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CONTROL OF LASER RADIATION PARAMETERS

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Efficient compression of the femtosecond pulses of an ytterbium laser in a gas-filled capillary

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***Abstract*. A 290-fs radiation pulse of an ytterbium laser system with a central wavelength of 1028 nm and an energy of 145 μJ was compressed to a 27-fs pulse with an energy of 75 μJ. The compression was realised on the basis of the effect of pulse spectrum broadening in a xenon-filled glass capillary for a pulse repetition rate of 3 kHz.**

Keywords: *femtosecond pulses, capillary, pulse compression.*

1. Introduction

At the present time, laser systems with Yb^{3+} ion doped active elements (hereinafter referred to as ytterbium lasers) are in greatest demand owing to their high efficiency and energy capabilities [1, 2]. The high efficiency of ytterbium lasers, which may exceed 80 %, is attained due to the low Stokes losses with the use of direct diode pumping of the active element. Specifically, for a ~ 980 nm wavelength of the diode pump radiation, the wavelength of ytterbium laser radiation is 1025 – 1080 nm. Along with high-power cw ytterbium lasers, wide use is made of pulsed laser systems, with femtosecond output pulses in particular. Light pulses with a duration shorter than 40 fs and an energy of several nanojoules were obtained from fibre ytterbium oscillators [3]. However, the duration of the output pulses of ytterbium laser systems which are designed on the master oscillator – amplifier model and operate in the $10^{-2} - 1$ mJ energy range is normally longer than 200 fs [4, 5]. Should the need arise to obtain high-energy light pulses no longer than 100 fs, advantage is therefore taken of the temporal compression of the ytterbium output laser pulses.

To compress laser pulses ranging from microjoules to several millijoules in energy, extensive use is made of a technique which relies on the pulse spectrum broadening due to phase self-modulation in their propagation through a capillary filled with a rare gas [6]. For instance, Hadrich et al. [7] compressed the 600-fs long output pulse of an ytterbium laser with an energy of 600 μJ to a ~ 70-fs long pulse. In this case, the energy of the compressed pulse amounted to only ~ 100 μJ. The relatively low efficiency of the nonlinear conversion stemming from the low capillary transmittance (20 %) narrows the field of application of this compressor type.

The objective of our work was to develop a nonlinear compressor of femtosecond ytterbium laser pulses with a high (above 50 %) energy efficiency.

2. Calculation of compressor parameters

In this Section we outline our analytical calculations, which permit us to select compressor parameters (the active medium and capillary dimensions) proceeding from the given parameters of the laser pulse and the requisite value of conversion efficiency.

The development of a compressor reliant on the pulse spectrum broadening in a capillary filled with a rare gas begins with the selection of the capillary length. Preference is given to capillaries shorter than 1 m in length. A short capillary length permits making a compact system. Furthermore, the adverse effect of irregularities of the shape and inner surface of the capillary on its transmittance and the spatial distribution of the output radiation becomes progressively stronger with capillary length.

We select a capillary of length L. The intensity attenuation coefficient α for the radiation of the lowest capillary mode EH_{11}, which exhibits minimal losses, is described by the expression [8]

$$\alpha = 0.146\frac{\lambda^2}{a^3}\frac{v^2+1}{\sqrt{v^2-1}}, \tag{1}$$

where λ is the wavelength of laser radiation; a is the inner capillary radius; and v is the ratio between the refractive indices of the wall material of the capillary and its filling gas. The attenuation of the light wave at the capillary output is defined by the product αL. Hence for a fixed length and a given value of transmission coefficient (conversion efficiency) it is possible to calculate the inner capillary radius. For the subsequent calculations we set the capillary transmittance equal to 80 %, which corresponds to $\alpha L = 0.2$, and consider a glass capillary assuming that $v = 1.5$. Under these parameters, the capillary radius

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$$a = (2\lambda^2 L)^{1/3}. \tag{2}$$

