

LETTERS

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Generation of optical pulses of duration down to 8 fs upon filamentation of collimated femtosecond laser radiation in argon

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***Abstract*. A new scheme providing self-compression of femtosecond laser radiation upon filamentation of a collimated beam in argon at a pressure of ~ 0.8 atm is experimentally realised. Pulses with the initial duration of 55 fs were compressed down to 8 fs, the peak power of the compressed pulse exceeding 20 GW.**

Keywords: *few-cycle optical pulses, filamentation, self-compression, collimated beam.*

At present, high-power few-cycle optical pulses are generated, as a rule, by broadening the spectrum of 30 – 70 fs pulses during the waveguide propagation of laser radiation in gases and the subsequent temporal compression of pulses with an external compressor constructed by using chirped mirrors or a system of prisms [1 – 3]. Recently, the possibility of self-compression of high-power femtosecond laser radiation upon its filamentation in a gas has been demonstrated experimentally [4 – 6]. In these papers, laser radiation was focused into the gas leading to the formation of a 10 – 50-cm-long filament at the output of which a high-power compressed pulse of duration < 10 fs was generated.

We showed in a numerical experiment [7] that when a high-power collimated laser beam is used, a significant pulse self-compression is also possible in the filament being produced. In this paper we present new experimental results confirming the conclusions of paper [7]. 80-GW, 55-fs pulses were compressed down to 8 fs with high stability.

A single filament was produced by 55-fs, 10-mJ pulses from a Ti : sapphire laser with a pulse repetition rate of 10 Hz [8]. The initial beam was split with a beamsplitter into two with the energy ratio 5 : 3. The first beam was used to produce a filament in a cell filled with gas and the second one was used as a reference beam for measuring the pulse duration by the SPIDER method in the scheme described in [9].

The beam of diameter 1.3 mm with a plane wavefront was formed at the cell input by a telescope consisting of a collecting lens (with the focal distance $f = 4.52$ m) and a convex mirror ($f = 1$ m). In this way, a relatively short single filament was produced. The cell length was 3 m. The input and output windows of the cell were made of 600-μm-thick quartz plates.

Inside the cell an aperture of diameter 100 to 1000 μm was placed, which could be displaced along the cell with the help of a magnetic clutch. The filament terminated behind this aperture because the aperture cut-off the so-called energy reservoir, thereby interrupting the energy supply to the central part of the filament. The spectral phase and the time envelope of the pulse behind the cell were measured by the SPIDER method [9].

The parameters of input radiation (4.5 – 5.0-mJ pulses, a beam of diameter 1.3 mm) and gas (argon at pressures of 0.8 – 0.9 atm), as well as the distance from the filament onset (1.5 – 1.8 m from the telescope output mirror) to the place where the aperture was mounted (1 m) were selected based on the spectral transformation of radiation along the filament [10]. Our measurements showed that mounting the aperture of diameter larger than 700 μm does not lead to the 'break' of the filament and the appearance of a diverging beam, which well agrees with the known data in the literature on the transverse size of the energy reservoir [11, 12] and with the results of our numerical simulation. At the aperture diameter smaller than 300 μm, the laser beam pointing instability prevents quantitative measurements by the SPIDER method (the axial part of the filament rarely passes through the aperture).

When the aperture of diameter 700 μm was used, we observed generation of 14 ± 3-fs pulses stable in duration and spatiotemporal shape. The spectrum and the temporal envelope of the intensity of a typical 12-fs pulse are presented in Figs 1a, b. The pulse spectrum broadens up to ~ 0.35 PHz due to filamentation and its spectral phase for the optimal position of the aperture (1 m from the filament onset) is almost flat with a deviation no more than 0.4 rad within the broadened spectrum (Fig. 1a). Note that at this position of the aperture, such a phase is obtained in a relatively narrow range of argon pressures (0.75 – 0.9 atm). At lower pressures, the pulse spectral width significantly decreases, while at larger pressures, the spectral phase is substantially distorted due to multiple filamentation. The temporal shape of the compressed pulse (Fig. 1b) is well

