REVIEW

Stretchers and compressors for ultra-high power laser systems

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Stretchers and compressors for ultra-high power laser systems

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Contents

Abstract. **This review is concerned with pulse stretchers and compressors as key components of ultra-high power laser facilities that take advantage of chirped-pulse amplification. The potentialities, characteristics, configurations and methods for the matching and alignment of these devices are examined, with particular attention to the history of the optics of ultra-short, ultra-intense pulses before and after 1985, when the chirped-pulse amplification method was proposed, which drastically changed the view of the feasibility of creating ultra-high power laser sources. The review is intended primarily for young scientists and experts who begin to address the amplification and compression of chirped pulses, experts in laser optics and all who are interested in scientific achievements in the field of ultra-high power laser systems.**

Keywords: *chirped-pulse amplification, optical parametric chirped-pulse amplification, petawatt lasers, stretcher, compressor, femtosecond pulses, diffraction gratings, grisms, laser system alignment.*

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1. Introduction

The development of ultra-high power laser pulse sources is a priority issue in modern physics. Whereas terawatt (1 TW = 10^{12} W) laser systems were thought of as ultra-high power sources until quite recently, this term is now being applied increasingly to multiterawatt and higher peak power levels. This is of course due to the explosive growth of the number of petawatt (1 PW = 10^{15} W) laser facilities in operation and under construction around the world [1]. A petawatt is a huge quantity, about hundred times the sum power of all the power stations in the world! This power exists for an extremely short time, though, tens to hundreds of femtoseconds (1 fs = 10^{-15} s), whereas the power stations generate power in continuous mode.

The production of terawatt laser systems has become a routine process, and manufacturers offer 'turn-key' sub-petawatt and even petawatt laser facilities [2]. In several countries, efforts are focused on laser systems with up to 10 PW of peak power (see [3] and references in [4]). Researchers at the Institute of Applied Physics (IAP), Russian Academy of Sciences, proposed a subexawatt (1 EW = 10^{18} W) laser system project [5].

It should be especially emphasised that, at present, only laser sources are capable of generating multiterawatt and petawatt peak powers. Focusing this ultra-high intensity radiation to a spot diameter of several microns produces a colossal intensity of electromagnetic radiation, in which the electric field is several orders of magnitude stronger than the intra-atomic field. Twenty years ago, we could only dream about such a unique tool for gaining insight into the properties of nature.

Today, the use of ultra-high power lasers in basic and applied research opens up new possibilities. The study of matter under extreme conditions offers unique opportunities for new discoveries at the junction of high-energy physics and ultra-high field physics, for modelling astrophysical processes under laboratory conditions and for exploring quantum electrodynamic phenomena and even the spatiotemporal structure of vacuum. Using an ultra-high intensity laser beam focused into a capillary tube or gas jet, electrons can be successfully accelerated to an energy of several gigaelectronvolts over a length of several centimetres. In conventional accelerators, this requires hundreds of metres. Great hopes are being placed on laser accelerators of heavier particles – protons and ions – potentially attractive for the radiological diagnosis of and proton therapy for cancer. Owing to the compact design and relatively low cost of modern ultra-high power lasers (in comparison with conventional accelerators), these could be employed in medical centres throughout the world.

Ultra-high power pico- and femtosecond laser radiation allows one to produce ultra-short hard X-ray and gamma pulse sources for materials characterisation with unprecedented spatial and temporal resolution. Reviews of priority issues in laser systems with petawatt peak powers can be found e.g. in Refs [4–16]. Some of them [4, 11, 12] and a number of review papers published in the last two decades [17–28] are concerned with the principles of building laser systems with terawatt to multipetawatt peak powers. In particular, a relatively recent (2011) paper by Korzhimanov et al. [4] reviews the petawatt laser facilities in operation and under construction and modern large-scale national and international laser projects.

An updatable table that lists the most powerful laser facilities can be found in Wikipedia [1]. It can be seen from that table that, in each of the past seven or eight years, one or two ultra-high power systems providing 0.5 PW of peak power or more have been put into operation. Helpful information can be found on the website of the International Committee on Ultra-High Intensity Lasers (ICUIL) [29], which coordinates research in the world's largest laser laboratories. In particular, there is an interactive map that shows labs in the world where ultra-high power laser systems have been built and are in service.

The physical principles behind the generation and amplification of pico- and femtosecond laser pulses and research with the use of ultra-short laser pulses and ultra-high power laser systems have a long history and are addressed in a number of monographs and textbooks [23, 25, 30–40]. A multi-author book [32] published by Springer in 1977, at the dawn of the femtosecond era, and containing excellent historical material is concerned with picosecond laser sources and their applications, primarily in studies of ultra-fast processes in chemistry and biology. The classic book *Optics of Femtosecond Laser Pulses*, authored by Akhmanov, Vysloukh and Chirkin [34] and published in 1988, still remains an indispensable guide and manual for many researchers. Among recent publications in Russian, it is worth noting excellent books by Kryukov [38, 40], which presents in popular form the basic physical principles of building femtosecond laser systems and their application field. Among publications in English, note the Progress in Ultrafast Intense Laser Science and Ultrafast Phenomena series (Springer) and a number of books [41–46] addressing the generation, amplification and stretching/compression of femtosecond pulses, their interaction with matter and living organisms.

It should, however, be kept in mind that the way to ultra-high laser powers has not been easy. For building modern ultra-high power laser systems, it was necessary to create sub-picosecond and femtosecond pulse sources, investigate the dispersion properties of optical materials and related schemes and find ways to amplify broadband light, stretch it in time and compress to ultra-short durations. Thus, it would be impossible to create ultra-high power, ultra-short laser pulse sources without solving a variety of problems which are of interest on their own. It is very important to have an idea of allied areas of optics that have played and continue to play a significant, or even critical, role in the development and evolution of the physics of ultra-high power laser systems. In this context, note the review papers in Refs [47–52], which were published in different years and deal with advances in making broadband solid-state laser oscillators and with the role of dispersion in the optics of ultra-short pulses.

This review comprises six sections. Section 2 addresses the advances made in the optics of ultra-short laser pulses by 1985, the year when the chirped-pulse amplification (CPA) method was proposed, which radically changed the ideas of the possibility of creating ultra-high power laser sources. This section highlights the prominent role of dye lasers – the only sources of subpicosecond pulses at the time – and describes the then-common approach for increasing their peak power and obtaining femtosecond pulses: self-phase modulation (SPM) of light in a medium – crystal, glass or fibre – broadens the emission spectrum of dye lasers, and the chirped pulses thus obtained are then compressed in time by dispersion systems based on prisms and diffraction gratings. A key component of all modern ultra-high power laser systems, almost without exception, is the classic Treacy compressor.

Section 3 focuses on the chirped-pulse amplification method. To fully implement the CPA concept, the Martinez stretcher, perfectly dispersion-matched to the Treacy compressor in different orders, and the Ti:sapphire laser as a reliable source of femtosecond pulses were required (and were created in the mid- to late 1980s). Particular attention is paid to optical parametric chirped-pulse amplification (OPCPA) [26–28, 53], an alternative to CPA. It was pointed out as early as 2002 [54] that available technologies allowed one to produce a 100-PW OPCPA system. It is gratifying to know that, over the past few years, the world's most powerful OPCPA-based laser facilities have been the PEARL and FEMTA systems (peak powers of 0.5 and 1 PW, respectively) [55, 56], built at the IAP and the All-Russia Research Institute of Experimental Physics (VNIIEF), Russian Federal Nuclear Center.

Section 4 is concerned with the key components of ultra-high power CPA and OPCPA laser systems – stretchers and compressors: their capabilities, performance, design, matching and alignment. Stretcher–compressor dispersion match in different orders is known to be critical for the ability to minimise the pulse duration and, hence, maximise the peak power. Major attention is paid here to techniques for diffraction grating alignment in compressors. We consider distinctive features of stretchers for OPCPA with frequency conversion and examine diffraction gratings whose optical damage resistance and finite dimensions restrict the output peak power of CPA laser systems. A promising approach is described for obviating this difficulty, through the use of tiled or mosaic gratings, and some characteristics of the stretchers and compressors for the ultra-high power CPA and OPCPA laser systems are presented.

2. Achievements in femtosecond laser optics before the advent of the CPA method

In the book *Ultrashort Light Pulses* [32], S.L. Shapiro wrote at the end of the Introduction section: "It is doubtful that more esoteric but basic problems, such as photon–photon interactions in a vacuum, will be addressed successfully in the near future. History, however, teaches us that new ingenious approaches or surprises are inevitably found."

Indeed, less than a decade later, in 1985, a method was proposed for obtaining ultra-high power laser pulses via the amplification of chirped (phase-modulated) light pulses, which enabled great advances in the field of terawatt and, later, petawatt laser powers. Ongoing progress in this area of research allows one to envisage the advent of multipetawatt laser facilities.

Almost 30 years have passed since the first CPA system was made. It is longer than the time span between the discovery of the laser in 1960 and the invention of CPA in 1985. What exactly was discovered, invented and investigated by the mid-1980s? What issues were thought to be the most important at the time? A priority issue was to create ultrashort laser pulse sources: subpicosecond and femtosecond lasers.

2.1. Ultra-short pulse sources: dye lasers

Dye lasers were essentially the only broadband laser sources until the late 1980s. The key achievements in femtosecond laser optics at the time were summarised in a brief review by Fork et al. [57]. In particular, the advent of the colliding pulse mode-locked dye laser in 1981 enabled the generation of pulses shorter than 0.1 ps [58]. Before that event, the pulse duration of dye lasers remained at the picosecond level for almost a decade. It was not until 1974 that a linear laser cavity configuration with two dye jets (gain and absorber jets) enabled a pulse duration of 0.5 ps [59]. A year later, 0.3-ps pulses were obtained [60] by compressing chirped pulses at the laser output using a Treacy grating-pair compressor [61]. Mourou and Sizer [62] proposed a novel approach to the generation of femtosecond pulses: in a synchronously pumped dye laser, they used a mixture of solutions of Rhodamine 6G and a fast recovery saturable absorber, which allowed them to obtain 70-fs pulses at an average power of 30 mW. By 1983, the shortest pulse duration in dye lasers was 65 fs [57].

2.2. Self-phase modulation as a means of reducing pulse duration

SPM of light in optical fibre began to be successfully used for reducing the pulse duration between the 1970s and the 1980s [63]. Since the refractive index of a medium is a nonlinear function of the intensity of an optical pulse propagating through it, the pulse spectrum broadens and the pulse acquires a linear chirp (linear variation of the frequency with time within the pulse envelope). The pioneering works on the self-phase modulation of laser radiation were done in 1967 for liquids [64], in 1970 for crystals and glasses [65] and in 1978 for optical fibres [63].

Fisher and Bischel [66, 67] proposed that the pulse spectrum be broadened via self-phase modulation directly in a Nd : glass laser amplifier and then compressed by a series of Gires–Tournois interferometers. The light intensity in the amplifier can thus be reduced by increasing the input pulse duration, which enables more efficient harvesting of the energy stored in the amplifier material.

In experiments carried out in 1982, 90-fs dye laser pulses were self-phase modulated by passing them through single-mode silica fibre. Subsequent compression by diffraction gratings (Fig. 1) yielded 30-fs pulses [68], in good agreement with numerical simulation results [69].