Higher-order modes, which have higher attenuation coefficients than the EH_{11} mode, begin to set in for high radiation intensities inside the capillary. The excitation of higher-order modes is associated with changes in the lateral profile of the refractive index of the active medium inside the capillary due to the contribution of its nonlinear part n_2. The highest radiation intensity whereby higher-order modes do not emerge is defined by the expression [9]

$$\frac{2\pi}{\lambda} a\sqrt{2n_2 I} = 2.4. \tag{3}$$

We substitute expression (2) in expression (3) to determine the highest radiation intensity for a capillary of length L with an 80-% transmission coefficient:

$$I = \frac{0.3\lambda^{2/3}}{L^{2/3} n_2}. \tag{4}$$

It is evident that the highest radiation intensity entails the largest broadening of the spectrum of the pulse at the capillary output.

The highest pulse energy whereby the pulse spectrum broadening is a maximum and the higher-order modes are not yet excited is defined by the expression

$$E = \pi 0.36 a^2 I\tau = 0.5\frac{\lambda^2 \tau}{n_2}, \tag{5}$$

where τ is the duration of the radiation pulse. The factor 0.36 in expression (5) appears due to the fact that the diameter of the lowest-order mode is equal to ~ 0.6 of the capillary diameter [8].

We calculate the capillary parameters and the characteristics of the active gas for the spectral broadening of a 300-fs long radiation pulse with an energy of 150 μJ and a wavelength of 1 μm. The capillary length L is taken to be equal to 20 cm. When the transmission coefficient of the capillary is equal to 80 %, its radius is 72 μm [see formula (2)]. For given pulse energy, duration, and wavelength of the pulse we obtain the requisite value of n_2, which is equal to 10^{-17} cm^2 W^{-1}. This value may be obtained using xenon at a pressure of ~ 8 atm as the active gas. (For xenon at a pressure of 1 atm, n_2 is equal to 12×10^{-19} cm^2 W^{-1} [10].) Under these conditions, the peak intensity I in the capillary calculated by formula (4) will not exceed 10^{13} W cm^{-2}. If it exceeds the value at which appreciable ionisation and its associated growth of absorption come into play, it will be necessary to change the capillary dimensions, because the radiation intensity inside the capillary lowers with increase in its length and accordingly in its diameter [see formula (4)]. In this connection the peak intensity value should be monitored. For the parameters of the laser pulse specified above and the calculated characteristics of the gaseous medium, the intensity of the light wave at which the ionisation of gas should be taken into account exceeds 10^{14} W cm^{-2} [11]. That is why changes in capillary dimensions are not needed in this case.

The method of calculation outlined above does not take into account the effect of dispersion of the active medium on the pulse shape in the propagation through the capillary. Estimates suggest that the capillary gas dispersion should be taken into account for pulses shorter than 20 fs.

As regards the spectral width of the laser pulse at the capillary output, the following remark is in order. In Ref. [7] it was shown that the degree of spectrum broadening – the ratio between the spectral width $\Delta\omega$ of the output pulse and the spectral width $(\Delta\omega)_0$ of the input pulse – is proportional to the nonlinear phase incursion: $\Delta\omega/(\Delta\omega)_0 \propto n_2(2\pi/\lambda)IL$. This estimate applies when the intensity is approximately constant throughout the capillary length, i.e. for a high capillary transmittance. In view of expression (4) we obtain

$$\frac{\Delta\omega}{(\Delta\omega)_0} \propto \left(\frac{L}{\lambda}\right)^{1/3}. \tag{6}$$

Therefore, in the generation of a pulse with a maximum spectral width using a high-transmittance capillary in the absence of excitation of higher-order spatial modes, the degree of spectral broadening and the degree of compression (the ratio between the pulse duration at the input and the compressed pulse duration) are independent of the type of gas used and are defined only by ratio between the capillary length and the wavelength of laser radiation. In this case, the dependence on the capillary length and the radiation wavelength is rather weak.

