Quantum Electronics **37** (2) 147 – 148 (2007)

PACS numbers: 42.65.Re; 42.79.Nv; 42.65.Ky
DOI: 10.1070/QE2007v037n02ABEH013432

New stretcher scheme for a parametric amplifier of chirped pulses with frequency conversion

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***Abstract*. The properties of hybrid prism – grating dispersion systems are studied. The scheme of a prism – grating stretcher matched to a standard compressor in the phase dispersion up to the fourth order inclusive is developed for a petawatt laser complex based on the optical parametric chirped-pulse amplification. The stretcher was used to obtain the $\sim$ 200-TW peak power of laser radiation.**

Keywords: *stretcher, compressor, chirped-pulse amplification, chirp inversion, petawatt laser.*

At present the generation of superhigh-power radiation pulses is achieved in most laser systems by amplifying ultrashort pulses stretched up to ~ 1 ns [chirped-pulse amplification (CPA)] [1]. Traditional CPA systems with laser amplification and systems based on the optical parametric chirped-pulse amplification (OPCPA) [2] use standard compressors based on parallel diffraction gratings [3], which provide the negative group-velocity dispersion, and also stretchers based on antiparallel gratings with a telescope turning over the image, which provide the positive group-velocity dispersion [4].

In [5], the original OPCPA scheme for a petawatt laser complex was proposed and studied. The injected broadband radiation at frequency ω_2 was converted in the first stage of the parametric amplifier in this scheme to conjugate radiation at frequency ω_1, which was amplified in the next stages and then compressed. In the case of three-wave interaction, the conjugate signal and idler waves have a mutually reversed chirp [6]. Therefore, the relation between phases of the spectral components of injected (Φ_2) and conjugate signal (Φ_1) radiations upon optical parametric reversed-chirp pulse amplification (OPRCPA) has the form [5]

$$\Phi_1(\omega_{10} + \Omega) = -\Phi_2(\omega_{20} - \Omega), \tag{1}$$

where $\Omega = \omega - \omega_0$ is the deviation of the current frequency from the central frequency.

Taking into account that radiation injected into the first stage of the parametric amplifier is preliminary chirped in a stretcher, $\Phi_2(\omega_2) = \Phi_{\rm str}(\omega_2)$, and by expanding the nonlinear phase (linear terms do not affect the pulse duration and profile) introduced by the stretcher into a Taylor series, we can easily obtain the expression for the nonlinear spectral phase of the excited signal wave:

$$\Phi_1(\omega_{10} + \Omega) = -\frac{\Phi_{\rm str}^{(2)}\Omega^2}{2} + \frac{\Phi_{\rm str}^{(3)}\Omega^3}{6} - \frac{\Phi_{\rm str}^{(4)}\Omega^4}{24} + \frac{\Phi_{\rm str}^{(5)}\Omega^5}{120} + \ldots, \tag{2}$$

where $\Phi^{(i)} = {\rm d}^i\Phi/{\rm d}\omega^i|_{\omega_0}$.

By neglecting the material dispersion in nonlinear crystals, we will assume that the phase of the signal wave does not change upon parametric amplification in the next stages. At the compressor output, where the phase shift $\Phi_{\rm com}(\omega_{10} + \Omega)$ is added to phase (2), we have

$$\Phi_{\rm sig}(\Omega) = -\Phi_{\rm str}(-\Omega) + \Phi_{\rm com}(\Omega). \tag{3}$$

The pulse will be compressed to its initial duration if $\Phi_{\rm sig}(\Omega) = 0$. Thus, the phase-matching conditions for the stretcher and compressor in the OPRCPA scheme are

$$\Phi_{\rm str}^{(i)} = (-1)^i \Phi_{\rm com}^{(i)}. \tag{4}$$

Relations (4) essentially differ from the known phase-matching conditions $\Phi_{\rm str}^{(i)} = -\Phi_{\rm com}^{(i)}$ for traditional CPA and OPCPA systems.

To fabricate a stretcher for the OPRCPA scheme, which would be matched with a standard compressor, we studied the possibilities of combined prism – grating dispersion systems. It is known [7] that a pair of prisms located between diffraction gratings in a diverging beam can introduce a greater contribution to the third-order dispersion than in the case of a collimated beam incident on prisms. Our analysis showed that by increasing the distance between prisms and also the angle between their working faces, the sign of the third-order dispersion of such a system can be changed. In particular, in the case of Brewster prisms, the distance at which the third-order dispersion vanishes is only a few tens of centimetres. In addition, the second-, third-, and fourth-order dispersions in a prism – grating system can be controlled within finite limits, which allows one to take into account the phase shift of signal radiation in the amplifier during adjustment and, thus, compensate accurately the dispersion of the OPRCPA system up to the fourth order inclusive. A similar

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Received 19 September 2006
Kvantovaya Elektronika **37** (2) 147 – 148 (2007)
Translated by M.N. Sapozhnikov

situation also takes place in a hybrid prism – grating system with antiparallel gratings.