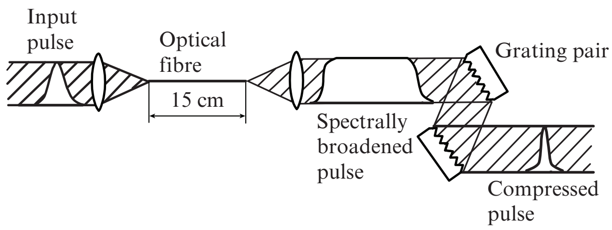

Figure 1. Pulse self-phase modulation in optical fibre, followed by compression with diffraction gratings [68].

In 1985, using a ring-cavity colliding pulse mode-locked dye laser, Valdmanis et al. [70] obtained record-short laser pulses of 27 fs. Later, Valdmanis and Fork [71] examined in greater detail how the pulse duration was influenced by self-phase modulation, group velocity dispersion (GVD), absorber saturation and gain saturation in the ring cavity of a dye laser having four intracavity prisms for dispersion compensation. A theoretical analysis of a passively mode-locked laser, including self-phase modulation, GVD and their reciprocal effects, was presented by Martinez et al. [72, 73] a year before. They pointed out the possibility of designing systems with controlled group velocity dispersion. Thus, the use of self-phase modulation ensured significant advances in the generation of ultra-short laser pulses, but with relatively low peak powers because the pulse energy was not very high.

At the same time, the role of higher order dispersion increases markedly at pulse durations of several tens of femtoseconds. In describing devices that control phase modulation, it is insufficient to include second-order dispersion, i.e. GVD, and one should take into account third-, fourth- and higher order dispersion. The role of third-order dispersion was discussed as early as the late 1970s by McMullen [74, 75], who examined its effect on the envelope of a linearly chirped pulse after compression, the development of asymmetry in the envelope of the compressed pulse and the formation of satellites. Dispersion compensators based on prisms and diffraction gratings turned out to be indispensable for controlling the phase of broadband pulses both inside laser cavities and outside.

2.3. Role of prisms and diffraction gratings in femtosecond laser technology. Treacy compressor

Prisms and gratings began to be utilised in optical systems in the pre-laser era but attracted special interest with the advent of lasers. In particular, gratings and prisms were actively used in tunable dye lasers [76–81] as frequency-selective elements. Studies of the dispersion properties of prisms and gratings in the 1970s–1980s proved very helpful for femtosecond laser development.

It is of interest to note that, historically, the first device specifically intended for compressing chirped pulses (or for producing a frequency chirp in initially short pulses) was a compressor proposed in 1969 by Treacy [61]. It comprises two parallel diffraction gratings, with their working surfaces facing one another and their lines parallel to each other (Fig. 2). When light is incident on the first grating of the compressor, its spectral components are diffracted at different angles. After reflection from the second grating, the light becomes again collimated, acquiring a frequency chirp (linear to a first approximation). Such a system has a negative GVD. The high dispersion of diffraction gratings allows the duration of the envelope of a femtosecond pulse to be increased via chirping by thousands and even tens of thousands of times. Thus, the classic chirped-pulse compressor was available by the beginning of the femtosecond era!

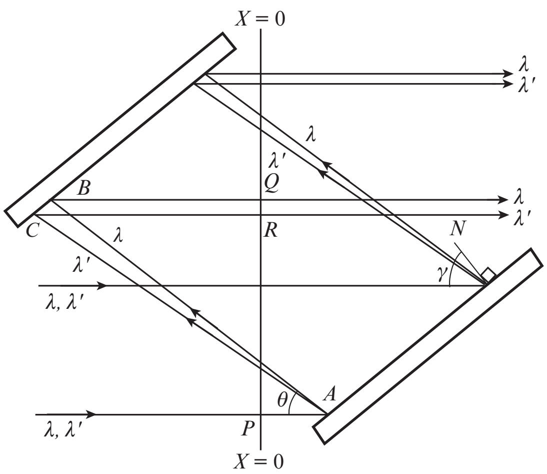

Figure 2. Schematic of the Treacy grating-pair compressor [61].

As to prisms, note that these were most widely used as intracavity dispersion compensators for reducing the pulse duration in ultra-short pulse sources. Introducing a glass prism as a dispersion element into a ring cavity of a dye laser, Dietel et al. [82] obtained pulses of 65 fs duration. As demonstrated by Gordon and Fork [83] in 1984, one prism placed in a ring cavity allows one to obtain both a positive and a negative GVD, which is of course extremely important for ultrashort laser pulse generation. In the same year, Martinez et al. [84] showed that angular dispersion was always accompanied by a negative GVD and proposed using this property to control the GVD in laser cavities. In addition, they studied the dispersion properties of prisms and flat plates from a transparent material at oblique incidence of a light beam on their surface and considered the scheme of a telescope as a device that increases angular dispersion. Three years later, using such a telescope placed between diffraction gratings, Martinez [85] invented a classic stretcher perfectly dispersion-matched to the Treacy compressor!

As shown by Fork et al. [86] in pioneering work concerned with prism dispersion compensators, a system of two prisms having identical apex angles and arranged so that their corresponding faces are parallel to each other (Fig. 3) may ensure a negative GVD even when there is no negative dispersion in the material. The proposed prism configuration has low loss and allows one to control the GVD near zero. The beam passed through the prism pair is collimated and parallel to the beam incident on the first prism. Bor and Rácz [87] explored a prism compressor as an analogue of the Treacy compressor and assessed the effect of its angular detuning on the slope of the pulse front of the compressed pulse.

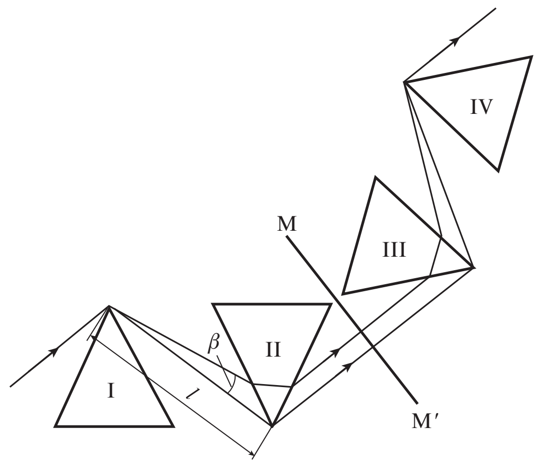

Figure 3. Prism system capable of ensuring a negative GVD [86].

2.4. Peak power of laser sources before the advent of the CPA method

Studies aimed at increasing the peak power of laser sources are a traditional area of research in physics. What achievements were made in this area before the advent of the CPA technique?

As pointed out in a review by Mourou et al. [20], the power of not only pico- but also femtosecond laser sources remained at the gigawatt level for more than 20 years (Fig. 4), from the mid-1960s, when a variety of mode locking techniques were demonstrated [88–90], until the mid-1980s, when the chirped-pulse amplification method was proposed [91], even though the pulse duration was decreasing steadily. In particular, in 1982 Migus et al. [92] performed successful experiments aimed at amplifying subpicosecond dye laser pulses and obtained 0.5-ps pulses with 3 GW of peak power. In the same year, Fork et al. [93] amplified 70-fs pulses to the gigawatt level, but they encountered a problem: in the four amplifiers used, in the form of cuvettes containing an aqueous dye solution (total path length near 20 cm), the pulse duration increased to 410 fs because of the GVD. They were confronted with other problems as well: pulse distortion because of the nonlinear frequency generation, wavelength dependence of the gain coefficient, absorption saturation and gain saturation. Owing to the pulse compression with the use of a grating pair, they obtained output pulses of 70 and 90 fs duration with a peak power of 0.3 and 2 GW, respectively. One of their purposes was that the pulse duration remained as short as possible during amplification. The inevitable increase in pulse duration as a result of dispersion-induced broadening was regarded as a harmful side effect.

For completeness, note that in the late 1970s and the early 1980s, the terawatt peak power level was reached by nanosecond lasers: immense large-aperture Nd : glass laser systems [94, 95] and iodine photodissociation lasers (e.g. Iskra-4 and Iskra-5 [14, 96, 97]) made it possible to obtain nano- and subnanosecond pulses with several kilojoules of energy. The main purposes in creating such lasers were to assess the feasibility of laser fusion and military applications. This class of laser systems lies beyond the framework of this review.

3. CPA method: a way to petawatt peak powers

The rather obvious way of increasing the peak power of lasers through the use of ultra-short (subpicosecond and femtosecond) pulses encountered the serious problem of optical damage to the gain medium. For example, in flashlamp-pumped Nd : glass laser amplifiers, intensities of $\sim$1 GW cm^{-2} lead to the onset of small-scale self-focusing (SSSF) [98], which distorts the transverse beam profile and causes optical breakdown in the amplifier material.

An effective way to remedy the problem is the chirped-pulse amplification method, proposed in 1985 by Strickland and Mourou [91]. This method ensured significant advances in ultra-high laser powers. The well-known plot illustrating the chronology of the growth of focused laser intensity [12] (Fig. 4) has a radical break and steep upturn in the mid- to late 1980s, which is obviously due to the advent of the CPA method.

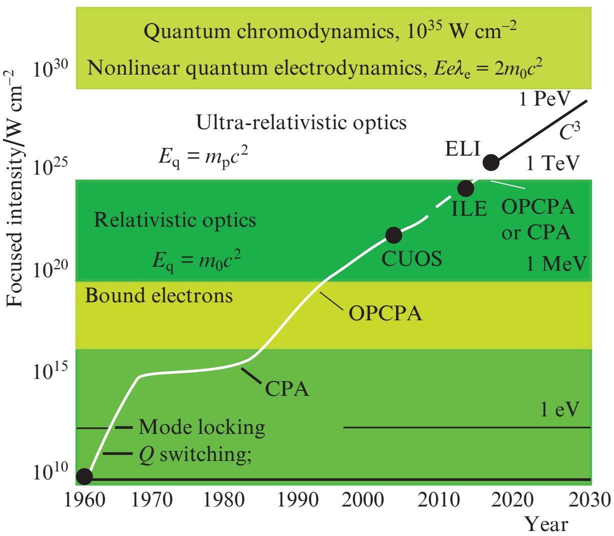

Figure 4. Chronology of the growth of focused laser intensity [12].

3.1. CPA concept

The basic principle of the CPA method is to amplify an ultra-short pulse pre-stretched in time and then compress it to its initial duration (Fig. 5). Stretching reduces the pulse peak power by orders of magnitude, which allows the pulse to be passed through the gain medium without unwanted self-focusing effects. Controlled ultra-short pulse stretching and compression are performed in a stretcher and compressor, respectively, owing to the dispersion of these optical devices.

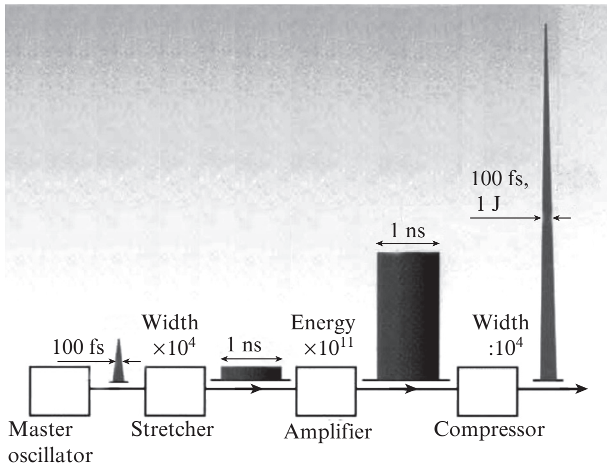

Figure 5. Schematic of the CPA method [20].

