Temporal autolocalization of femtosecond light pulses in the filaments observed in fused silica

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Abstract. We observe temporal self-compression of the axial component of femtosecond laser pulse in the filamentation regime in fused silica and find optimized conditions for the maximum compression. Using spatial filtration, we extract the axial component of the pulse compressed down to the duration of 63 fs from the initial 160 fs one. The compressed pulse can be used as a probe in pump-probe measurements to improve their temporal resolution.

Key words: femtosecond laser, filamentation, self-compression, fused silica.

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1. Introduction

Nonlinear changes of the refractive index of a medium under powerful femtosecond laser irradiation result in development of long and narrow high-intensity filaments and the related plasma channels. The process of femtosecond filamentation is closely interrelated with spatiotemporal transformations of laser pulses. Apart from a transverse localization of the filament as tight as several microns in its diameter, a temporal localization of the pulse also occurs, featuring self-shortening and subsequent division into several separate pulses [1].

Considerable success has recently been achieved in self-compression of femtosecond laser pulses in gases. It has been shown both experimentally and theoretically [2–6] that the initial several-tens-of-femtoseconds-long pulses can be compressed down to almost one oscillation cycle. Using such extremely compressed IR pulses, attosecond pulses in the UV can be obtained in the process of high-order harmonic generation [7, 8]. The self-compression and temporal splitting of the femtosecond pulses have also been observed experimentally in some condensed media [9].

We suggest a qualitative explanation of the temporal self-compression and splitting of not transform-limited laser pulses, using a simple moving focus model [10, 11] (see Fig. 1). Only those temporal ‘slices’ of the input laser pulse whose power P exceeds the critical self-focusing power $P_{cr} = 3.72\lambda^2/8\pi n n_2$ [12] (with λ being the wavelength of light, n the refractive index, and n_2 the nonlinear refractive index) collapse on the beam axis. The distance to the collapse point is described by a half-empiric Marburger formula:

$$L_c = \frac{0.367 L_{DF}}{\sqrt{[(P/P_{cr})^{1/2} - 0.852]^2 - 0.0219}}, \tag{1}$$

where L_{DF} is the Rayleigh length. As follows from Eq. (1), the bigger the P value the shorter the collapse distance L_c becomes. In fact, a complete collapse of the femtosecond laser pulse is stopped by intensity clamping mechanisms [1]. The collapse points of different temporal ‘slices’ of the pulse are ‘spread’ along the propagation axis according to their powers P, thus forming an extended filament in the frame of the moving focus model. The filament starts from the point of minimum L_c, formed by the temporal ‘slice’ at the pulse maximum. It is evident that the duration of this on-axis self-focused pulse component is smaller than that of the input pulse, because it is formed only by the partial temporal ‘slice’. Setting a small aperture D1 at the point of the filament start, one can extract the temporally compressed pulse. The nearest pair of the lower-power temporal ‘slices’ collapses further onward. Hence, an aperture D2 would extract a temporally split double pulse.

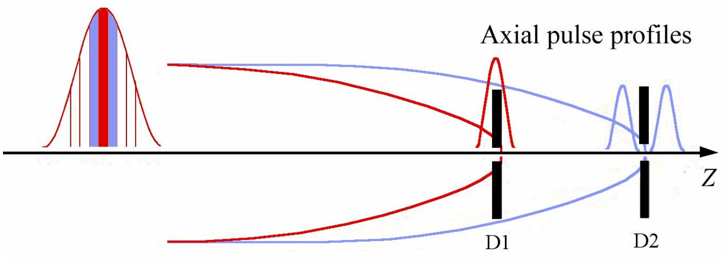

Fig. 1. Illustration of principles used for nonlinear self-compression and splitting of femtosecond laser pulses.

More complex is the self-compression process of the transform-limited pulses, i.e. the pulses of physically limited duration, which satisfy the condition $\Delta\omega_0 T_0 = 1$ (with $\Delta\omega_0$ and T_0 denoting the half-widths at the level $1/e$ of respectively the frequency band and the pulse duration). At first glance it would seem that a further pulse compression is impossible. However, besides of the self-focusing, the nonlinear changes of the refractive index in a Kerr medium cause widening of the pulse frequency band due to self-phase modulation [13]. As a result, the Fourier limitation becomes weaker, thus allowing the subsequent temporal compression. With further propagation of the pulse, the compression is replaced by temporal splitting, resulting eventually in a rather complicated temporal shape [14, 15].

