 W), a spectral compressor with a DDL consisting of a pair of dispersion prisms P made of SF11 glass and a returning-mirror M3, a Newport F-SE (780 nm) SMF, and a recording system [an Ando AQ6315 optical spectrum analyser (OSA) and an APE Pulse-Check autocorrelator].

In the course of the experiment, the laser radiation was delivered to a Mach – Zehnder interferometer, in which the

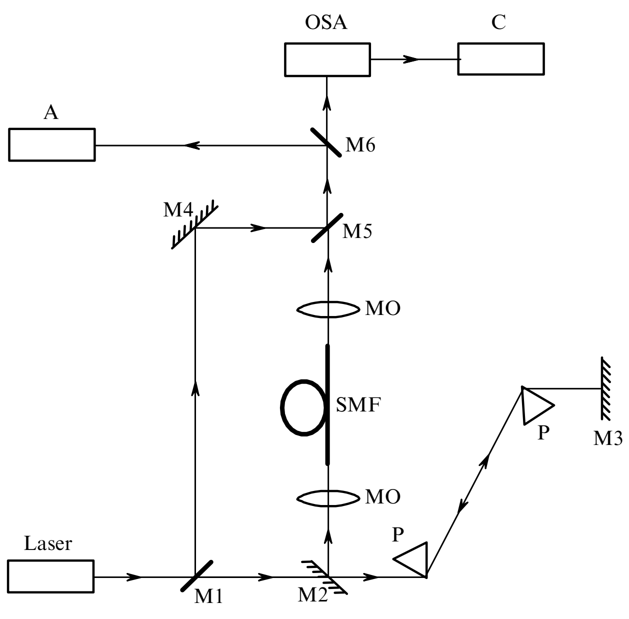

Figure 1. Scheme of the experimental setup: (M1 – M6) mirrors; (P) prisms; (MO) microobjectives; (A) autocorrelator; (OSA) optical spectral analyser; (C) computer.

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Received17 July 2009; revision received 20 September 2010
Kvantovaya Elektronika **40** (10) 868 – 872 (2010)
Translated by M.N. Basieva

beam was split into two parts by a semitransparent mirror M1. The smaller part (20 %) was used as a reference wave for spectral interferometry. The large part of the pulsed radiation (80 %) was directed to the spectral compressor. The prisms were placed so that the beam was incident at the Brewster angle and propagated through their vertices. In the DDL with an anomalous dispersion, the spectrum does not change, while the pulse becomes longer and negatively chirped. After passing the DDL, the beam was coupled by a microobjective into the SMF, where the self-phase modulation lead to cancellation of the chirp and to spectral compression of the pulse.

The output spectrally-compressed pulse and the reference pulse were delivered to the OSA, which recorded the spectral-interference pattern: the overlap of the spectral harmonics of the signal and reference waves resulted in a total spectral pattern with beatings due to the difference in their spectral phases. Computer processing of the recorded spectral-interference pattern allowed us to reconstruct the spectral phase of the studied pulse formed in the spectral compressor by a method described in [15]. The measured spectrum of this pulse together with its reconstructed phase make is possible to completely reconstruct the USP temporal amplitude and phase using the Fourier transform, i.e., to completely characterise the pulse under study. For temporal measurements in the course of experiments we also recorded the intensity autocorrelation functions. The experimental stages are illustrated in Fig. 2. To eliminate methodical error, we performed control spectral and correlation measurements at the entrance and exit of the DDL, which confirmed the spectrum stability and the expected degree of USP stretching.

The experiments were combined with the numerical simulation of the process based on the nonlinear Schrödinger equation taking into account the Kerr nonlinearity and the group velocity dispersion, which adequately describes the studied process for pulse durations of about 100 fs [9]. The equation was numerically solved by the split-step fast-Fourier-transform algorithm.