The spectral components of the broadband light passed through stretcher lag each other. As a result, the pulse becomes phase-modulated (chirped) and stretched in time. The GVD in the compressor is of opposite sign to the dispersion in the stretcher, so the corresponding spectral components catch up with each other and the pulse becomes compressed to nearly its original duration. At present, the CPA method is used in almost all laser systems generating ultra-short pulses with terawatt to petawatt peak powers.

Thus, in 1985 Strickland and Mourou [91] proposed the chirped-pulse amplification method and built the first CPA system, based on the then-common approach to ultra-short pulse generation (Fig. 6): the beam of a mode-locked Nd : YAG laser generating 150-ps pulses at a repetition rate of 82 MHz was focused into a single-mode optical fibre of 1.4 km length, where the pulse spectrum experienced broadening and the pulse acquired a linear chirp due to GVD and self-phase modulation. The pulses at the fibre output were 300 ps in duration and had a rectangular temporal envelope, with a spectral width of 5 nm and an average power of 2.3 W. After amplification in a Nd : glass regenerative amplifier (where the Pockels cell ensured 100 cavity passes for the pulses), the pulse energy was 1 – 2 mJ. Finally, the stretched pulses were compressed in a double-pass Treacy grating-pair compressor using 1700 lines mm^{-1} gratings. The angle of incidence of the light on the first grating was 65°, and the compressor length was 25 cm. The pulses were compressed to 1.5 – 2 ps. Even though the pulse peak power was still in the gigawatt range, the chirped-pulse amplification principle paved the way for a substantial increase in the peak power of laser sources.

As shown by Fork et al. [99], a major problem with pulse compression in systems containing an optical fibre and grating compressor lies in third-order dispersion. Their results demonstrate as well that successively passing a short pulse through a four-grating and a four-prism compressor allows one to control the second- and third-order dispersion of the pulse. The duration of the pulses thus obtained was 6 fs. Similar conclusions were drawn by Christov and Tomov [100]. It was clear, however, that the compression method in question was of no utility for building ultra-high power systems: placing optical elements (prisms) in the path of a high-

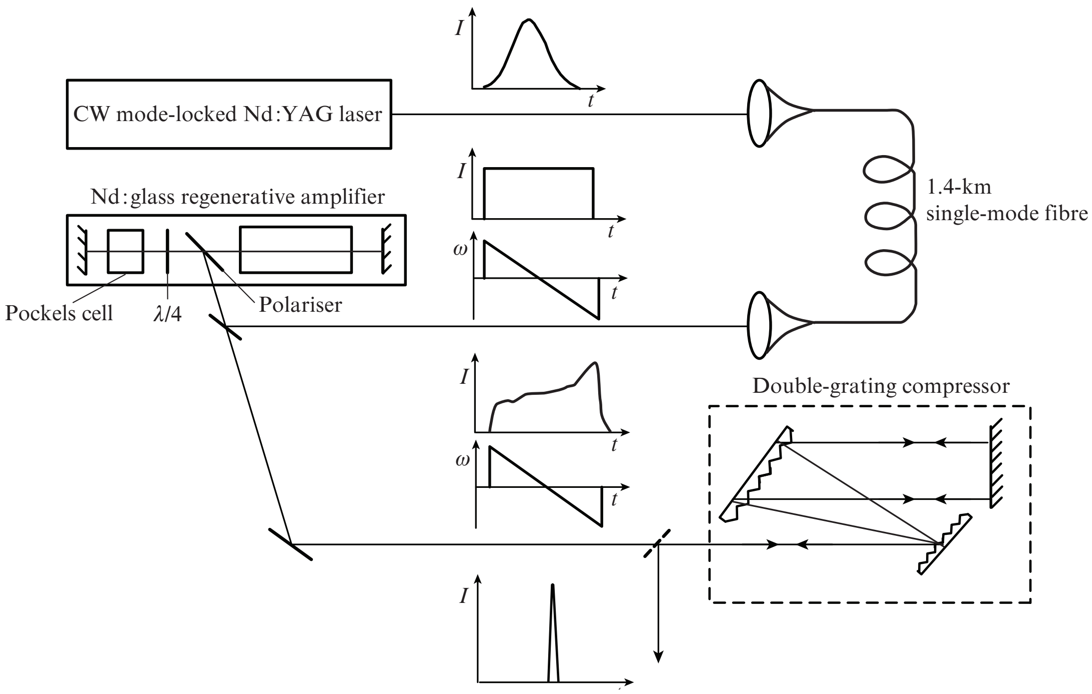

Figure 6. First CPA scheme [91].

power output beam would inevitably lead to breakdown of the prisms and catastrophic beam distortion.

3.2. Martinez stretcher: a classic stretcher for CPA systems

In 1987, Martinez [85] proposed an ingenious stretcher configuration: a system containing two antiparallel diffraction gratings with a telescope in between (Fig. 7). Owing to the image inversion and transfer, it became possible to vary the dispersion from zero (when the gratings are arranged so that the image of one grating coincides with the position of the other) to any value, with both positive and negative second-order dispersion. In addition, the magnitude of the dispersion can be exactly matched over all orders (can be made to be identical in magnitude and of opposite sign) to the dispersion of the Treacy compressor provided the gratings are identical in groove density and the beam is incident on the gratings at the same angle. Thus, using these devices, any pulse can be stretched in time to an arbitrarily long duration and then compressed to its original duration without distortion.

Shortly thereafter, stretching/compression ratios of 10^3 to 10^4 were demonstrated in Nd:glass systems. Maine et al. [101] described the operation of two distinct compact (table-top) terawatt CPA facilities having fibre and grating stretchers. In one system, 0.5 TW of peak power was obtained through chirping 55-ps pulses in a single-mode fibre of 1.3 km length. The resultant linearly chirped 300-ps pulses with a spectral width of 3.5 nm and a centre wavelength of 1053 nm were amplified in Nd:glass and then compressed in a double-pass compressor consisting of gold-coated holographic 1700 lines mm^{-1} gratings. The system showed great potential for making a petawatt laser source with amplification in large-aperture Nd:glass amplifiers.

Both simulation and experimental work showed clearly that the fibre stretcher/grating compressor configuration was of limited utility in the CPA method because of the dispersion mismatch between the fibre and grating pair. At the same time, the Martinez stretcher, containing antiparallel gratings, is capable of ensuring an almost perfect match to the Treacy compressor. A deviation from perfect match may be caused by the finite beam and grating size, the phase shift added by the amplifier, inaccurate adjustment of the individual devices and a stretcher–compressor mismatch.

The other CPA system described by Maine et al. [101] employed a grating–grating configuration of the stretcher–compressor system: 80-fs dye laser pulses at a wavelength 617 nm were stretched by a thousand times, to 85 ps, in a Martinez stretcher and then compressed to 90 fs in a Treacy compressor, like in a study reported by Pessot et al. [102] a year before.

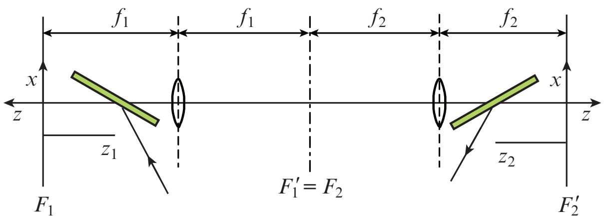

Figure 7. Martinez stretcher [85], with antiparallel gratings, ensuring positive GVD. Volume transmission gratings are presented.

3.3. Ti:sapphire as a gain medium for ultra-short pulse generation and amplification

Despite the obvious advances made in building terawatt laser systems in the mid- to late 1980s (after the twenty-year 'halt' at the gigawatt level, it was, of course, a breakthrough), a further approach to multiterawatt and petawatt peak powers encountered difficulties related to the absence of stable, reliable and easy-to-operate sources of ultra-short (femtosecond) laser pulses.

But a unique coincidence, so to speak, occurred: at about the same time, in 1986, a new gain medium was demonstrated, titanium-doped corundum, which is referred to as Ti:sapphire [103]. More precisely, Ti:sapphire was known even a short time before (see references in [103]) and was used starting at 1982 for both cw and pulsed, frequency-tunable lasing. Ti:sapphire has one of the largest luminescence bandwidths among laser materials (Fig. 8), which allows it to generate and amplify pulses several femtoseconds in duration [43, 47]. It was not until the late 1980s to the early 1990s that femtosecond pulsed Ti:sapphire lasers became the subject of intense research and activity. The first Ti:sapphire lasers [104–106], which generated 50-fs and longer pulses, took advantage of the passive and active mode locking techniques that had been well developed for dye lasers. Subsequently, wide use was made of self-mode locking, discovered in a Ti:sapphire gain element and based on the Kerr effect (KLM) [107–109]. It turned out that femtosecond pulses were even easier to obtain than picosecond ones and that Ti:sapphire solid-state oscillators had very high stability and reliability.

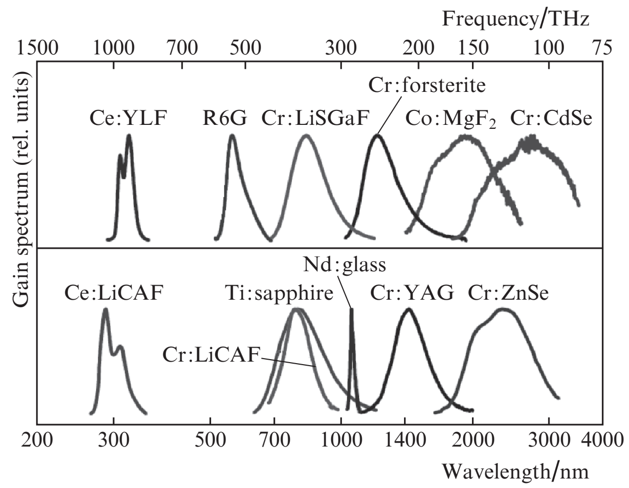

Figure 8. Luminescence spectra of the most widely used broadband materials [43].

Probably, the very first laser system that included a Ti:sapphire oscillator and regenerative amplifier was the one reported in 1991 by Squier et al. [110]. It generated 100-fs pulses with 1 mJ of energy (10 GW of peak power) at a repetition rate of 20 Hz. In the same year, terawatt (60 mJ, 125 fs, 0.5 TW) [111] and multiterawatt (0.45 J at 95 fs and 0.23 J at 60 fs, 3–5 TW) [112] systems with Ti:sapphire amplifiers were demonstrated. To reduce the Ti:sapphire laser pulse duration, it is very convenient to control the cavity dispersion using an intracavity prism pair [86, 106, 107, 113]. In 1992, owing to second- and third-order dispersion compensation by a prism pair in the cavity of a Ti:sapphire laser, Lemoff and Barty [114] obtained pulses with a duration as short as 20 fs.

Spielmann et al. [47] presented a review of broadband femtosecond sources, with focus on Ti:sapphire lasers, and analysed the configuration of ultra-short pulse sources having an intracavity prism dispersion compensator. They pointed out that uncompensated higher order phase dispersion in a laser cavity was a key factor limiting the pulse duration. In addition, they paid attention to the potential offered by cavity dispersion compensation using chirped mirrors, which enabled 11-fs pulse generation from a Ti:sapphire laser [115, 116]. Owing to self-phase modulation, coupling 13-fs Ti:sapphire laser pulses into optical fibre enabled white light (supercontinuum) generation. Using a prism compressor and a grating compressor placed in series, Baltuska et al. [117] achieved pulse compression to 5 fs. In addition, passive mode locking by semiconductor saturable absorber mirrors (SESAMs) was proposed for ultra-short pulse generation [118–120].