3. Experimental results and their discussion

Our pulse compression experiments were carried out using a TETA-3 (Avesta-Project Ltd.) femtosecond laser system. The laser system comprised a master oscillator and a regenerative amplifier. Use was made of chirped pulse amplification with the subsequent temporal compression of the output radiation pulse. The master oscillator was a diode-pumped Yb^{3+} ion doped fibre laser. An ytterbium ion doped potassium-yttrium vanadate [$Yb^{3+}:KY(WO_4)_2$] crystal was the active element of the regenerative amplifier. The regenerative amplifier was also pumped by the radiation of semiconductor diodes. The pulses at the output of the laser system possessed a duration of 290 fs and ranged up to 150 μJ in energy. The radiation wavelength was equal to 1028 nm, and the pulse repetition rate was 3 kHz. The beam had a Gaussian intensity distribution and its diameter was equal to 4 mm at a 1/e^2 intensity level; its divergence was 1.05 times the diffraction limit.

The optical diagram of the experiment is depicted in Fig. 1. The laser radiation was focused with a lens with a focal distance of 20 cm into a 20-cm long glass capillary with an inner diameter of 140 μm. The capillary was accommodated in a 30-cm long xenon-filled cell with an inner diameter of 1 cm. Upon spectral broadening of the pulse in the capillary, its temporal compression was realised with the aid of a compressor made up of two quartz prisms. The compressor prism separation was equal to ~ 2 m. To reduce the compressor dimensions, an additional mirror was placed between the quartz prisms. An ASP-100M spectrometer (Avesta-Project Ltd.) was employed to record the pulse spectrum. The pulse duration was measured with an ASF-20 autocorrelator (Avesta-Project Ltd.).

Prior to the execution of pulse compression experiments, we measured the capillary transmission coefficients at different xenon pressures. The resultant dependence is shown in Fig. 2. At xenon pressures below 6 atm, the capillary transmission coefficient was independent of the

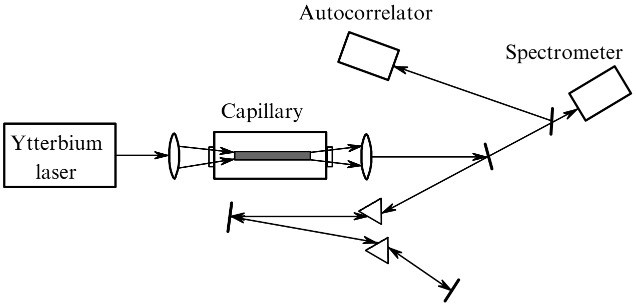

Figure 1. Schematic representation of the compressor of ytterbium laser radiation pulses.

pressure and was equal to ~ 60 %, which was lower than the value (80 %) calculated for a similar capillary in the previous Section. The difference of the measured figure from the calculated one is supposedly due to the loss of radiation in its injection into the capillary and its scattering at the capillary walls. The output radiation intensity distribution corresponded to the lowest-order mode EH_{11}. Beginning with a xenon pressure of ~ 7 atm we observed a drastic lowering in capillary transmittance. As this took place, in the intensity distribution at the capillary output there emerged structures characteristic of higher-order modes – rings, axial structure violations. The measured xenon pressure whereby higher-order modes began to set in was in good agreement with the calculated one.

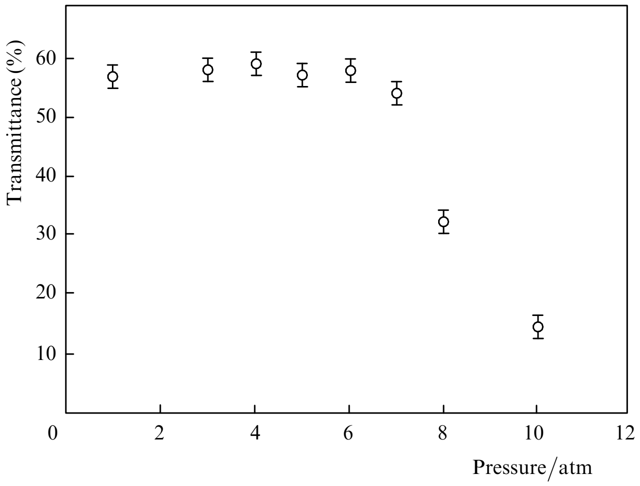

Figure 2. Capillary transmission coefficient as a function of xenon pressure.

