Quantum Electronics **48** (7) 621–624 (2018)

https://doi.org/10.1070/QEL16702

Compressor of femtosecond laser pulses based on supercritical xenon

N.V. Didenko, A.V. Konyashchenko, L.L. Losev, V.S. Pazyuk

Abstract. **A time compressor of femtosecond laser pulses is developed using supercritical xenon as an active medium. Laser pulses with a duration of 300-fs and an energy of 8 μJ are compressed to 23 fs with an efficiency of 40 %.**

Keywords: *femtosecond pulses, xenon, supercritical fluid, time compression; self-phase modulation.*

1. Introduction

Broadening of the spectrum of an initial laser pulse propagating in the nonlinear medium of a pulse compressor based on the nonlinear effect of self-phase modulation and subsequent compression of the chirped pulse [1] is described by the expression [2]

$$\frac{\Delta(z)}{\Delta_0} \approx \frac{2\pi n_2}{\lambda}\int_0^z I(\zeta)\,\mathrm{d}\zeta \text{ (for the case } \Delta/\Delta_0 > 2), \qquad (1)$$

where Δ_0 and $\Delta(z)$ are the spectral widths of pulses at the entrance to the nonlinear medium and at a distance z from the entrance, respectively; λ is the centre wavelength of the laser radiation; n_2 is the nonlinear refractive index, and I is the laser radiation intensity.

To achieve a larger spectral width of the pulse at the exit from the nonlinear medium and, hence, a shorter pulse duration after compression, one uses various waveguide structures (hollow optical fibres, silica fibres, etc.) to increase the product of the radiation intensity and the medium length, which determines the spectrum broadening. In addition, a wider pulse spectrum can be obtained by choosing a medium with a higher refractive index n_2. For efficient coupling of laser radiation and its propagation in an optical fibre, the pulse power must be lower than the self-focusing critical power, i.e. [3],

$$\frac{E}{\tau} < P_{\mathrm{cr}} = \frac{\lambda^2}{2\pi n_0 n_2},$$

where E and τ are the laser pulse energy and duration and n_0 is the linear refractive index. Therefore, to compress nanojoule femtosecond laser pulses, one uses solid-state (silica and glass) fibres with nonlinear refractive indices n_2 from 10^{-15} to 10^{-16} cm^2 W^{-1} [4]. The nonlinear refractive index in gas media can be varied in a rather wide range by choosing the composition and pressure (nonlinear refractive index is proportional to the gas pressure). The use of light inert gases (helium, neon) with low nonlinear refractive indices ($\sim 10^{-20}$ cm^2 W^{-1} atm^{-1}) made it possible to compress femtosecond laser pulses with energies up to 10 mJ and obtain subterawatt pulses [5]. Heavy inert gases (krypton, xenon) with a nonlinear refractive index of $\sim 10^{-18}$ cm^2 W^{-1} atm^{-1} at pressures of 10–100 atm were used to compress pulses with energies of 0.1–1 mJ [6]. Compression of microjoule laser pulses requires gas media with pressures exceeding 100 atm, the use of which runs into problems with fabrication and operation of compressors. In this connection, it is of interest to use supercritical xenon as a nonlinear medium of compressors.

At temperatures and pressures exceeding critical values (16.7 °C and 58.4 atm, respectively), xenon becomes a supercritical fluid, whose density and, hence, nonlinear refractive index vary in a wide range (up to the value of n_2 of fused silica) with insignificant changes in pressure (Fig. 1) [7]. This opens the possibility of designing a compressor of microjoule pulses at a pressure not exceeding 100 atm.

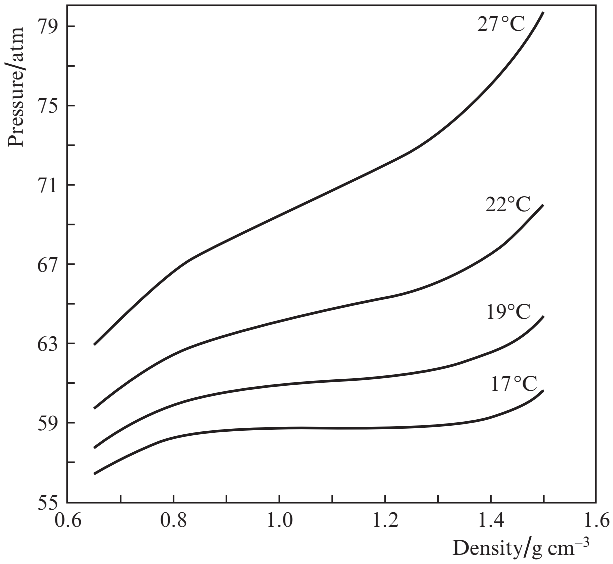

Figure 1. Relation between the supercritical xenon density and pressure at different temperatures. The dependences are plotted based on the data of [7].