The number of gain media with a broad luminescence band, suitable for femtosecond pulse generation and amplification, increases steadily (Fig. 8). References can be found e.g. in a review by Sibbett et al. [31]. Here we will mention only one more important broadband solid-state laser medium: chromium-doped forsterite crystals, with a centre luminescence wavelength of 1250 nm. The first report on this laser material appeared in 1988 [121]. Shortly thereafter, in 1991, a Cr:forsterite laser was reported to generate 31-ps pulses in an active mode locking regime and 260-ps pulses under synchronous pumping [122]. In 1992, Seas et al. [123] reported the generation of 60-fs pulses using active mode locking by an acousto-optic modulator. The average laser output power was 85 mW.

In 1993, several laboratories demonstrated Cr:forsterite lasers based on the nonlinear Kerr effect and obtained pulses with durations as short as 100 fs [124, 125]. In the same year, optimising the second- and third-order cavity dispersion via the selection of the material of prisms at the laser output, Yanovsky et al. [126] obtained pulses 30–35 fs in duration. Passing the beam through prisms placed outside the cavity reduced the pulse duration to 25 fs. In 1998, using a CPA laser system with a Cr:forsterite regenerative amplifier, Jonusauskas et al. [127] obtained 54-fs pulses with energies of up to 50 μJ and a repetition rate of 1 kHz. In 2001, pulses with a duration as short as 14 fs were obtained [128]. In 2004, Agranat et al. [129] demonstrated a terawatt Cr:forsterite laser system with a pulse energy of 90 mJ and pulse duration of 80 fs.

Nevertheless, Ti:sapphire lasers are currently the most widespread sources of ultra-short laser pulses. By the late 1990s, the pulse duration offered by these sources was several femtoseconds [130, 131], which corresponds to two or three field oscillation periods. It is important to note that a key component of the cavity in ultra-short pulse laser sources is a second- and third-order dispersion compensator utilising prisms or chirped mirrors.

3.4. OPCPA: an attractive alternative to CPA systems

In addition to the classic CPA method (chirped-pulse amplification in a medium with population inversion), intense attention has recently been paid to systems based on optical parametric chirped-pulse amplification (OPCPA) (Fig. 9) and hybrid systems containing both parametric and laser amplifiers. At present, this is one of the most attractive approaches to building multipetawatt laser systems. Its development began in the late 1970s to the early 1980s with the observation of the parametric generation of a broadband continuum in nonlinear crystals under pumping with picosecond laser

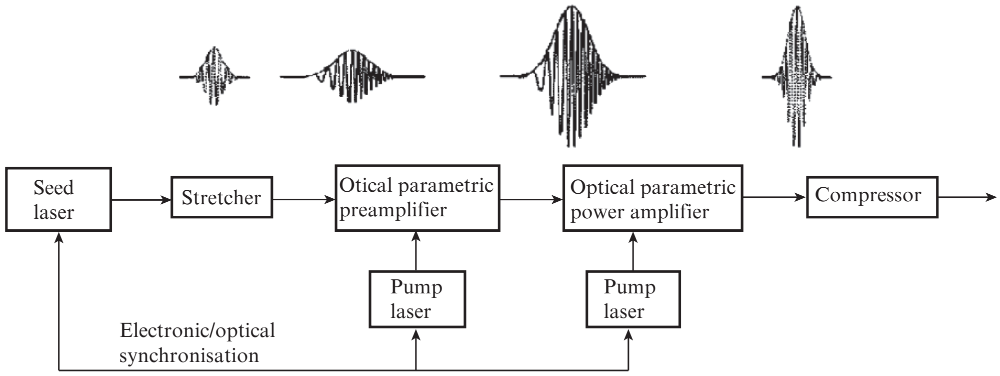

Figure 9. Schematic of the OPCPA method [27].

pulses [132, 133]. In 1985, using optical parametric chirped-pulse amplification, Danelyus et al. [134] experimentally demonstrated reversal of a linear chirp of picosecond pulses. This finding and other theoretical and experimental results on the parametric amplification of phase-modulated pulses were presented in a review by Piskarskas et al. [135].

The first study with the use of the OPCPA method [136] was carried out in 1992 (Fig. 10). Pulses with a duration of 1.7 ps and a centre wavelength of 1.055 μm from a mode-locked Nd:glass laser were chirped in optical fibre, which increased the pulse duration to 5 ps and broadened the pulse spectrum to 155 cm^{-1}. Using a noncollinear parametric three-wave interaction geometry in a BBO nonlinear crystal, pulse energy amplification by more than four orders of magnitude was demonstrated. Pumping was provided by a frequency-doubled neodymium laser. The chirped pulses were compressed to a duration of 70 fs by a 600 lines mm^{-1} grating compressor. The output pulse peak power was as high as 0.9 GW.

Ross et al. [137] demonstrated the potential of the OPCPA method both for ultra-short pulse generation and for obtaining ultra-high intensities. The main advantages of OPCPA over CPA are the record large gain bandwidth (reaching several thousand inverse centimetres under certain conditions, which corresponds to a transform-limited pulse duration of several femtoseconds), large gain coefficient and low thermal loads in the gain elements. In the case of parametric amplification, the spontaneous luminescence level is low, there is no self-excitation, and the temporal pulse contrast is thus high. Modern technologies enable the growth of KDP and DKDP nonlinear crystals up to 30–40 cm in size, which is sufficient for the use in the output amplifier stages of ultra-high power (petawatt) laser systems.

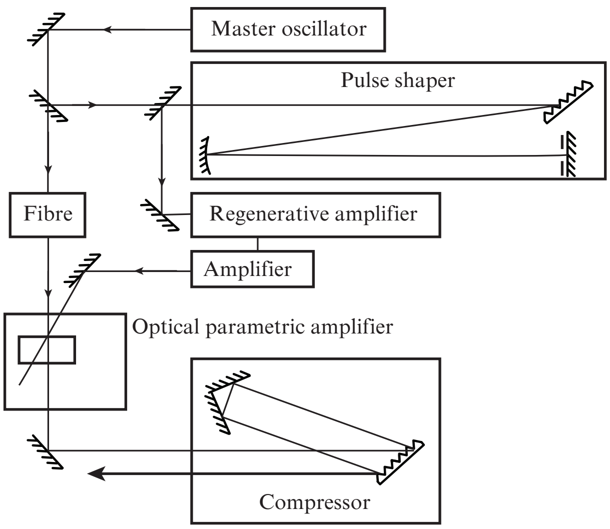

Figure 10. Schematic of the first OPCPA system [136].

It was also pointed out by Ross et al. [137] that the pulse energy of Ti:sapphire lasers reached 1 J and that the pulse duration was as short as about 30 fs, i.e. the highest possible peak power of Ti:sapphire systems was about 30 TW. (Nevertheless, shortly thereafter, in 1998, Yamakawa et al. [22, 138] obtained pulses with 100 TW of peak power using a Ti:sapphire CPA system.) They proposed a multipetawatt OPCPA system configuration which included a femtosecond Ti:sapphire master oscillator, a cascade of parametric KDP amplifiers pumped by a frequency-doubled neodymium laser and a standard grating compressor. Three years later, Matousek et al. [139] proposed a multipetawatt KDP OPCPA system pumped by a frequency-doubled Asterix IV iodine laser [140].

In 2000, Ross et al. [141] obtained 1.3 TW of peak power in an OPCPA system. At Rutherford Appleton Laboratory (RAL, United Kingdom), a two-stage parametric amplifier demonstrated a gain of 10^{10}. At the output of the system after compression, the pulse energy reached 0.4 J and the pulse duration was 300 fs. The centre wavelength of the signal radiation was 1054 nm, and the final amplifier stage was a KDP nonlinear crystal. Pumping was provided by a Vulcan laser (RAL).

The potential and competitiveness of OPCPA in comparison with Ti:sapphire regenerative amplifiers were demonstrated by Jovanovich et al. [142]. A three-stage parametric system using BBO nonlinear crystals enabled pulses from a femtosecond Ti:sapphire master oscillator to be amplified from 0.5 nJ to 31 mJ and compressed to 310 fs. The signal wavelength was 1054 nm. The main limitations on the pulse duration after compression were interpreted in terms of spherical and chromatic aberrations in the stretcher. In the same year, Jovanovich et al. [143] proposed using hybrid CPA systems, combining the advantages of the parametric and laser amplification approaches, for ultra-high power pulse generation.

The first multiterawatt OPCPA system was built in 2002 at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences [144]. A Mirra-900 Ti:sapphire laser generating 120-fs pulses at a wavelength of 1064 nm was utilised as a femtosecond master oscillator. A part of its output was amplified by Nd:YAG and Nd:glass amplifiers. After frequency doubling, it was used to pump parametric amplifiers based on LBO and KDP nonlinear crystals. Three-stage amplification in the LBO and KDP nonlinear crystals ensured a gain of 4×10^{10} and a pulse peak power of 3.67 TW. The pulse energy reached 570 mJ and the pulse duration after compression was 155 fs. A year later, the same system allowed 120-fs pulses with 16.7 TW of peak power to be obtained [145]. An LBO crystal was used in the third stage, like in the first two.

The early 2000s saw intense theoretical studies of parametric broadband amplification processes [24, 54, 146], aimed at optimising OPCPA schemes, examining requirements for signal and pump stability and synchronisation and studying the temporal and spectral characteristics of amplified pulses. Ross et al. [54] pointed out as early as 2002 that the available technologies allowed one to create a 100-PW OPCPA system. Advances in OPCPA were the subject of extensive reviews in 2004 [26] and 2006 [27].

In 2005, researchers at Rutherford Appleton Laboratory obtained chirped (uncompressed) pulses with up to 35 J of energy using a KDP nonlinear crystal in the output amplifier stage. For lack of a vacuum chamber, they used a compressor assembled in air, and only a small part of the signal beam was directed to it. After compression, the pulse duration was 84 fs. Thus, this OPCPA system potentially might generate pulses with peak powers of up to 350 TW [147, 148].

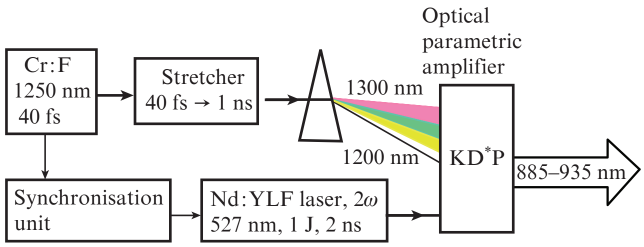

Figure 11. OPCPA with frequency conversion [150].

In 2001, researchers at IAP (Nizhnii Novgorod) and VNIIEF (Sarov) began work aimed at creating the first petawatt laser system in Russia. They developed a novel laser configuration: OPCPA with frequency conversion in a DKDP nonlinear crystal [149–151] (Fig. 11). One fundamental distinction of this configuration from the conventional one is that a stretched pulse is launched into the first parametric amplifier stage at one wavelength, whereas the other amplifier stages and compressor receive radiation with a conjugate wavelength resulting from three-wave interaction in the first stage. Thus, pulses with different wavelengths are stretched and compressed.

Note that, despite the diversity of the above CPA and OPCPA systems, in all of them the pulses being stretched and compressed have identical wavelengths, which allows one to successfully use the conventional matched couple: Martinez stretcher/Treacy compressor.