Based on this analysis, we developed a prism – grating stretcher for the OPRCPA system (Fig. 1) [5]. The additional phase introduced by the stretcher was calculated numerically based on the geometrical optics laws and the law of reflection of beams at different wavelengths from diffraction gratings. The stretcher was based on a 1200-lines mm^{-1} diffraction grating. Mirror (*1*) reflects the input beam on the grating at an angle of 68.5°. The role of the second grating is played by the grating part on which the beams reflected by orthogonal mirrors (*2*) and (*3*) are incident. Prisms with the same apex angle 68.3° were made of a BK 7 optical glass. The working faces of prisms are parallel to each other. Parallel beams reflected a second time from the grating is directed back by roof mirror (*4*) in a new tier parallel to the figure plane and separated from the first tier by 2 cm. The effective distance between stretcher gratings is 69.7 cm.

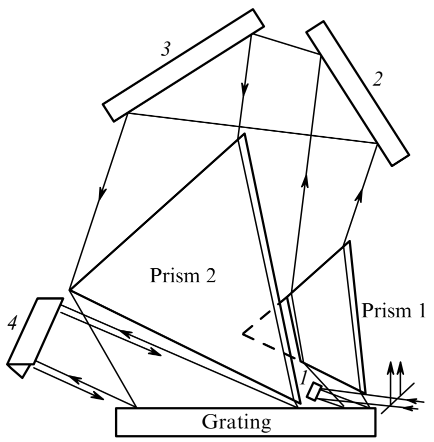

Figure 1. Scheme of a hybrid prism – grating stretcher for the OPRCPA system [5] and beam paths in it [(*1*–*4*): mirrors].

The stretcher can stretch the initial 40-fs pulses from a Cr : forsterite laser approximately to 0.6 ns. The central wavelength of radiation is 1250 nm. The width $2\Omega_m$ of the transmission band of the stretcher is $\sim 1000\ cm^{-1}$, which corresponds to the spectral width of a 40-fs pulse measured at the e^{-4} level. The input beam diameter achieves 2 cm. The central radiation wavelength in the matched compressor is 911 nm, the angle of incidence of the beam on the grating is 43.1°, and the distance along the normal between gratings is 133.8 cm.

The influence of variations in the positions of elements of the prism – grating stretcher on the dispersion characteristics of the stretcher/compressor system is illustrated in Fig. 2. One can see that it is possible in principle to develop the algorithm for adjustment of the system to the working point, which can provide virtually independent control of the second, third, and fourth dispersion orders. The residual dispersion of this stretcher is the fifth-order dispersion of the phase $\Phi^{(5)}$. The sign of $\Phi^{(5)}$ corresponds to the appearance of a prepulse; however, this mismatch can be compensated with the help of additional phase correctors, for example, AOPDF [8].

The new stretcher was used to create a light source emitting 45-fs pulses with parametric DKDP-crystal

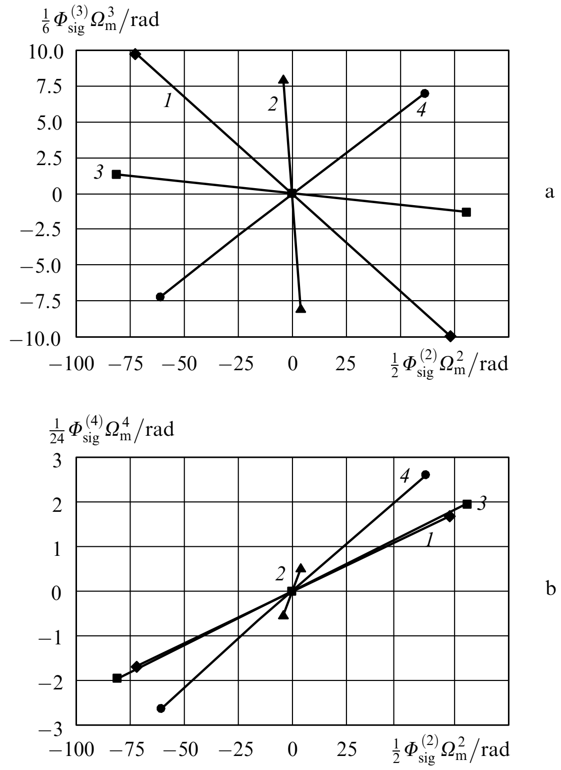

Figure 2. Dependences of phase mismatches of the third (a) and fourth (b) orders on the quadratic phase mismatch for a prism – grating stretcher; (*1*–*4*) are characteristic adjustment curves corresponding to the grating displacement perpendicular to the working surface by ±0.1 cm (*1*), the displacement of prism 1 along the normal to the grating by ±0.1 cm (*2*) and along the grating plane by ±0.2 cm (*3*), and to the change in the angle of incidence of the beam on the grating by ±10′ (*4*).

amplifiers with a record-breaking output power of ~ 200 TW [9]. We also calculated a stretcher for a system in which chirped radiation amplified in the OPRCPA scheme is summed with quasi-monochromatic radiation at 1054 nm and then is compressed in a 1700-lines mm^{-1} diffraction grating compressor.

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