3. Results

Our numerical investigations performed for different lengths of DDL and SMF confirmed the statement that the formation of rectangular pulses depends only on the ratio of the distance d between the prisms (hereinafter called the DDL length) and the SMF length f [13]: rectangular USPs are formed at $d/f \approx 1.6 k_2^{(f)}/k_2^{(d)}$, where $k_2^{(f)} = 10^3$ fs^2 cm^{-1} and $k_2^{(d)} = 0.6 \times 10^3$ fs^2 cm^{-1} are the second-order group velocity dispersion coefficients for SMF and DDL, respectively. In dimensionless variables, this condition has the form $Z/\zeta \approx 1.6$ (~ 2 in [13]), where $\zeta = f/L_D^{(f)}$, $Z = d/L_D^{(d)}$, $L_D^{(f)} = \tau_0^2/k_2^{(f)}$, $L_D^{(d)} = \tau_0^2/k_2^{(d)}$, and τ_0 is the initial pulse duration [9]. Under these conditions, the spectral compression is maximum.

The experiments were performed for the DDL length $d = 90$ cm ($Z = 5.4$) and the SMF length $f = 22$ cm ($\zeta = 3.2$). The degree of the USP spectral compression at

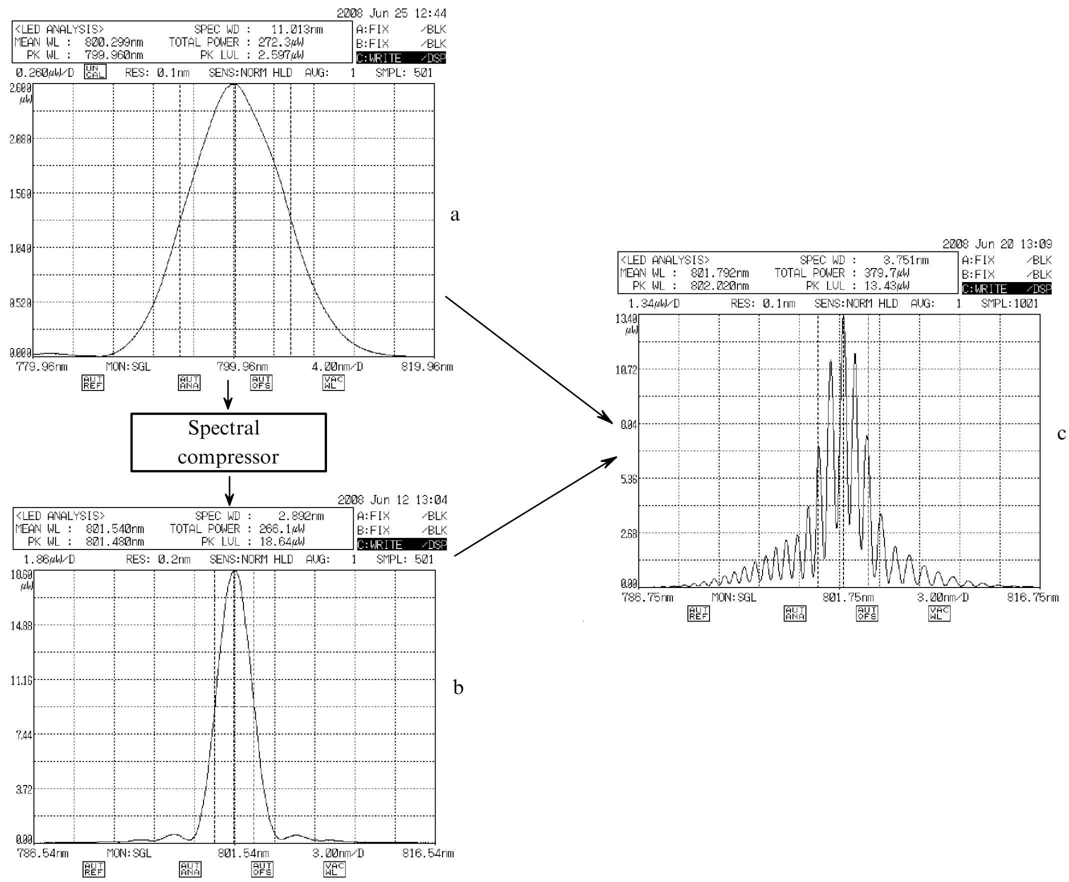

Figure 2. Successive experimental spectrograms: spectral profile of the initial pulse (a), spectrum at the exit from the spectral compression system (b); and spectral interference pattern (c).