Designed specifically for OPCPA with frequency conversion, a novel, prism–grating hybrid stretcher [152] and a

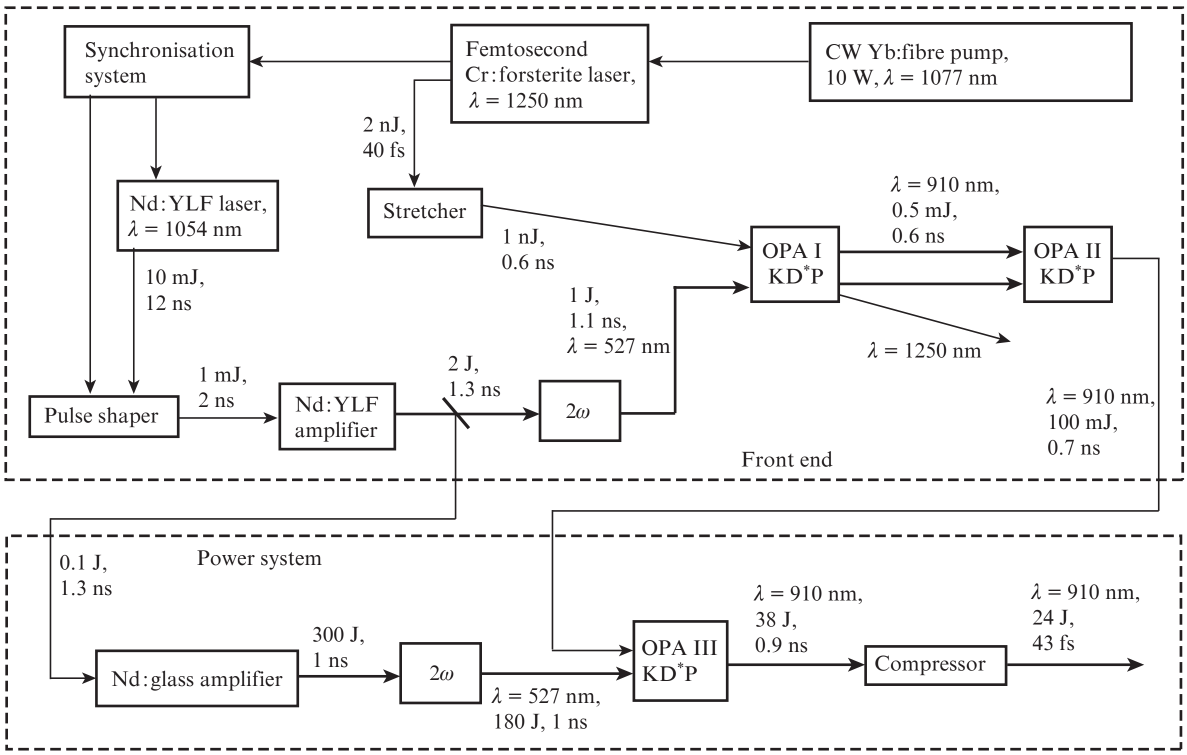

Figure 12. PEARL OPCPA laser system with 0.56 PW of peak power [55].

compressor with the classic Treacy configuration were matched to each other up to the fourth order dispersion term inclusive. In 2004, a terawatt power was obtained in a laser system [153, 154], a year later the peak power exceeded 100-TW level [155, 156], and by the end of 2006 a pulse peak power of 0.56 PW was reached on the PEARL (PEtawatt pARametric Laser) laser facility, built at IAP (Fig. 12) [55, 157].

Figure 13 presents data from a report by Piskarskas [53], which illustrate the recent progress in OPCPA laser systems. Note that the graph does not include the – still unsurpassed – record result obtained at VNIIEF in 2008 on the FEMTA laser facility, built in cooperation with IAP. The use of the second harmonic of the Luch kilojoule laser system [158] for pumping the output stage of the parametric amplifier, based on a DKDP crystal 20×20 cm in dimensions, made it possible to obtain pulses with a peak power as high as 1 PW [56, 159].

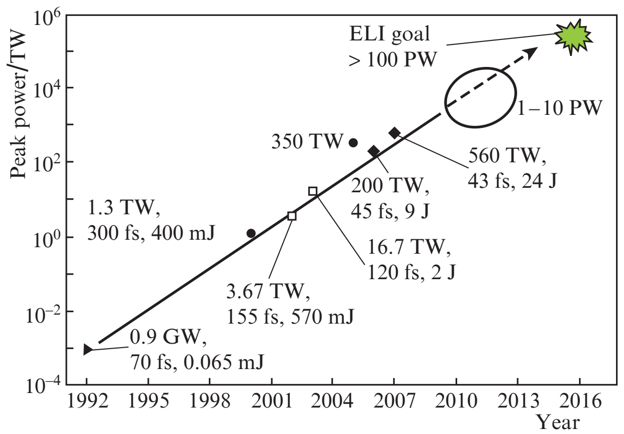

Figure 13. Progress of OPCPA laser systems [53] (▶, Vilnius University; ●, Rutherford Appleton Laboratory; □, Shanghai Institute of Optics and Fine Mechanics; ◆, Institute of Applied Physics, Nizhnii Novgorod).

Very recently, at the end of 2013, a CPA – OPCPA laser system with a centre wavelength of 800 nm was presented in which the front end was based on Ti : sapphire amplifiers and the output stage employed parametric amplification in an LBO nonlinear crystal measuring 80 mm in size [160]. The pulse duration was 33.8 fs and the pulse peak power was 0.61 PW. For the amplified light to retain its broad spectrum, a dip was produced in its central region by a special filter, At high pump intensities, this prevented back-transfer of signal energy to the pump beam. The system used an Offner telescope in the stretcher with a 1200 lines mm^{-1} grating and a four-grating compressor consisting of gold-coated holographic 1480 lines mm^{-1} gratings.

Among recent reports, attention should be paid to a petawatt OPCPA laser system [161] in which the final stages of the parametric amplifier are pumped by the third harmonic of a PALS iodine laser system (Asterix IV) [140]. Signal radiation, with a centre wavelength of 800 nm (generated by a Ti : sapphire master oscillator), is planned to be amplified in a large-aperture KDP nonlinear crystal. Experiments are already under way on a prototype system: SOFIA iodine photodissociation laser [162].

The largest multupetawatt OPCPA laser systems under construction are Vulcan-10PW (RAL) [163 – 165] and

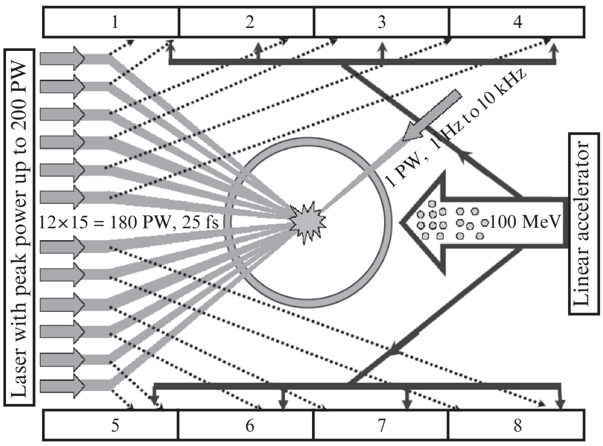

Figure 14. General layout of the subexawatt laser channels, main target chamber, linear accelerator and research laboratories [5]:
(1) Laboratory of Superstrong Fields, (2) Laboratory of High-Energy Physics, (3) Laboratory for Modelling Astrophysical Phenomena and Early Cosmology, (4) Laboratory of Nuclear Optics, (5) Laboratory of Neutron Physics, (6) Laboratory for Studying the Properties of Vacuum, (7) Laboratory of Attosecond and Zeptosecond Physics, (8) Laboratory of Fundamental Metrology.

PEARL-X (IAP) [4, 11]. XCELS [5], one of the latest Russian megaprojects, is by far the largest subexawatt OPCPA-based laser system project (Fig. 14).

4. Compressors and stretchers: key components of ultra-high power laser systems

As was pointed out repeatedly, a key issue in designing high power CPA and OPCPA laser systems is the ability to compensate the higher order phase dispersion in an ultra-short pulse. In particular, the amplification of pulses shorter than 30 – 50 fs at stretching/compression ratios in the range 10^4 to 10^5 encountered difficulties related to the necessity to compensate the dispersion induced by laser elements: gain medium, transparent mirrors and others. Lemoff and Barty [166] pointed out that novel stretcher configurations were needed to ensure higher order dispersion control. The same was discussed by Itatani et al. [167]: even though Ti : sapphire oscillators ensure pulse durations as short as 8 fs, pulses shorter than 30 fs are difficult to obtain in high-power CPA systems because amplification is accompanied by narrowing of the pulse spectrum and accurate phase delay compensation is necessary.

4.1. Possibilities to control the dispersion of compressors and stretchers

In CPA systems, chirped-pulse compressors are exposed to the highest optical load. They have the same configuration in all systems: classic Treacy compressor, based on parallel diffraction gratings [61] without any additional transmission elements. Particular configurations differ only in the arrangement of the gratings and the presence of 'folds' formed by flat mirrors: all the compressors have the same design. Owing to the mirrors being orthogonal to each other (roof-mirror reflector), the compressor design can be made more compact: it can include one, two or four gratings. The two degrees of freedom of a compressor – angle of incidence of the beam on its gratings and the compressor base – enable control over second- and third-order dispersion.

Even though the classic Martinez stretcher [85] consists of a larger number of optical elements than does the Treacy compressor, it also has two degrees of freedom. However, since the intensity of radiation passing through the stretcher is not very high, additional elements, including transmission ones, can be incorporated into the scheme, thereby increasing the number of degrees of freedom. As a rule, it is ultra-short pulse stretchers which are modified to ensure higher order dispersion compensation and control in CPA systems. Note that one clear and simple method for evaluating both ideal and mismatched stretchers and compressors is ray tracing [168, 169], which builds on the determination of the phase shift when a beam passes through a system of gratings and flat and spherical mirrors. Occasionally, the matrix formalism is employed to evaluate dispersive systems [170–172]. Druon et al. [173] represented the optical components of stretchers and compressors by operators, which were shown to be a convenient tool for assessing dispersion in complex optical systems.

To match phase delays up to the fourth order phase dispersion term inclusive, White et al. [174] proposed using an air-spaced doublet lens. Lemoff and Barty [166] presented a cylindrical-mirror stretcher configuration. A Martinez stretcher configuration employing only reflective optics (spherical mirrors as elements of an inverting telescope) was reported by Rudd et al. [175]. In 1995, Du et al. [176] proposed that an inverting telescope in the Offner aberration-free configuration [177] be used in a stretcher (Fig. 15). (A similar scheme was proposed independently by Cheriaux et al. [178].) Analysis of these schemes [179] indicates that, if the amplifier in a CPA system has material dispersion, they enable exact dispersion compensation only for the second and third orders. At the same time, the stretchers proposed in Refs [166, 174] ensure fourth-order dispersion compensation. A novel grating-pair stretcher configuration based on an Offner triplet with cylindrical mirrors was used by Itatani et al. [167] to obtain 26-fs pulses with 13 TW of power. This stretcher configuration was shown to have a number of advantages over the spherical mirror configuration, associated primarily with the larger vertical beam size on the second (convex) mirror and the smaller angular spread of wave vectors at the output [180]. A simple achromatic stretcher configuration with one spherical mirror was demonstrated by Ross et al. [181].