N.V. Didenko, A.V. Konyashchenko, L.L. Losev, V.S. Pazyuk P.N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: lllosev@mail.ru

Received 12 April 2018
Kvantovaya Elektronika **48** (7) 621–624 (2018)
Translated by M.N. Basieva

In recent years, investigations have been performed on generation of broadband radiation upon propagation of femtosecond laser pulses in a hollow fibre filled with supercritical xenon [8, 9]. Generation of supercontinuum upon focusing of laser radiation into a chamber with supercritical xenon was studied experimentally [10]. However, there are no experimental data on compression of pulses spectrally broadened in supercritical xenon.

The aim of this work was to produce a compressor of femtosecond laser pulses with an energy not exceeding 10 μJ based on spectral broadening due to self-phase modulation in supercritical xenon.

2. Pulse duration at the fibre output

When considering self-phase modulation in high-density media, in particular, in supercritical xenon, one must take into account temporal pulse dispersion. An increase in the chirped pulse duration at the output from a nonlinear medium makes it necessary to use optical elements with a high negative dispersion to achieve chirped pulse compression, which may cause some problems. This becomes especially critical in the case of using chirped mirrors as negative-dispersion elements. Since the size of a mirror limits the number of possible reflections from its surface and, therefore, the total negative dispersion introduced by the mirror, it is desirable to estimate the chirped pulse duration at the entrance to the time compressor to be developed by rather simple formulas.

Let us consider lossless propagation of a pulse with energy E and duration τ in an optical fibre with a constant cross section area S, which is filled with a medium with a nonlinear refractive index n_2. From (1) we can obtain the equation for the change in the pulse spectral width:

$$\frac{\mathrm{d}\Delta}{\mathrm{d}z} = \frac{2\pi n_2 \Delta_0}{\lambda} \frac{E}{S\tau}. \tag{2}$$

The pulse dispersion during propagation is described by the equation [11]

$$\frac{\mathrm{d}\tau}{\mathrm{d}z} = \beta\Delta, \tag{3}$$

where β is the group-velocity dispersion coefficient.

From Eqns (2) and (3), one can derive the equation relating the pulse duration and spectral width:

$$\tau = \tau_0 \exp\left[\frac{\beta\lambda\Delta_0 S}{4\pi n_2 E}\left(\frac{\Delta^2}{\Delta_0^2} - 1\right)\right], \tag{4}$$

where τ_0 is the pulse duration at the entrance to the nonlinear medium. This expression will be used below to analyse the experimental results.

3. Experimental setup

We studied compression of femtosecond pulses of a TETA ytterbium laser (Avesta, Russia). The laser emitted 300-fs pulses at a wavelength of 1030 nm with a spectral width of 6 nm and a repetition rate of 3 kHz. The spatial intensity distribution over the beam cross section was close to Gaussian. The pulse energy was varied by a polarisation attenuator, which consisted of a half-wave phase plate and a Glan – Fresnel polarisation prism placed in front of the lens focusing the radiation into a cell with supercritical xenon. A quartz capillary served as an optical fibre. The experiments were performed with capillaries of two types, namely, the first capillary was 60 cm long with an inner diameter of 150 μm and the second was 12 cm long with an inner diameter of 100 μm. The radiation from the capillary output was collimated by a lens and sent into a time compressor consisting of two chirped mirrors. The compressed pulse duration was measured with an ASF-15 autocorrelator (Avesta).

To obtain xenon in the supercritical state, xenon was condensed in a cooled vessel, from which it was then delivered into the cell with a capillary. The xenon pressure in our experiments was 62 atm at a temperature of 23 °C, which corresponds to a supercritical xenon density of 0.7 g cm^{-3}.

4. Discussion of results

Laser radiation was focused into capillaries 150 and 100 μm in diameter by lenses with focal lengths f = 40 and 25 cm, respectively. In both cases, the efficiency of energy coupling into the capillaries was maximum and equal to 80%. The measured dependences of the transmission of both capillaries filled with xenon on the input laser pulse energy showed that their transmission begins to sharply decrease as the energy exceeds 8 μJ (Fig. 2) The beginning of a decrease in the capillary transmission, which occurs at different radiation intensities in the capillaries and at the same power, is related to overcoming a critical self-focusing power. Based on the measured critical power, we calculated the nonlinear refractive index n_2 of supercritical xenon to be $(3-4)\times10^{-17}$ cm^2 W^{-1}.