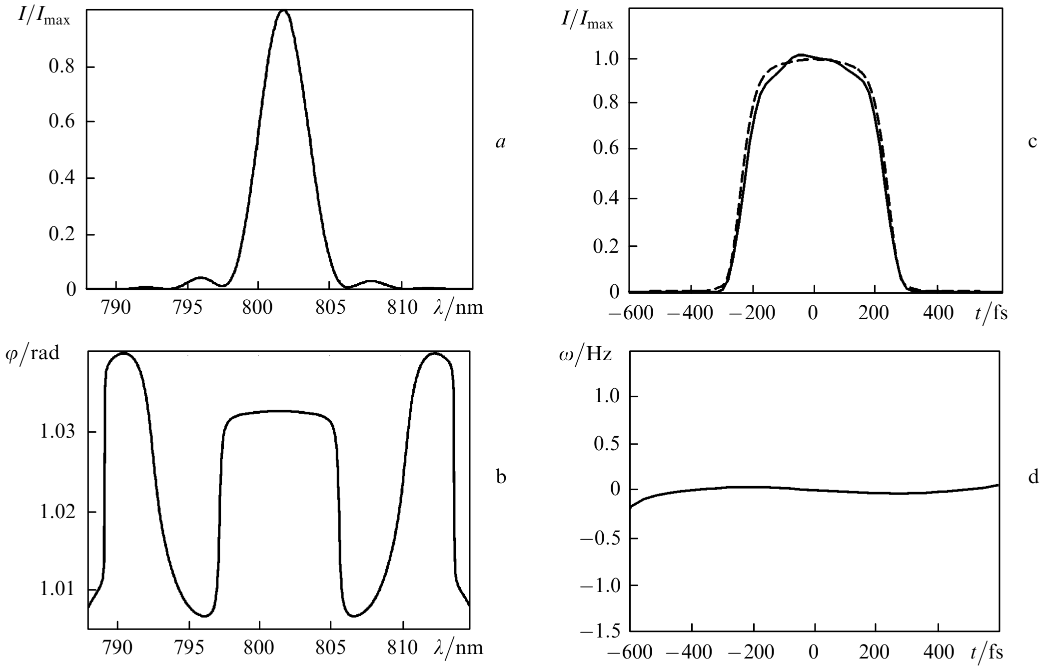

Figure 3. Measured spectrum (a), reconstructed spectral phase (b), temporal profile (c), and chirp (d) of a pulse at $d = 90$ cm and $f = 22$ cm. The dashed curve corresponds to the temporal pulse profile obtained in the numerical experiment

the exit of this system was 2.8, i.e., the bandwidth in the case was 3.7 nm. The compressed spectrum with small satellites has a shape of a sinc-like function which is the Fourier transform of a rectangular function (Fig. 2b). The measurement results are shown in Fig. 3. From Figs 3b and 3d, one can see that phase modulation of the obtained rectangular USPs is almost absent, i.e., the pulses are transform-limited. The dashed curve in Fig. 3c, which corresponds to the results of numerical simulation with the corresponding radiation and setup parameters, well agrees with the experimental data.

The reconstructed pulse profiles were used to calculate the intensity autocorrelation functions, which were compared with the functions recorded with the autocorrelator. Figure 4 shows the autocorrelation functions of a rectangular USP. As is seen, the measured and calculated autocorrelation functions quantitatively agree with each other.

Figure 5 presents the dependence of the degree of spectral compression on the average radiation power in the SMF for $d = 90$ cm and $f = 22$ cm. The power was changed by changing the efficiency of coupling into the SMF. One can see that the pulse bandwidth narrows with increasing power, but widens again at a power exceeding 120 mW. The experimental results agree with calculations. The experimental and numerical investigations showed that rectangular pulses are formed in the region of the maximum spectral compression. The numerical investigation also revealed that, for other DDL and SMF lengths with the same ratio $Z/\zeta \approx 1.6$, the dependence of the spectral compression on the average power in the SMF has the same shape but a different scale. For example, at larger DDL lengths, one observes an increase both in the degree of the maximum spectral compression and in the corresponding power.