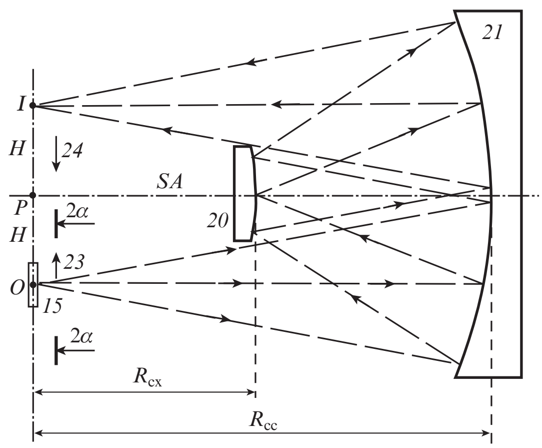

Figure 15. Offner aberration-free telescope configuration [177].

Banks et al. [182] proposed a novel, compact Martinez stretcher design which employed a unique diffraction grating with a mirror strip in the middle. The stretcher consists of four reflective optical elements (diffraction grating, spherical or parabolic mirror, flat mirror and roof-mirror reflector) and can stretch a 20-fs pulse by 40 000 times. The stretcher design is insensitive to adjustment errors and easy to align. Tuning the parameters of the stretcher elements enables material dispersion compensation in the amplifiers of the CPA system and ensures dispersion match to the compressor up to the fourth order. Almost a decade later, this stretcher, in modified form, was used in the Texas Petawatt Laser [183].

One compressor configuration enabling dispersion compensation to the fourth order was proposed by Gonzalez Inchauspe and Martinez [184]. An additional degree of freedom in a grating-pair compressor is ensured by tilting the plane of beam propagation relative to the plane normal to the grating lines. This is sufficient to compensate the material dispersion in the amplifier and the self-phase modulation-induced dispersion in the fibre.

As pointed out by Bagnoud and Salin [185], the effects of different orders of dispersion on the shape of ultra-short pulses might compensate each other: detuning second- and third-order dispersion may partially compensate the effects of the fourth and fifth orders, respectively.

To improve the dispersion match in the stretcher–amplifier–compressor system, Kane and Squier [179] and Squier et al. [186] proposed that gratings differing in groove density be used in the stretcher and compressor. This idea has been implemented in a number of state-of-the-art Ti:sapphire CPA lasers [187–189] generating $\sim$30-fs pulses and enables dispersion compensation in CPA systems to the fourth order inclusive. For the same purpose, Wang and Leng [190] proposed using a combination of two grating stretchers differing in groove density. To control dispersion in CPA systems, use is often made of an acousto-optic programmable dispersive filter (AOPDF) [191–194].

Also, it is sometimes reasonable to use grisms, along with prisms and gratings, for dispersion matching [195]. Grisms are dispersive elements in the form of transmissive or reflective diffraction gratings deposited directly on prisms. In particular, in 1995 Kane and Squier [196] proposed an approach that enabled second- and third-order material dispersion compensation in CPA systems using a fibre stretcher/grism compressor configuration. As shown later [197], whereas the GVD in the Treacy grating compressor is negative and the third-order dispersion is positive, the use of grisms in a compressor may ensure negative third-order dispersion [197]. Grisms cannot be used in the compressors of ultra-high power systems, because there are transmissive optical elements, but they are attractive candidates for use, e.g., in CPA and OPCPA systems with pulse durations of several femtoseconds [198, 199].

4.2. Alignment of the diffraction gratings of a compressor

The dispersion properties of prism and grating compressors and the effects of their misalignment and the stretcher–compressor dispersion mismatch in different orders on the characteristics of the output signal have been the subject of extensive research starting in 1994 [200, 201]. One of the first studies of the Treacy grating compressor as the output stage of a CPA system at arbitrary grating orientations was carried out by Osvay and Ross [200]. In an aligned compressor, the working surfaces and grating lines should be parallel. Nevertheless, a wrong choice of the angle of incidence of light on the gratings or a misadjusted compressor base leads to incomplete dispersion compensation in the stretcher – compressor system, reduces the pulse intensity contrast and may produce prepulses destroying the target before the main pulse arrives. If the gratings and lines are not parallel, there is residual uncompensated angular dispersion (angular chirp), resulting in a tilt of the pulse front. This in turn reduces the intensity at the focus because of the increase in effective pulse duration. Thus, measuring the compressed pulse duration is insufficient for adjusting a CPA system: one should monitor other parameters as well, in particular the angular chirp in the output pulse [52].

Estimates of the necessary accuracy in adjusting the compressor of the Vulcan petawatt CPA laser system [202] suggest that the gratings should be oriented exactly at the proper angles of incidence, otherwise only the GVD will be compensated, whereas the higher order dispersion will not. According to estimates of the angles that will ensure a substantial increase in pulse duration in the Vulcan petawatt system, a deviation of the angle of incidence from the calculated one by 10 – 20 mrad or an angle of 20 – 50 μrad between the gratings results in an uncompensated additional 200 fs for a 500-fs pulse. Spectral clipping (see also Ref. [203]), nonplanarity of the compressor or stretcher gratings and beam divergence at the compressor input also increase the pulse duration and, in addition, adversely affect beam focusing into a minimum spot.

Following the ideas of Osvay and Ross [200], Zhang et al. [204] evaluated the accuracy of adjusting an ultra-high power (petawatt) Nd : glass CPA system at a pulse duration of 0.5 ps and beam diameter of 1 m. According to their results, the grating lines and planes can be aligned parallel to within 15 μrad.

To minimise the compressed pulse duration in adjusting a CPA system, Osvay and Ross [200] proposed a method for assessing the residual angular dispersion of a compressor from the focal spot of broadband or dual-frequency radiation passed through it. From the deviation in two orthogonal directions, one can infer the magnitude and nature of compressor grating misalignment. Estimates suggest that, at a beam diameter of 10 cm and pulse duration of 100 fs, gratings can be aligned by this method to within 0.4 mrad.

Somewhat later, Collier et al. [205] described a technique for adjusting the compressor of the Vulcan petawatt CPA laser system. The vertical rotation axis of the gratings and the angle of incidence of the beam on the compressor gratings were preadjusted geometrically to an accuracy of 1 mrad or better using a small-aperture beam. The grating lines were aligned with the same accuracy. The gratings were aligned using a dichroic laser source by successive iterations to an accuracy of 2 mrad. Owing to such adjustment, 0.5-PW pulses with a duration of 840 fs and energy of 400 J were obtained from Vulcan in 2003.

The alignment of a dual-grating compressor was addressed by Miesak and Negres [206]. They emphasised that it was a challenging problem because CPA systems function only near optimal adjustment. The proposed procedure was based on measurements of the propagation direction of the input and output beams in the compressor. The grating alignment accuracy was not very high (~1.3 mrad), and the authors did not aim at aligning the grating lines, nor did they took into account or checked the flip mirror alignment accuracy and nor did they examined a procedure for monitoring the angle of incidence of the beam on the grating.

The tilt of the pulse front caused by misalignment of stretcher or compressor gratings at a large beam diameter was addressed by Pretzler et al. [207], who proposed interferometric techniques for angular chirp measurement and compensation. They pointed out that they did not know any optical or mechanical methods for assessing the alignment of compressor gratings from the three angular degrees of freedom with an accuracy better than 0.1 mrad in existing CPA systems. It was shown that grating misalignment by 0.1 mrad at a beam diameter of 25 cm led to a tilt of the pulse front by 0.2 mrad and, as a consequence, to an increase in pulse duration (30 fs) at the focus by five times.

Chanteloup et al. [208] examined the problem of controlling the tilt of the pulse front. They derived formulas describing the evolution of the envelope of a nonuniform pulse (when the wave front differs from the pulse front) propagating after it had passed through a misaligned grating pair of a compressor.

In 2001, Sacks et al. [209] proposed real-time minimisation of the pulse front tilt and compressed pulse duration using a purpose designed single-shot autocorrelator. For the alignment of the stretcher – compressor system, Varjú et al. [210] proposed that the angular dispersion be determined by spectral interferometry.

Using a purpose-designed spectrometer capable of constructing a two-dimensional image (spectrum/diagram: spectrum on one axis and wave vector direction on the other), Freidman et al. [150, 151] and Lozhkarev et al. [154, 156] measured the angular chirp (angular dispersion) of both the parametric superluminescence and signal beam at the output of the first stage of a broadband parametric amplifier in an OPCPA laser system with frequency conversion. The spectrometer was also used to monitor the residual angular dispersion of the signal beam at the compressor input and output. The measurements were made in two orthogonal planes: to this end, the spectrograph was sequentially rotated through 90° relative to the normal to the entrance slit.

A number of studies [211 – 213] were concerned with the formation of angular dispersion and temporal distortions of femtosecond pulses because of stretcher or compressor misalignment. Their results demonstrate that simultaneously measuring the angular dispersion and pulse duration is the most accurate alignment procedure for prism and grating compressors.

In Ref. [214], accurate alignment and optimisation of the stretcher – compressor system were carried out by measuring the power of the second harmonic of the signal beam. At a given pulse energy (the measurements were made at a frequency of 70 MHz without amplification), the compressor base was varied so as to find the maximum second harmonic output power, corresponding to the shortest pulse.

To align the grating compressor of the OMEGA EP petawatt-class ultra-high power CPA laser facility (Rochester, USA), Guardalben [215] proposed using a dual-frequency laser source (following Collier et al. [205]) or a broadband light source. One frequency should approach the Littrow frequency for the grating in its working position. The described algorithm is an iteration procedure for approaching perfect alignment. In numerical simulation, an essentially perfect matching accuracy for two rays at wavelengths of 1047 and 1053 nm was reached at the 25th iteration step. The corresponding grating alignment error was 0.25–0.5 µrad.

To align the compressor of the Hercules 300-TW CPA system (Michigan, USA), Chvykov and Yanovsky [216] in 2009 proposed a method in which the compressor gratings were used as a diffraction interferometer. The proposed method for aligning the grating surfaces and line directions takes advantage of wide narrow-band He–Ne laser beams incident on the gratings along the normal to their surfaces and at the first- and second-order Littrow angles, which allows their direction to be accurately determined. In the geometry examined in that study, the beams reflected from the first and second gratings interfere. The method ensures $\sim$1 µrad alignment accuracy when use is made of wide alignment beams covering the entire aperture of a 50-cm diffraction grating. As shown by Liu et al. [217] in a study concerned with CPA compressor alignment, far-field measurements of the direction of beams reflected from compressor gratings may ensure alignment accuracy comparable to that in previously proposed methods.

A new technique for aligning grating compressors of ultra-high power CPA and OPCPA systems, ensuring an angle adjustment accuracy of several microradians, was proposed in Ref. [218]. In this technique, the working surface and grating line direction are aligned with the vertical rotation axis of the grating using an autocollimator and a glass cube placed on top the grating mount (Fig. 16). The opposite, polished faces of the cube are pairwise parallel. The use

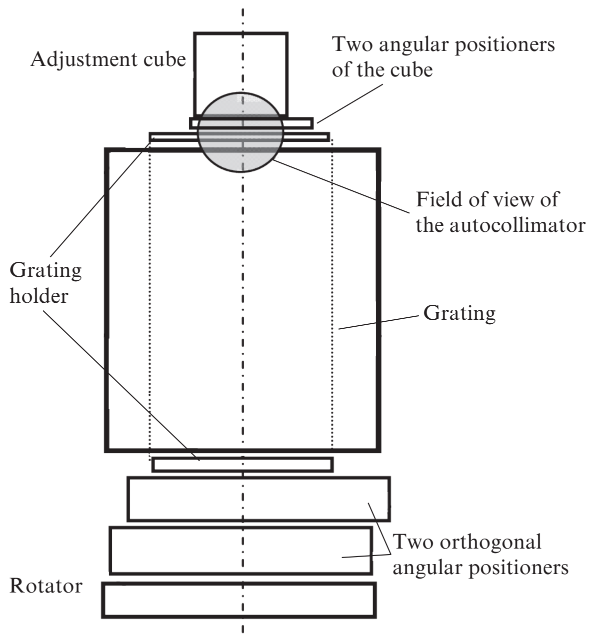

Figure 16. Schematic of the compressor grating module [218].

of this technique for adjusting the compressor of the PEARL subpetawatt laser facility made it possible to align the diffraction gratings in the three rotational degrees of freedom with an accuracy of several microradians and to adjust the angles of incidence of radiation on the gratings, also with an accuracy of several microradians.