The extraction of the compressed component is not, however, a simple task. Apertures set on the filament axis can indeed be used to this end in gaseous media, though such a scheme is not valid for condensed media. To the best of our knowledge, the pulse compressed in solids has not been extracted so far. One of the reasons for this is small energy of the filamented pulse in solids, which limits possible applications.

However, a weak pulse can be used as a probe in time-resolved pump-probe experiments, which do not require high energies. A pulse of the same laser, its second harmonic, or white supercontinuum are used, as a rule, for both pumping and probing in the pump-probe experiments [16–18]. The probe duration in such a case is at best the same as that of the pump, thus limiting the temporal resolution of the experiment. Then using of shorter probe pulses should allow observation of ‘faster’ details of the interaction of pump pulses with the media.

2. Experimental results and discussion

We have performed an experiment on self-compression of the femtosecond laser pulse in the filaments in fused silica, extracted the compressed component, and found the conditions of minimum duration of the compressed pulse. A scheme presented in Fig. 2 has been used for controlling the pulse intensity and shaping its cross-section profile.

A narrow beam with the diameter ~ 2 mm is cut with an aperture A1 from a wide (the diameter

~ 7 mm at the FWHM) horizontally polarized beam of a regenerative amplifier Legend F-1K-HE ($\lambda = 820$ nm, the duration of 160 fs, and the repetition rate of 1 kHz). The polarization plane of the pulse can be changed while rotating a half-wave plate $\lambda/2$, thus varying the pulse energy behind a vertically arranged Glan polarizer P. A centrally peaked ring intensity pattern is formed at the position of an aperture A2 at the distance of 2 m from the aperture A1, as a result of diffraction. The higher-order diffraction rings are cut off, while the central peak (the Airy spot) passes the aperture A2 with the diameter of 2 mm to be further used in the self-compression experiments. The maximum output pulse energy is equal to 10 μJ.

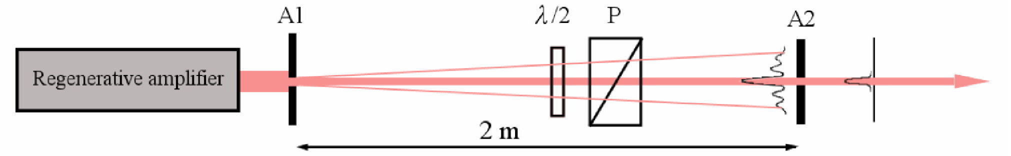

Fig. 2. Intensity control and profile shaping of the pump beam.

A principal scheme of the self-compression experiment is shown in Fig. 3. The beam is focused with a lens (the focal distance of 14 cm) onto a polished input face of a 1 cm-thick fused silica slab, where self-focusing and filamentation occur. The relaxation of free carriers generated by multiphoton absorption processes in filament causes a photoluminescence in the transverse direction, which is collected by a ×3.7 microscopic lens and then recorded with a CCD camera.

The exit spot of the beam is imaged upon the aperture D of variable diameter by a microscopic ×16 lens. Given the 200-fold magnification of the exit spot, the aperture D allows to extract the light of the 'hot' filament core. In fact, this aperture acts similarly to the aperture D1 in Fig. 1, though it is set at the magnified image of the filament, rather than directly at the latter. The 2 mm diameter of the aperture D corresponds to the 10 μm circle on the exit face of the fused silica slab around the beam axis, while a typical diameter of the femtosecond filament in the fused silica is equal to 3–4 μm [16–18]. The autocorrelation function of the beam, which passes the aperture D, is measured with an APE Autocorrelator mini. The large magnification mentioned above is used because of the requirements of autocorrelator for the input beam parameters (namely, the collimated beams should have their diameters not less that 2 mm).

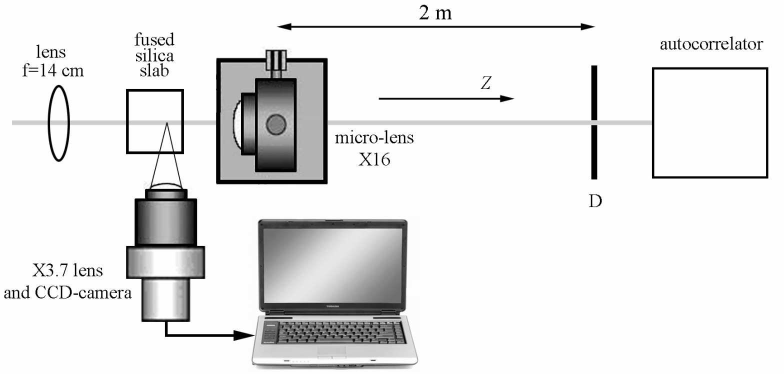

Fig. 3. Principal scheme of self-compression and compressed-pulse extraction experiment.