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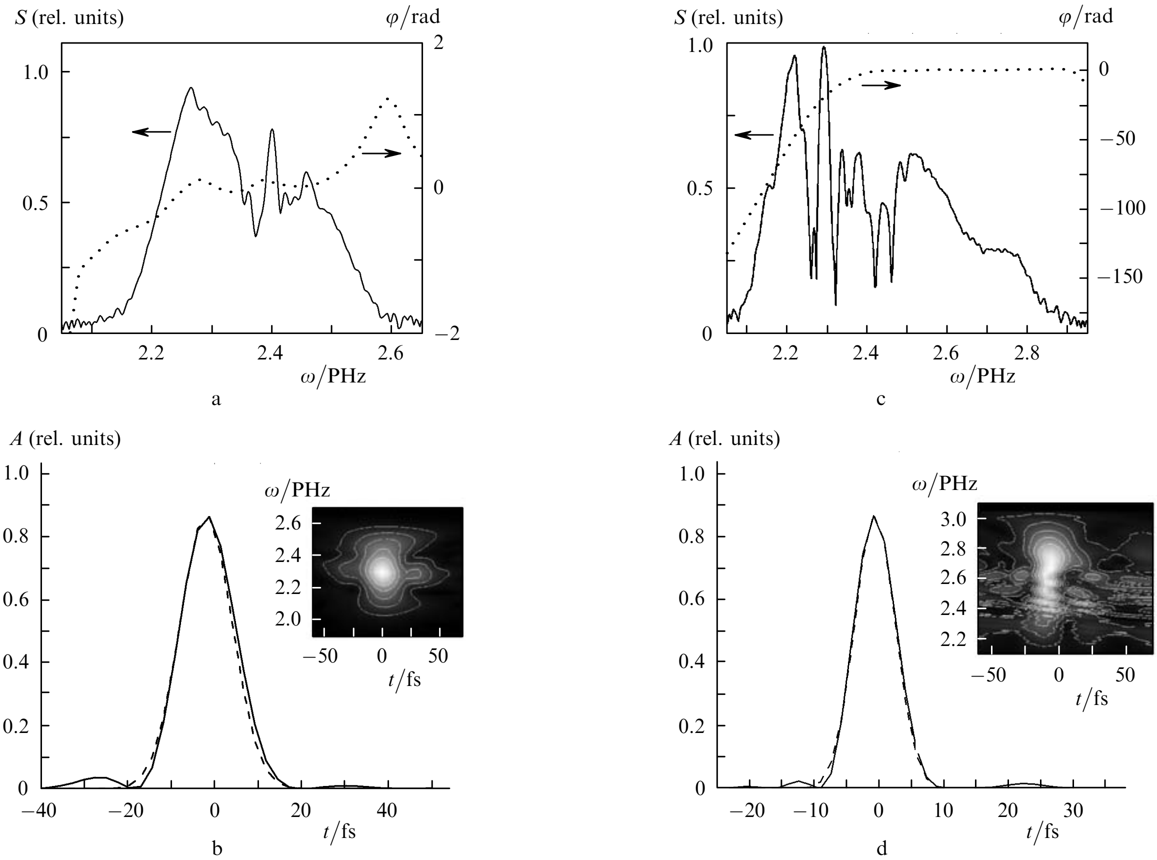

Figure 1. Recovered spectral phase φ and amplitude S (a, c), as well as the temporal shape A (experiment is shown by a solid curve and the Gaussian approximation – by a dashed curve) (b, d) of pulses obtained upon filamentation in argon by using an aperture of diameter 700 (a, b) and 300 μm (c, d). The insets illustrate spectral – temporal diagrams of the pulses (thin white curves correspond to six levels of brightness for a uniform scale).

approximated by a Gaussian with a FWHM of 12 fs. The temporal structure of the pulse contains a number of prepulses and postpulses, which, however, have amplitudes that are significantly smaller than that of the pulses obtained in [4, 6]. These prepulses and postpulses can also appear in our case during processing the signals by the SPIDER method, which involves three Fourier transforms at the finite time or frequency interval. The inset in Fig 1b shows the spectral – temporal $\omega - t$ pulse diagram reconstructed from the spectral amplitude and phase of the pulse by using the PGFROG algorithm [13]. One can see that the pulse is significantly limited both in the temporal and spectral regions and is close to a transform-limited pulse.

Figure 1c presents the frequency distribution of the intensity and the spectral phase of the pulse obtained in argon under the same conditions with the aperture of diameter 300 μm. One can see that the pulse spectrum was broadened approximately twice, while the spectral phase remained constant on the most of the spectrum width. The pulse duration was less than 8 fs (see the Gaussian approximation in Fig. 1d). The spectral – temporal diagram of the pulse (inset in Fig. 1d) shows that the pulse energy is mainly concentrated in the limited region of this diagram; however, the pulse is not transform-limited. Nevertheless, even under these conditions prepulses and postpulses have small amplitudes.

An important feature of the obtained self-compression regime is a high stability of the pulse duration and energy. Thus, the fluctuations of the compressed pulse duration at the optimal gas pressure were notably suppressed (for the aperture diameter of 700 μm, the compressed pulses were obtained in 92 % of realisations with the duration fluctuation of 3-fs) and proved even smaller that the fluctuations of the initial pulse duration. According to our estimates obtained by comparing the results of measurements of the total filament energy with the numerical simulation, the compressed pulse energy was 400 – 500 μJ for the aperture diameter 700 μm and 250 μJ for the diameter 300 μm.

Thus, the self-compression regime obtained in the study has a number of significant advantages over the conventional geometry using laser radiation focusing, namely: a substantial stability of the temporal compression related to the self-consistent regime of the filament formation due to the Kerr nonlinearity of the medium and its ionisation (without geometrical focusing); the possibility of ‘extraction‘ of a compressed pulse at the required distance from the filament onset and, as a result, the possibility to optimise pulse parameters; and a weak sensitivity of the compressed pulse parameters to fluctuations of the input radiation parameters.

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