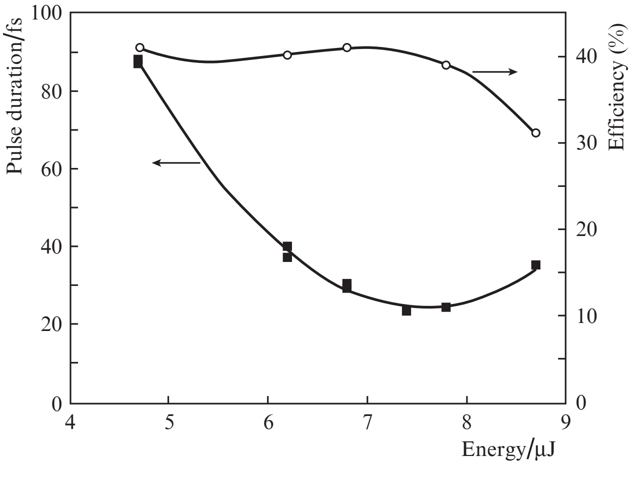

Figure 2. Dependences of the compressed pulse duration and the energy efficiency on the laser pulse energy at the input of the capillary with an inner diameter of 100 μm.

Figure 3 presents the emission spectra at the output of the capillaries measured at a laser pulse energy of 8 μJ. One can see that the spectral widths are close to each other and are about 100 nm. The spectrum modulation depth is lower for the capillary with a diameter of 150 μm and a length of 60 cm. The decrease in the modulation depth and the increase in the constant component in the spectrum are characteristic for self-phase modulation processes, in which noticeable influence is exerted by pulse dispersion. Calculations showed that the minimum pulse duration (in the case of identical phases of

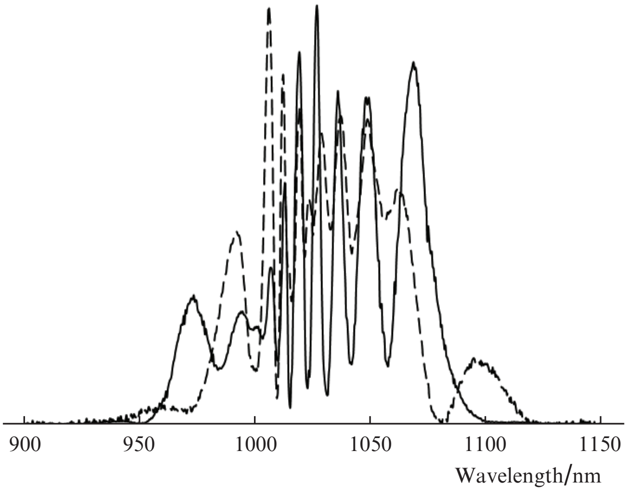

Figure 3. Spectra of pulses at the output of capillaries with inner diameters of (solid curve) 100 and (dashed curve) 150 μm.

the spectral components) for the corresponding spectrum is 21 fs for the capillary 150 μm in diameter and 22 fs for the capillary with a diameter of 100 μm.

Time compression of chirped pulses emitted from the cell with xenon occurred as the pulse propagated through a multipass system of two chirped mirrors. We used Layertec mirrors 25 mm in diameter with a negative group-delay dispersion coefficient $D = -100$ fs^2 per reflection. At a collimated light beam diameter of about 1 mm, it was possible to obtain 12 reflections from each mirror (in total, 24 reflections) without loss of power.

In the scheme with the capillary 150 μm in diameter and 60 cm long, we did not obtain complete compression of the chirped pulse. The compressed pulse duration was observed to continuously decrease with increasing number of reflections from the chirped mirrors. At the maximum possible number of reflections, the compressed pulse duration was ~100 fs. The incomplete compression can be explained by insufficient negative dispersion introduced by the chirped mirrors. The estimates presented below confirm this suggestion.

Using (4) and parameters $\beta = 15$ fs^2 mm^{-1} [12], $\lambda = 1030$ nm, $\Delta_0 = 0.011$ fs^{-1} (which corresponds to 6 nm), $\Delta = 0.18$ fs^{-1} (100 nm), $n_2 = 3\times10^{-17}$ W cm^{-2}, $\tau_0 = 300$ fs, and $E = 6$ μJ, we obtain that the pulse duration in the capillary with an inner diameter of 100 μm (the fundamental mode diameter 60 μm) increases from 300 fs at the entrance to 420 fs at the exit, while the pulse duration in the capillary 150 μm in diameter increases to 620 fs. Therefore, since the number of reflections for compression of such pulses by chirped mirrors is determined by the expression $N \approx \tau/D\Delta$, it is necessary to provide 24 reflections from the used chirped mirrors for the capillary 100 μm in diameter and 34 reflections for the 150-μm capillary. In our experiment, the latter condition for the capillary with a diameter of 150 μm was not fulfilled.