The minimum output pulse duration 63 fs is observed for the input pulse energy $E = 2$ μJ. With slowly increasing E, the optimum energy manifests itself microscopically as the appearance of filament-induced luminescence, which is located just at the output face of the slab. Visually, a white supercontinuum emission appears at $E = 2$ μJ in the direction of the optical axis.

The autocorrelation functions of the output beam measured for different diameters of the aperture D in the linear mode (at $E = 0.5$ μJ) and in the filamentation mode (at $E = 2$ μJ) are shown in Fig. 4. Here τ is the width of the autocorrelation function at the FWHM.

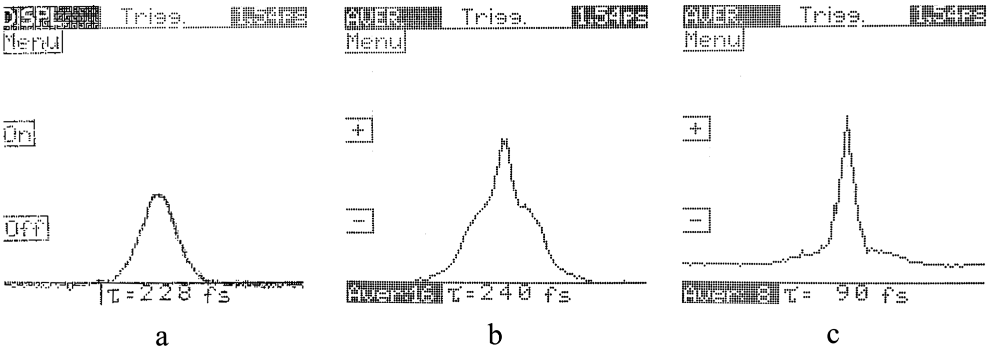

Fig. 4. Photographs of autocorrelator traces taken from the display of APE Autocorrelator mini: (a) output pulse in the linear mode at $E = 0.5$ μJ, (b) output pulse in the nonlinear mode at $E = 2$ μJ and 5 mm aperture D, and (c) output pulse at $E = 2$ μJ and 2 mm aperture D.

The autocorrelation function width $\tau = 228$ fs of the input pulse is the same as that of the output one in the linear mode at $E = 0.5$ μJ (see Fig. 4a). Assuming the Gaussian temporal shape of the pulse, one gets its width at the FWHM as $0.7\tau = 160$ fs. Although in reality the shape of the pulse can differ from the Gaussian one, we conditionally accept this value. With the diameter of 5 mm for the aperture D (see Fig. 4b), apart from the intense filament core, there passes also a part of enveloping energetic reservoir of a lower intensity. Therefore, we obtain a superposition of the compressed and wide pulses in the autocorrelator trace. With a smaller diameter of 2 mm (see Fig. 4c) of the aperture D, we observe an almost ‘clean’ and more than twice compressed pulse with $\tau = 90$ fs, which corresponds to the pulse duration of 63 fs at the FWHM, if one assumes the Gaussian shape.

To the best of our knowledge, the extraction of the femtosecond pulses compressed in the condensed media, has not been implemented before. Notice that in order to achieve this, we have used an original method for the spatial filtration, setting the aperture not directly at the filament, but at its magnified image.

3. Conclusions

We have implemented the temporal compression of the femtosecond laser pulse from its initial duration of 160 fs down to 63 fs, using the self-compression phenomenon in the filaments occurring in fused silica. To extract the compressed pulse, we have used the spatial filtration for the 200-fold magnified image of the filament. The compressed pulse can be used as a probe in time-resolved pump-probe measurements, improving more than twice their temporal resolution.