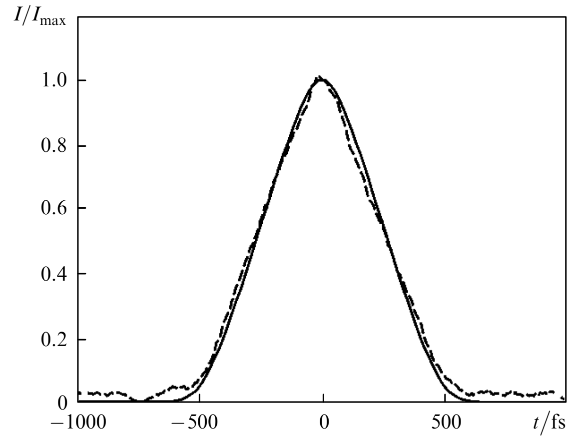

Figure 4. Correlation functions of a rectangular pulse: calculated from the temporal pulse profile (solid curve) and measured (dashed curve).

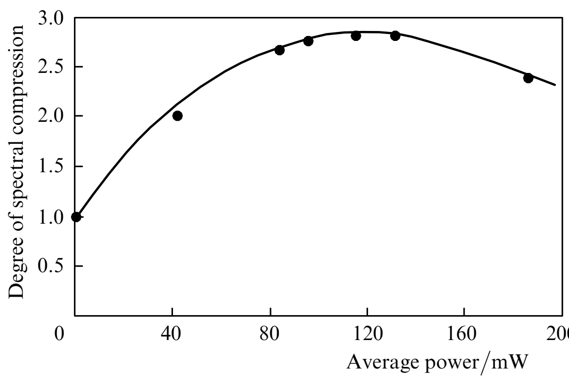

Figure 5. Dependence of the degree of spectral compression on the average radiation power in the SMF at $d = 90$ cm and $f = 22$ cm. The points and the solid curve correspond to the experimental and calculated data, respectively.

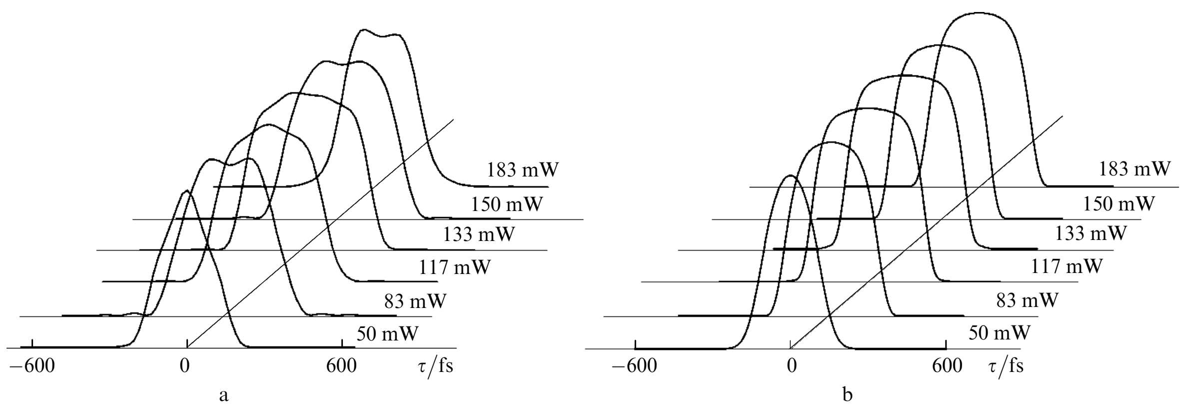

Figure 6. Experimental (a) and calculated (b) temporal pulse profiles at $d = 90$ cm and $f = 22$ cm and different average powers in the SMF. The pulse amplitudes are normalised to their peak values.

At powers that do not correspond to the maximum spectral compression, the USP profile differs from rectangular. The temporal profiles of pulses at the exit from the spectral compression system at different average powers in the SMF are shown in Fig. 6.

The formation of rectangular USPs at the same ratio $Z/\zeta = 1.6$ but different DDL and SMF lengths [$d = 142$ cm ($Z = 10.3$) and $f = 44$ cm ($\zeta = 6.7$)] is demonstrated in Fig. 7. One can see that the reconstructed pulses also have a rectangular shape. The bandwidth in this case was 3 nm, i.e, the spectrum was compressed by a factor of 3.5. Our investigations showed that, as well as in [4–7], the steepness of the pulse edges is determined by the initial Gaussian pulse duration and does not depend on the compressor parameters. However, at long DDLs, when the spectral compression is high, the formed pulses are longer. Taking the duration ratio of the durations of the pulse edge and top as a rectangularity criterion [4], we can say that the shape of pulses obtained at longer DDL and SMF is closer to rectangular.