The shortest compressed pulses were obtained by using the capillary with a diameter of 100 μm. The number of reflections from the chirped mirrors in the optimal regime was 22. Figure 2 shows the dependence of the compressed pulse duration on the laser pulse energy at the capillary input. The minimum pulse duration was 23 fs (on the assumption of a sech^2 pulse shape). The autocorrelation function of the compressed pulse is shown in Fig. 4. Our measurements showed that the central peak contains ~65% of the pulse energy. The appearance of low-intensity wings of the pulse is explained by a difference between the frequency chirp caused by self-phase modulation and the linear chirp at the pulse edges [13].

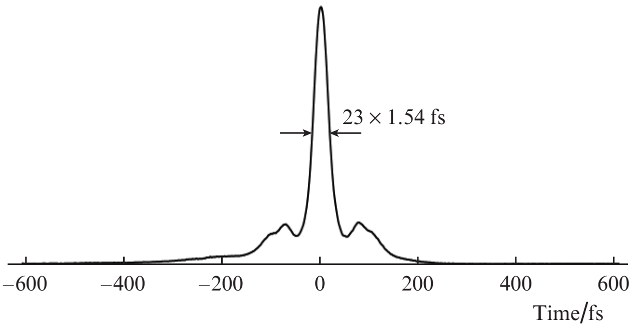

Figure 4. Autocorrelation function of a compressed pulse in the scheme with a capillary with an inner diameter of 100 μm.

The pulse contrast can be increased by second harmonic generation in a crystal. This can also lead to an additional (approximately twofold) pulse compression [14].

5. Conclusions

Thus, we have designed a compressor of femtosecond laser pulses based on supercritical xenon. Ytterbium laser pulses with a duration of 300 fs and an energy of 7–8 μJ are compressed to 23 fs with an efficiency of 40% due to spectral broadening in xenon with a pressure of 62 atm (density 0.7 g cm^{-3} at a temperature of 22 °C).

Note also that the use of a short (12 cm) capillary allowed us to create a cell with xenon with a small volume (~5 cm^3) and a length of 20 cm. The entire system, including the compressor based on chirped mirrors (the distance between the mirrors is ~10 cm), is rather compact and safe in operation.

References

1. Nisoli M., De Silvestri S., Svelto O. *Appl. Phys. Lett.*, **68**, 2793 (1996).
2. Pinault S.C., Potasek M.J. *J. Opt. Soc. Am. B*, **2**, 1318 (1985).
3. Xia J., Altucci C., Amoruso S., Bruzzese R., Velotta R., Wang X. *Opt. Express*, **16**, 3527 (2008).
4. Lako S., Seres J., Apai P., Balazs J., Windeler R.S., Szipocs S. *Appl. Phys. B*, **76**, 267 (2003).
5. Bohman S., Suda A., Kaku M., Nurhuda M., Kanai T., Yamaguchi S., Midorikawa K. *Opt. Express*, **16**, 10684 (2008).
6. Konyashchenko A.V., Kostryukov P.V., Losev L.L., Tenyakov S.Yu. *Quantum Electron.*, **41**, 989 (2011) [*Kvantovaya Elektron.*, **41**, 989 (2011)].
7. Sifner O., Klomfar J. *J. Phys. Chem. Ref. Data*, **23**, 63 (1994).
8. Azhar M., Joly N.Y., Travers J.C., Russel P.St.J. *Appl. Phys. B*, **112**, 457 (2013).
9. Hasan I., Akhmediev N., Chang W. *Opt. Lett.*, **41**, 5122 (2016).
10. Mareev E., Bagratashvili V., Minaev N., Potemkin F., Gordienko V. *Opt. Lett.*, **41**, 5760 (2016).
11. Herrmann J., Wilhelmi B. *Lasers for Ultrashort Light Pulses* (Amsterdam: North Holland, 1987).

12. Bideau-Mehu A., Guern Y., Abjean R., Johannin-Gilles A. *J. Quantum Spectrosc. Rad. Transfer*, **25**, 395 (1981).
13. Konyashchenko A.V., Kostryukov P.V., Losev L.L., Tenyakov S.Yu. *Quantum Electron.*, **42**, 231 (2012) [*Kvantovaya Elektron.*, **42**, 231 (2012)].
14. Didenko N.V., Konyashchenko A.V., Kostryukov P.V., Losev L.L., Pazyuk V.S., Tenyakov S.Yu., Bryukhanov V.V. *Quantum Electron.*, **46**, 675 (2016) [*Kvantovaya Elektron.*, **46**, 675 (2016)].