Acknowledgments

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References

1. Couairon A and Mysyrowicz A, 2007. Femtosecond filamentation in transparent media. Phys. Rep. **441**: 47–189.
2. Hauri C P, Kornelis W, Helbing F W, Heinrich A, Couairon A, Mysyrowicz A, Biegert J and Keller U, 2004. Generation of intense, carrier-envelope phase locked few cycle laser pulses through filamentation. Appl. Phys. B. **79**: 673–677.
3. Hauri C P, Guandalini A, Eckle P, Kornelis W, Biegert J and Keller U, 2005. Generation of intense few-cycle laser pulses through filamentation – parameter dependence. Opt. Express. **13**: 7541–7547.
4. Xiaowei C, Xiaofang L, Jun L, Pengfei W, Xiaochun G, Ruxin L and Zhizhan X, 2007. Generation of 5 fs, 0.7 mJ pulses at 1 kHz through cascade filamentation. Opt. Lett. **32**: 2402–2404.
5. Koprinkov I G, Suda A, Wang P and Midorikawa K, 2000. Self-compression of high- intensity femtosecond optical pulses and spatiotemporal soliton generation. Phys. Rev. Lett. **84**: 3847–3850.
6. Kosareva O G, Panov N A, Uryupina D S, Kurilova M V, Mazhorova A V, Savel’ev A B, Volkov R V, Kandidov V P and Chin S L, 2008. Optimization of a femtosecond pulse self-compression region along a filament in air. Appl Phys. B. **91**: 35–43.
7. Hentschel M, Kienberger R, Spielmann Ch, Reider G A, Milosevic N, Brabec T, Corkum P, Heinzmann U, Drescher M and Krausz F, 2001. Attosecond metrology. Nature. **414**: 509–513.
8. Kienberger R, Goulielmakis E., Uiberacker M, Baltuska A, Yakovlev V, Bammer F, Scrinzi A, Westerwalbesloh Th, Kleineberg U, Heinzmann U, Drescher M and Krausz F, 2004. Atomic transient recorder. Nature. **427**: 817–821.
9. Diddams S A, Eaton H K, Zozulya A A and Clement T S, 1998. Amplitude and phase measurements of femtosecond pulse splitting in nonlinear dispersive media. Opt. Lett. **23**: 379–381.
10. Lugovoi V N and Prokhorov A M, 1968. A possible explanation of the small-scale self-focusing filaments. JETP Lett. **7**: 117–119.
11. Kandidov V P, Dormidonov A E, Kosareva O G, Chin S L and Liu W, 2009. Self-focusing and filamentation of powerful femtosecond laser pulses. Self-focusing: past and present. Ed. by R. W. Boyd. New York: Springer, 371–398.
12. Marburger J H, 1975. Self-focusing: theory. Prog. Quant. Electr. **4**: 35–110.
13. Shen Y R, The principles of nonlinear optics. Hoboken: Wiley (2003).
14. Smetanina E O, Kompanets V O, Chekalin S V and Kandidov V P, 2012. Femtosecond laser pulse filamentation under anomalous dispersion in fused silica. Part 1. Numerical investigation. Quant. Electron. **42**: 913–919.
15. Smetanina E O, Kompanets V O, Chekalin S V and Kandidov V P, 2012. Femtosecond laser pulse filamentation under anomalous dispersion in fused silica. Part 2. Experiment and physical interpretation. Quant. Electron. **42**: 920–924.
16. Blonskii I V, Kadan V N, Shpotyuk O I, Dmitruk I N and Pavlov I A, 2009. Direct observation of the space-time transformation of a femtosecond laser pulse in fused quartz. JETP Lett. **89**: 535–539.
17. Blonskyi I, Kadan V, Shpotyuk O and Pavlov I, 2009. Plasma effect on propagation of filamented femtosecond laser pulse in fused silica. Ukr. J. Phys. Opt. **10**: 100–108.

18. Blonskyi I, Brodyn M, Kadan V, Shpotyuk O, Dmitruk I and Pavlov I, 2009. Spatiotemporal dynamics of femtosecond filament induced plasma channel in fused silica. Appl. Phys. B. **97**: 829–834.

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***Анотація**. Спостережено часову самокомпресію аксіальної компоненти фемтосекундного лазерного імпульсу в режимі філаментації в плавленому кварці і знайдено оптимізовані умови максимальної компресії. З використанням просторової фільтрації відокремлено аксіальну компоненту імпульсу та скорочено її до 63 фс від початкової тривалості 160 фс. Скорочений імпульс можна використовувати як зондуючий для покращення часової роздільної здатності у вимірах за схемою "збудження–зондування".*