Li et al. [219] reported a method for monitoring the position of a diffraction grating for the three angular degrees of freedom. The method is based on assessing the drift of the focal spots of laser beams incident on a grating along the normal and at the Littrow angle and reflected from it. The tilt and tip angles of the grating plane were measured with an accuracy of $\sim$0.5 µrad, and the accuracy in determining the drift angle upon a change in the direction of the grating lines was $\sim$1.7 µrad. Li et al. [219] pointed out however that the method was sensitive to the stability of the monitoring system proper, which consisted of a wide variety of optical components.

For compressor alignment, Börzsönyi et al. [220] proposed assessing the output beam angular dispersion using a Fabry–Perot etalon. Their technique allows the residual angular dispersion to be measured in two orthogonal directions in a single laser shot, with an accuracy comparable to that of one-dimensional measurements [52, 151, 154, 211, 213].

4.3. Distinctive features of stretchers for OPCPA with frequency conversion

In a conventional CPA scheme, there is only one type of signal radiation (to be amplified), whereas in the OPCPA scheme, two waves (signal and idler) are amplified. The case where one of these two phase-conjugate waves is chirped in a stretcher, then amplified in a parametric amplifier and, finally, compressed does not differ fundamentally from CPA from the viewpoint of stretcher–compressor match. At the same time, there is the possibility to use phase-conjugate waves in a stretcher and compressor, i.e. to inject idler radiation into the first stage of the parametric amplifier and then to launch the conjugate radiation originating from three-wave interaction into the other amplifier stages and compress it. This unconventional scheme – OPCPA with frequency conversion (with idler wave injection into the first amplifier stage) – is used in the PEARL and FEMTA petawatt laser systems [55, 56].

As early as the mid-1980s, experimental evidence was presented that, when a linearly chirped pulse was parametrically amplified in a nonlinear crystal, the conjugate wave had a reversed linear chirp [134, 135]. Laenen et al. [221] observed chirp reversal-induced fourfold idler pulse compression in the cavity of a parametric oscillator with intracavity normal-dispersion transmissive elements (nonlinear crystal, lens and dichroic mirror). In the early 2000s, the linear chirp reversal effect was used to produce complex pulse profiles in the mid-IR spectral region [222].

If in the case of pulse durations longer than 100 fs we limit our consideration to a linear chirp, then the OPCPA scheme with frequency conversion can employ a system of parallel diffraction gratings (Treacy compressor) as both a stretcher and a compressor. In the case of shorter pulses, however, higher order dispersion should be taken into account and compensated.

As shown by Freidman et al. [149], in the OPCPA scheme with frequency conversion a chirped pulse will be compressed

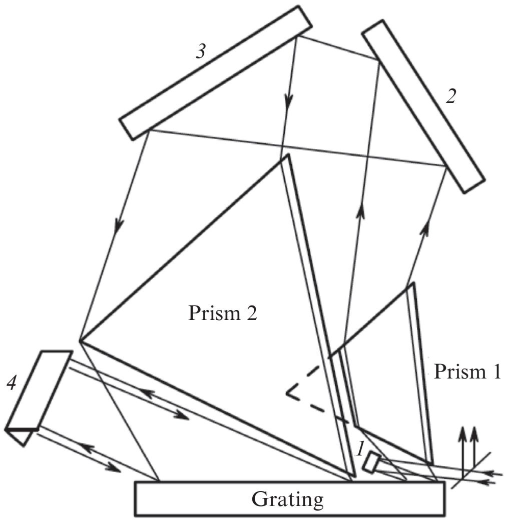

Figure 17. Prism–grating hybrid stretcher [152].

to about its original duration if the even-order dispersion terms of the stretcher are equal to those of the compressor and the odd-order dispersion terms are equal in magnitude and opposite in sign. A prism–grating hybrid stretcher [152, 153, 223] in which a prism pair is placed between parallel gratings (Fig. 17) was designed and built for the PEARL and FEMTA ultra-high power OPCPA laser facilities, which operate far from degenerate phase matching. The prism–grating stretcher is phase-matched to the Treacy grating compressor to the fourth order dispersion term inclusive and allows one to obtain petawatt pulses shorter than 50 fs.

Akahane et al. [224] and Wang et al. [225] recently proposed OPCPA systems with frequency conversion (linear chirp reversal) near degenerate phase matching. In systems studied experimentally, a single dispersive component – a glass block [224] or a Treacy system of parallel diffraction gratings [225] – served as both a stretcher and a compressor.

4.4. Diffraction gratings for pulse compressors in ultra-high power laser systems. Tiled gratings

The ongoing growth of laser pulse energy makes it necessary to substantially increase the beam size in order to reduce the intensity incident on optical elements. This is particularly important for long-term operation of compressor diffraction gratings because their optical damage threshold is several times lower than those of anti-reflection and mirror coatings and amplifier materials. It is the durability and size of diffraction gratings which currently limit the output power of ultra-high power CPA laser systems.

At present, gold-coated holographic gratings have the largest homogeneous reflection bandwidth, which allows them to be used in CPA systems with pulse durations from tens of to several femtoseconds. The intensity damage threshold of such gratings in the femtosecond range is typically within 0.5 J cm^{-2} [226, 227] and their characteristic size across their lines reaches 50 cm.

Multilayer gratings with dielectric coating have a higher optical damage resistance [228–230] but are incapable of ensuring the reflection bandwidth sufficient for dealing with femtosecond pulses and are thus typically employed in compressors of picosecond and subpicosecond CPA systems. Record large dielectric gratings, 91 cm in size (!), were designed and fabricated for the compressor of the LFEX CPA laser system. Their damage threshold for 1-ps pulses was $\sim$3 J cm^{-2} and their diffraction efficiency exceeded 95% [231].

The effective size of diffraction gratings in compressors can be increased through the use of grating assemblies

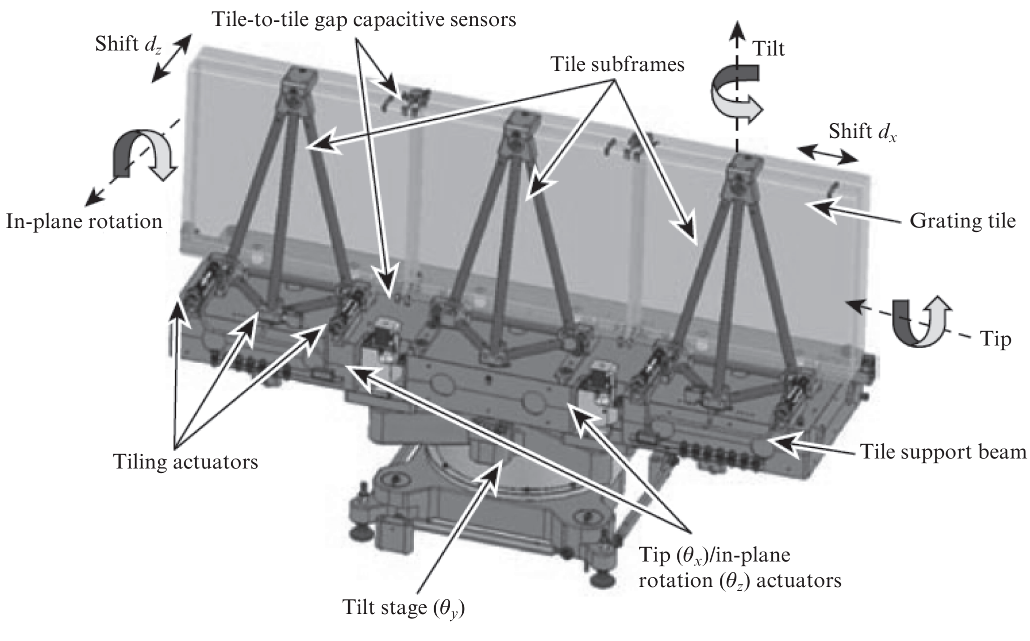

Figure 18. Tiled-grating assembly of the compressor of the OMEGA EP laser system [235].

(mosaic or tiled), which act as one large diffraction grating [204, 232–234]. The problems posed by their alignment are very similar to those considered above in the context of compressor grating adjustment.

At present, several ultra-high power CPA laser systems in operation and under construction use compressors with tiled grating assemblies. The OMEGA EP Nd : glass laser system (LLE, Rochester) [235] has two amplification channels for producing picosecond kilojoule pulses with up to 1 PW of total peak power. Each channel is equipped with a four-grating compressor, and each grating consists of three parts (Fig. 18). Several studies have been concerned with theoretical and experimental issues in the alignment of these gratings [236–238], which made it possible to obtain long-term stability of the angular position of the constituent parts of the grating with an accuracy of 0.1–0.2 μrad. The gratings were adjusted by an interferometric technique.The tiled grating assembly of the compressor of the Pico2000 system (LULI, Palaiseau, France) is also phased using an interferometric technique [239]. For the LFEX petawatt laser facility (ILE, Osaka, Japan), a new, four-pass compressor was developed [240], whose beautiful optical layout with ray paths resembles a crystal. The compressor is based on two tiled grating assemblies and, owing to the configuration chosen, it is tolerant to some types of angular grating misalignment and slight grating-to-grating period variations. An unconventional arrangement of compressor gratings is used in the Gekko MII 100-TW system (Osaka University, Japan) [241]. One of the gratings consists of two segments, and the beam hits it twice as it passes through the compressor.

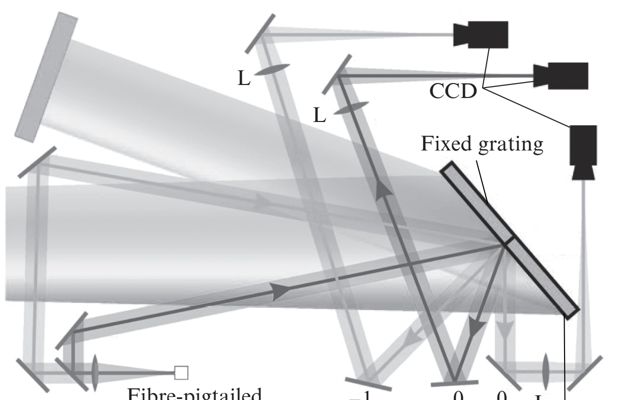

Figure 19. Tiled grating adjustment system in the POLARIS laser facility [242].

The unique technique for aligning the tiled diffraction gratings of the POLARIS CPA laser system under construction (Jena, Germany) [242], by focusing beams reflected into mirror and diffraction orders (Fig. 19), makes it possible to align the tiled grating elements in three angular and two translational degrees of freedom. The compressor and stretcher of the POLARIS were examined in detail in Ref. [243]. Using cw laser radiation at two different frequencies within the transmission band of the compressor, the orientations of the gratings facing each other were adjusted with a 20-μrad accuracy.