It should be emphasised that, in addition to the maximum compression, one more necessary condition for formation of rectangular USPs is $Z/\zeta = 1.6$. To confirm this, we studied the spectral compression at a ratio $Z/\zeta \approx 1$. In particular, at $d = 90$ cm ($Z = 5.4$) and $f = 44$ cm ($\eta = 6.7$) (Fig. 8), the temporal pulse profiles, as was expected, have a non-rectangular shape. In this regime, the pulse stretched in the DDL is compressed due to the dispersion in the SMF, which blocks the spectral compression [13]. In the experiment, the maximum degree of spectral compression in this case was 1.2.

It should be noted that our results also agree with the

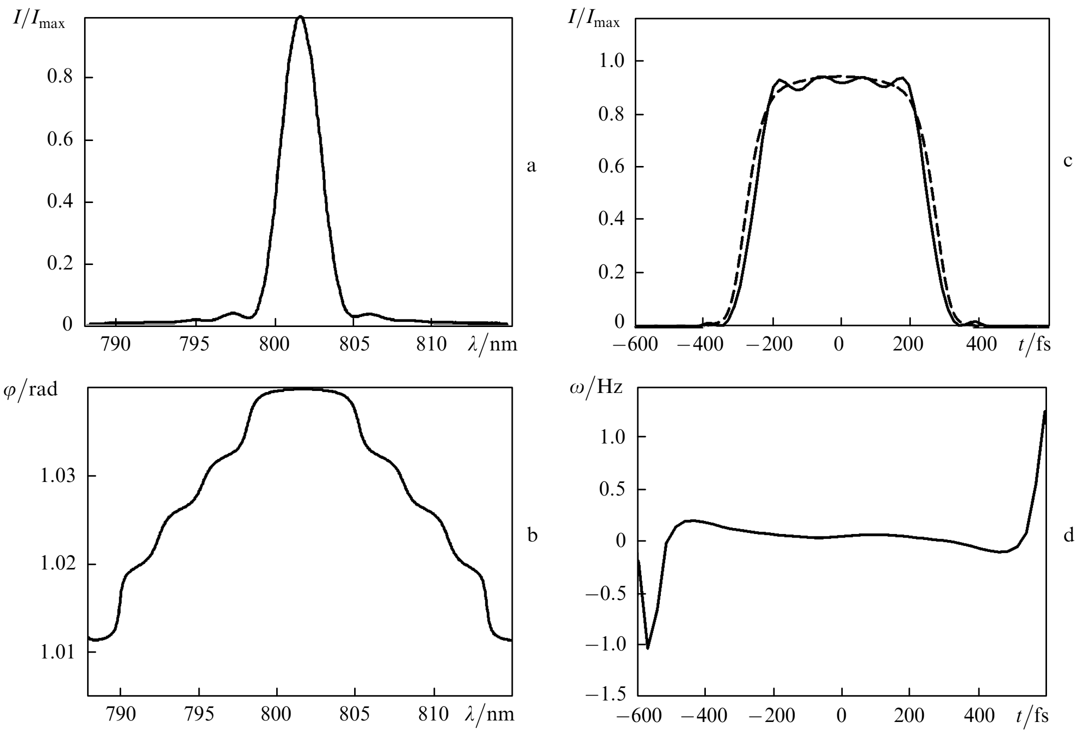

Figure 7. Measured spectrum (a), reconstructed spectral phase (b), temporal profile (c), and chirp (d) of a pulse at $d = 142$ cm and $f = 44$ cm. The dashed curve corresponds to the temporal pulse profile obtained in the numerical experiment.