Figure 3 shows the spectra of laser radiation pulses at the input and output of the capillary at a xenon pressure of 7 atm. The ~ 7-nm wide spectrum of the initial laser pulse was broadened to ~ 70 nm on transit through the capillary. Irregular shape is characteristic of the pulses experiencing phase self-modulation [12].

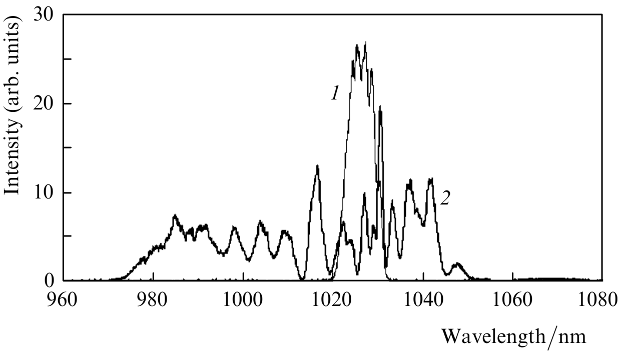

Figure 3. Spectra of laser pulses at the input (*1*) and output (*2*) of the capillary.

The highest degree of pulse compression (~ 10) was attained for a xenon pressure of 7 atm. In the context of our experiment this was the highest gas pressure at which higher-order modes were not generated in the capillary. The autocorrelation functions of the input and compressed pulses are shown in Fig. 4. If it is assumed that the pulse shape is $\mathrm{sech}^2 x$, the pulse duration is equal to 27 fs after compression. The energy efficiency of conversion to the compressed pulse, which was determined by the losses in the capillary and the prism compressor system, was equal to 52 % (the pulse energy at the compressor input was equal to 145 μJ and to 75 μJ at the output). The high conversion efficiency was reached due to a high (~ 60 %) capillary transmittance and low losses in the prism compressor. The compressor prisms were oriented in such a way that the linearly polarised radiation was incident on their faces at a close-to-Brewster angle.

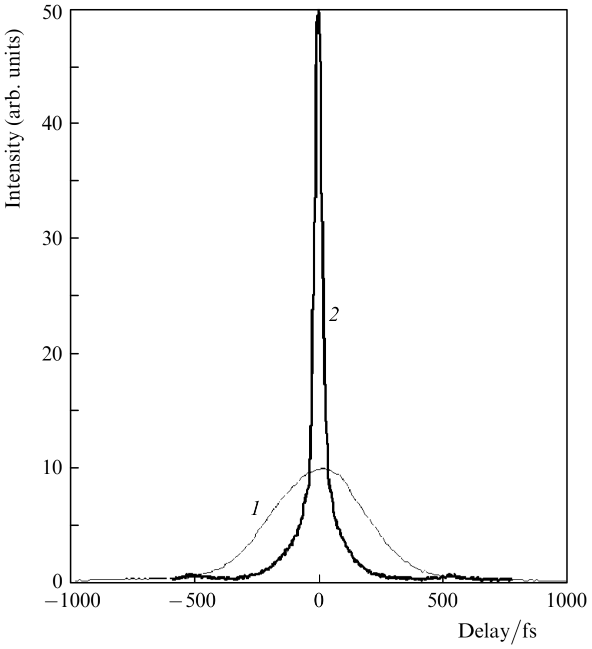

Figure 4. Autocorrelation function of the initial (*1*) and compressed (*2*) pulses.

4. Conclusions

Therefore, the results of our analytical calculation of a femtosecond pulse compressor, which is based on the pulse spectrum broadening due to the phase self-modulation in a gas-filled capillary, are in reasonably good agreement with experimental data. The 290-fs long output pulse of an ytterbium laser was compressed to a 27-fs long pulse in a glass capillary filled with xenon. An energy efficiency of 52 % was attained in the initial-to-compressed pulse conversion. As a result, the pulse power at the compressor output was five times higher than the power of the initial laser pulse.

The compression of higher-energy pulses (with energies above 10 mJ) may be realised on the basis of pulse chirping in the ionisation of capillary-filling gas [13, 14].

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