A method for adjusting mosaic gratings with the use of far-field measurements at two wavelengths [244, 245] ensures grating element orientation adjustment with an accuracy better than 6 μrad, planarity within $\sim$14 nm and a transverse shift (distorting the grating period) of 1.8% of the grating period. Zuo et al. [246] proposed adjusting the relative displacement of two gratings along the normal to their working surface using an interferometric technique. Measurements at various angles of incidence allowed them to bring the planes of the gratings into coincidence with an accuracy better than 0.1λ.

Note that the requirements for the quality of the light reflected from tiled grating assemblies are similar to those for light in the problem of coherent laser beam combining. Indeed, parts of a signal beam incident on different diffraction gratings should be phased to within a fraction of their wavelength, and the beam propagation directions should coincide to within the diffraction angle [247].

An attractive method for precision alignment (phasing) of tiled grating assemblies via spectral decomposition of a far-field image of the compressed radiation reflected from such a grating was described by Hornung et al. [248]. They experimentally and theoretically investigated the mismatch between the elements of a tiled grating: mutual displacement of the grating elements across the grating lines in two orthogonal directions and rotation of one element of the tiled grating about the axis parallel to the lines. This method was used to demonstrate the coherent combining of two multiterawatt beams each of which was compressed by its own diffraction grating in the tiled compressor [249].

An interesting way to avoid the use of tiled grating assemblies was proposed for the PETAL international multi-petawatt project [250, 251]: a main beam is split into several, smaller aperture beams, each of them is then compressed independently, and then the beams are coherently combined to each other using a segmented mirror. The segment positioning accuracy should be no worse than that in the case of arrayed gratings, but the mirror has less degrees of freedom.

It is also worth noting an interesting optical scheme which enables an increase in effective diffraction grating size and which supposedly was proposed independently by Hein [252] and Li et al. [253] in 2010. The basic idea of this scheme is that a flat mirror normal to the working surface of a grating allows the surface of the grating to be used twice, thereby increasing its effective size by a factor of 2. Li et al. [254] presented a model for evaluation of the scheme and carried out theoretical and experimental comparisons of grating–grating and grating–mirror schemes. There results demonstrate that, despite the simplification of the adjustment procedure owing to the smaller number of adjustable parameters, the long-term stability of such systems must meet more stringent requirements.

4.5. Stretchers and compressors in ultra-high power CPA and OPCPA laser systems

The development of the CPA method culminated in the advent of a number of petawatt laser systems. In this section of the review, we will run briefly through a number of CPA and OPCPA laser systems, with focus on the most powerful of them, and highlight the distinctive features of the stretchers and compressors they employ.

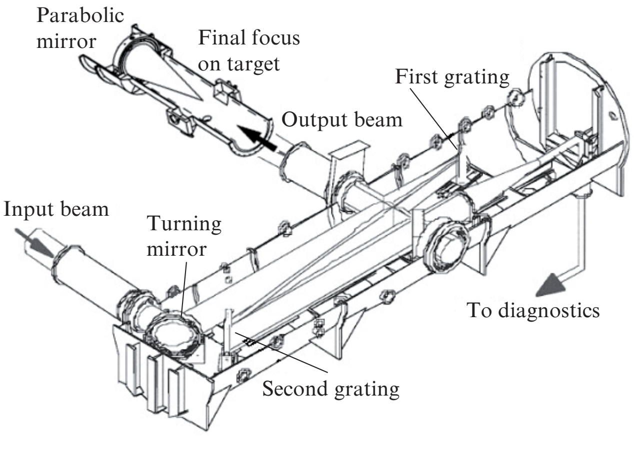

Figure 20. Pulse compressor and target chamber of the first petawatt laser system at Livermore [256].

The first petawatt system [255, 256] was built in 1996 at Lawrence Livermore National Laboratory (LLNL, USA) using a NOVA Nd : glass laser. Pulses with a duration of 100 fs from a Ti : sapphire laser (centre wavelength of 1054 nm) were stretched to 3 ns by a single-grating Martinez stretcher and then amplified to a kilojoule level in Nd:glass amplifier stages. The amplified chirped pulses were compressed in a single-pass Treacy grating-pair compressor (Fig. 20) based on unique gold-coated 94-cm-diameter holographic 1480 lines mm^{-1} diffraction gratings. The peak power of the compressed pulses was as high as 1.5 PW at a pulse duration of 440 fs. Subsequently, the system was dismantled.

To date, LLNL has built the NIF 192-channel 500-TW Nd : glass laser system intended for laser fusion research at a pulse energy of 1.8 MJ at the third harmonic wavelength, 351 nm. NIF's four amplifier channels are allocated to the ARC project [257], aimed at creating eight picosecond (1 – 50 ps) diagnostic beams, each providing 0.5 PW of peak power. Pulse compression occurs in eight unique compact sandwitched compressors [258], in which grating pairs, whose working surfaces face each other, differ in groove density and base, which ensures that there is no spatial chirp at the output. The compressors use multilayer dielectric gratings 91 × 45 cm in dimensions.

The Vulcan petawatt laser facility [259, 260] employs a 'double-decker' stretcher consisting of two identical double-pass Offner triplets and one common diffraction grating. The incident beam passes first through one stage and then through the other, which it reaches owing to an roof-mirror reflector. This configuration made it possible to reduce aberrations and the cost of the stretcher. After passing BBO preamplifier OPCPA stages, the beam is amplified in a phosphate – silicate glass combined amplifier. The pulses are compressed in a single-pass Treacy system utilising two 94-cm gratings from Livermore.

The petawatt module of the GEKKO XII Nd : glass facility (Japan) [261, 262] uses two Martinez stretchers based on diffraction gratings (1480 lines mm^{-1}) and long-focus lenses. In the first stretcher, 150-fs pulses from a GLX-200 master oscillator are stretched in time to 1.5 ns; in the second stretcher, the pulse duration increases from 1.5 to 3 ns. The front end of the petawatt module contains two BBO OPCPA stages. A double-pass compressor consisting of two gold-coated 1-m-diameter diffraction gratings (1480 lines mm^{-1}, damage threshold of 0.56 J cm^{-2}) allows one to obtain 470-fs output pulses with 0.9 PW of power. The efficiency of the compressor (four reflections from the gratings) is ∼70%.

An OPCPA/CPA hybrid petawatt laser system with an output amplifier stage in a phosphate – silicate glass combined amplifier was built in Texas (USA) [182]. Its stretcher, having a modified configuration [182], stretches 100-fs pulses from a Ti : sapphire master oscillator (centre wavelength, 1058 nm) to a 2-ns duration. A compressor based on multilayer dielectric grating compresses the pulses to 167 fs, raising their peak power to 1.1 PW.

CPA laser systems with amplification in Ti : sapphire crystals ensure petawatt peak powers at moderate pulse energies owing to short pulse durations. The first of such systems [187] was built at the Japan Atomic Energy Research Institute (JAERI). The output amplifier stage used a Ti:sapphire crystal with a 80-mm aperture. The peak power obtained was 850 TW and the compressed pulse duration was 33 fs. The stretcher included a gold-coated ruled grating (1200 lines mm^{-1}) and an Offner triplet based on reflective optical elements. The Treacy compressor, consisting of four gold-coated holographic gratings (1480 lines mm^{-1}), had a transmittance of 75%.

The most powerful CPA Ti : sapphire laser system, with a peak power of 2 PW at a pulse duration of 26 fs [263], was created at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. The diameter of the gain element in the output amplifier stage was 100 mm. The approach used to generate a cross-polarised wave (XPW) [264, 265] in the front end of the system made it possible to obtain a contrast of $\sim 1.5 \times 10^{-11}$ over a period of 100 ps after the main pulse. A purpose-designed spectral filter allows one to suppress narrowing of the spectrum upon amplification and compensate the large redshift of the centre wavelength due to the gain saturation in the output amplifier. An Offner aberration-free stretcher used reflective optics, and the stretched pulse duration was 1.4 ns. In the first version of the CPA system [188], the stretcher and compressor differed in grating density (1200 and 1480 lines mm^{-1}, respectively). At the end of 2013 [266], a new stretcher grating was mounted, with a groove density of 1480 lines mm^{-1}. In addition, the angles of incidence of the beams on the compressor gratings were increased in order to reduce the intensity incident on their working surface.

The PULSER I and PULSER II CPA Ti : sapphire laser systems [189, 267] (Republic of Korea), with a peak output power of 1 and 1.5 PW, respectively, have a common front end, which includes two stretchers. One is based on a glass block placed immediately after the femtosecond master oscillator, and the other is a standard Offner telescope grating stretcher placed after a Dazzler AOPDF [191], multipass amplifier and saturable absorber-based contrast-enhancement system. The AOPDF is used to compensate the redshift and narrow down the spectrum in the output laser amplifiers. The stretcher uses a gold-coated holographic diffraction grating (1400 lines mm^{-1}), and the four-grating compressors of PULSER I and II use similar gratings but with a groove density of 1480 lines mm^{-1}. The transmittance of the compressors is 74%, and the output pulse duration is ∼30 fs in both systems.

Yet another CPA Ti : sapphire laser system, with an output peak power of 1.16 PW [268], was built at the Institute of

Physics, Chinese Academy of Sciences (Beijing). For contrast enhancement, an ultra-short (10 fs) pulse from a master oscillator is first amplified in two stages of a noncollinear parametric amplifier (NOPA). Next, the pulse is stretched to 600-ps duration in an Offner triplet stretcher and sequentially passes through amplifier stages in Ti:sapphire gain elements. In a Treacy compressor consisting of four gold-coated holographic gratings (1480 lines mm^{-1}), the amplified pulse is compressed to 27.9 fs. The transmittance of the compressor is 69 %. Owing to this configuration, the output signal had a contrast of 10^{10} over a period of 400 ps after the main maximum.

Built by Thales (France) for Lawrence Berkeley National Laboratory, the BELLA laser system [2, 269] is the first petawatt CPA Ti : sapphire laser facility operating at a repetition rate of 1 Hz (!). It utilises a dual CPA configuration: the first CPA stage (with its own stretcher and compressor) is intended for improving the quality of ultra-intense pulses, especially their contrast, through XPW filtration. The second CPA stage is a power unit: to reach a dispersion match between the Offner telescope stretcher and Treacy gold-coated holographic grating compressor, it also utilises a Dazzler AOPDF. At present, a petawatt-scale CPA Ti : sapphire system with a similar configuration [270] is being built in Romania for the National Institute for Lasers, Plasma and Radiation Physics with active participation of Thales.

5. Conclusions

This review has described the potentialities, characteristics and design of key elements of ultra-high power CPA and OPCPA laser systems: stretchers and compressors intended for stretching and compressing amplified chirped pulses. Issues have been addressed that are related to stretcher – compressor phase matching and the adjustment and alignment of stretchers and compressors. Particular attention has been paid to the history of the optics of ultra-short, ultra-intense pulses: from dye lasers to stable and reliable solid-state lasers, with focus on Ti : sapphire; from freakish fibre stretchers with difficult-to-control third- and higher order dispersion to dispersion-matched diffraction grating stretcher – compressor systems that can be evaluated analytically; from subpicosecond ultra-intense pulses to pulses tens of femtoseconds in duration, in which the role of higher order dispersion is considerably more important; from many years of treading water at the gigawatt level to terawatt, petawatt and multipetawatt laser systems based on parametric and laser chirped pulse amplification.

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