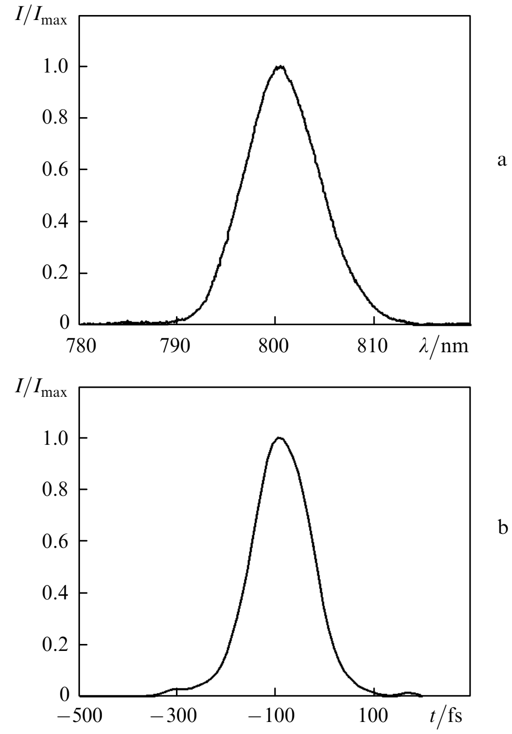

Figure 8. Spectrum (a) and temporal profile (b) of a pulse in the regime of blocked spectral compression at $d = 90$ cm and $f = 44$ cm.

data reported in [12]. This study was not aimed at obtaining pulses of a particular shape, but, due to the used ratio $Z/\zeta \approx 1.7$, the pulses at the exit of the spectral compressor also had a flat top and a sinc-like spectrum.

4. Conclusions

The formation of transform-limited rectangular pulses in a spectral compression system is studied experimentally. It is shown that the formation of such pulses does not depend on the DDL and SMF lengths, but depends only on the ratio of the distance between the prisms and the waveguide length. The investigations showed that rectangular USPs are formed at the DDL-to-SMF length ratio $Z/\zeta \approx 1.6$ in the region of the maximum spectral compression. At DDL lengths shorter than SMF lengths, spectral compression is blocked.

The obtained results can be useful for the problems of control, transfer, and recording of optical signals.

References

1. Agrawal G. *Nonlinear Fiber Optics* (New York: Academic Press, 1995; Moscow: Mir, 1996).
2. Citrin D.S. *Phys. Rev. Lett.*, **77**, 4596 (1996).
3. He G.S., Liu S.H. *Physics of Nonlinear Optics* (Singapore: World Scientific, 1999).
4. Will Ingo, Klemz Guido. *Opt. Express*, **16** (19), 14922 (2008).
5. Cialdi S., Boscolo I., Flacco A. *J. Opt. Soc. Am. B*, **21**, 1693 (2004).
6. Cialdi S., Boscolo I. *Nucl. Insrtrum. Meth. Phys. Res. A*, **538**, 1 (2005).
7. Wang D., Fujioka S., Lim H.C., Thanakom K., Kim S.-Y., Kikuchi K. *Dig. Conf. CLEO-2006* (Lohg Beach, California, 2006) p. JThC105.
8. Wang W., Wang Y., Allaart K., Lenstra D. *Proc. Symp. IEEE/LEOS Benelux Chapter* (Ghent University, Belgium, 2004).
9. Akhmanov S.A., Vysloukh V.A., Chirkin A.S. *Optics of Femtosecond Laser Pulses* (New York: AIP, 1991; Moscow: Nauka, 1988).
10. Markaryan N.L., Muradian L.Kh., Papazyan T.A.*Kvantovaya Elektron.*, **18** (7), 865 (1991) [*Sov. J. Quantum Electron.*, **21** (7) 783 (1991)].
11. Oberthaler M., Hopfel R.A. *Appl. Phys. Lett.*, **63** (8), 1017 (1993).
12. Washburn B.R., Buck J.A., Ralph S.E. *Opt. Lett.*, **25** (7), 445 (2000).
13. Kutuzyan A.A., Mansuryan T.G., Yesayan G.L., Akopyan R.S., Muradian L.Kh. *Kvantovaya Elektron.*, **38** (4), 383 (2008) [*Quantum Electron.*, **38** (4), 383 (2008)].
14. Froehly C., Lacourt A., Vienot J.C. *J. Opt. (Paris)*, **4**, 183 (1973).
15. Takeda M., Ina H., Koyabashi S. *J. Opt. Soc. Am.*, **72** (1), 156 (1982).