

SPH 618

Optical and Laser Physics

University of Nairobi, Kenya

Lecture 6

AMPLIFIERS

Prof. Dr Halina Abramczyk

Max Born Institute for Nonlinear Optics and
Ultrashort Laser Pulses, Berlin, Germany,
Technical University of Lodz, Lodz, Poland

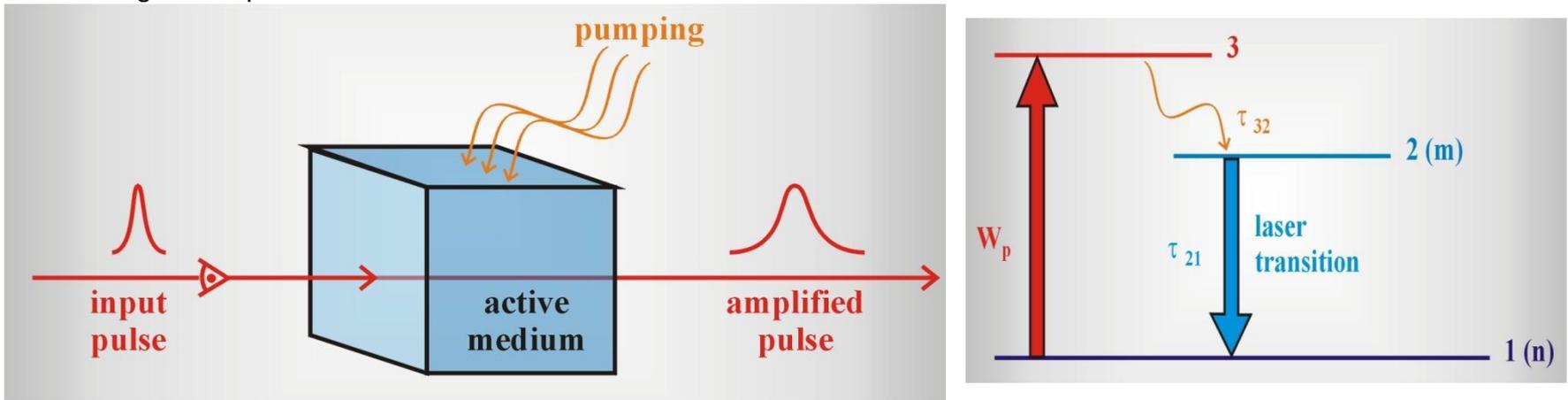
AMPLIFIERS

- Output pulse energies from femtosecond lasers typically do not exceed a few nanojoules, and peak powers of megawatts. For many applications, higher energies or peak powers are required. Researchers are seeking methods to shorten pulses, to increase peak powers and peak intensities on targets. Given the limits on further trimming of the pulse duration, further increases in peak power and peak intensities can only be obtained by increasing output energy. Amplification of energy from the femtosecond lasers makes possible terawatt peak powers. Amplification, combined together with the initial pulse stretching and compression as a final stage can convert terawatt systems into petawatt lasers with subpicosecond pulses.
- So far the highest energies, peak powers and irradiance can be achieved in Nd:glass amplifiers, not those based on Ti:sapphire. The most powerful laser in the world (in 2003) is “Vulcan” in Rutherford Appleton Laboratory, United Kingdom delivering 2.5 kJ in two 150 nm beams, 1 pW, 10^{21} W/cm² and Nova system at Lawrence Livermore National Laboratory delivering 1.3 kJ pulse at 800 ps that can be compressed to 430 fs to achieve 1.3 pW and 10^{21} W/cm².

AMPLIFIERS

When a laser pulse passes through an optically active material in which the population inversion is maintained by a pumping source, it gains energy from the stimulated emission generated by itself in the medium. As a result the output pulse is amplified

The gain G which can be achieved and the energy which can be extracted from the amplifier is the main parameter in the design of amplifiers.



One can show that the amplification in a three level system can be described by Frantz Nodvik equation

$$G = \frac{E_s}{E_{in}} = \ln \left\{ 1 + \left[\exp \left(\frac{E_{in}}{E_s} \right) - 1 \right] G_0 \right\}$$

where $G_0 = \exp(g_0 L)$ is the small-signal single-pass gain and

$$E_s = \frac{h\nu}{\gamma\sigma} = \frac{E_{st}}{\gamma g_0}$$

AMPLIFIERS

There are four most important configurations for laser light amplification:

- multistage power amplifier (fig. 6.3),
- multipass amplifier (MPA) (fig. 6.4),
- regenerative amplifier (RGA) (fig. 6.5),
- chirped pulse amplifier (CPA) (fig. 6.6).

AMPLIFIERS (oscillator-amplifier configuration)

The multistage power amplifier consists of a laser oscillator and a pumped active medium called amplifier.

The amplifier is driven by the oscillator, which generates an initial pulse of moderate power and energy. The pulse from the oscillator passes the active medium of the amplifier and its power grows, in extreme cases, up to 100 times. The pulse can be amplified further by adding the next amplifier in the configuration presented in fig. 6.3. These configurations are used for longer pulses. The double-pass amplifiers are used for typical picosecond system and can deliver 125 mJ pulses of less than 60 fs at 20 Hz with a solid-state saturable-absorber-based oscillator.

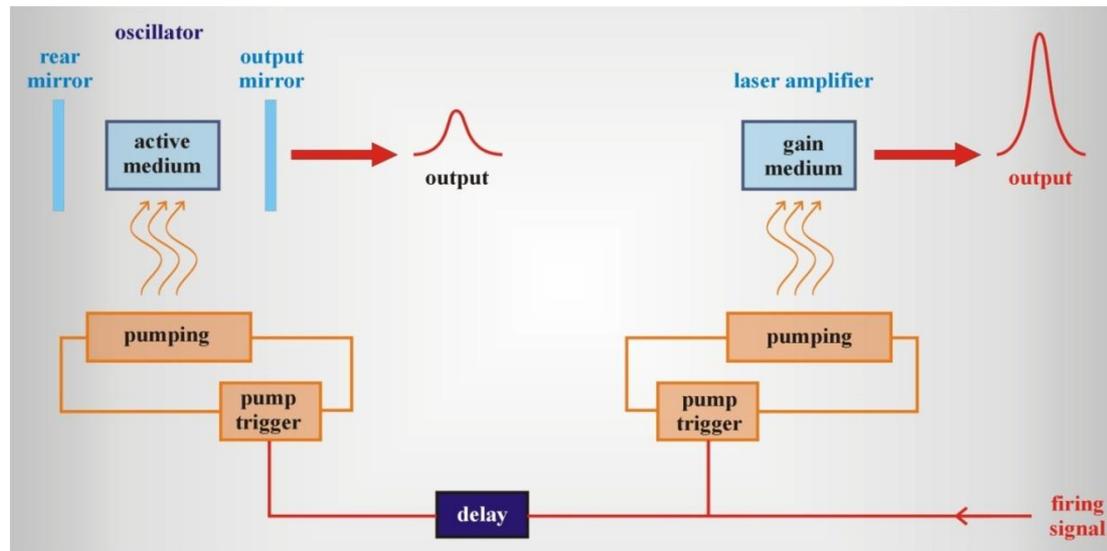


Fig. 6.3 Oscillator-amplifier configuration

AMPLIFIERS (multipass amplifier)

Multipass amplifiers (fig. 6.4) are used when extremely short pulses are required, shorter than 35 fs at 1 kHz and energy of 1.5 mJ. This configuration is simple and less sensitive to thermal lensing, therefore provides excellent beam quality, and is relatively easy to calculate and compensate dispersion in the system.

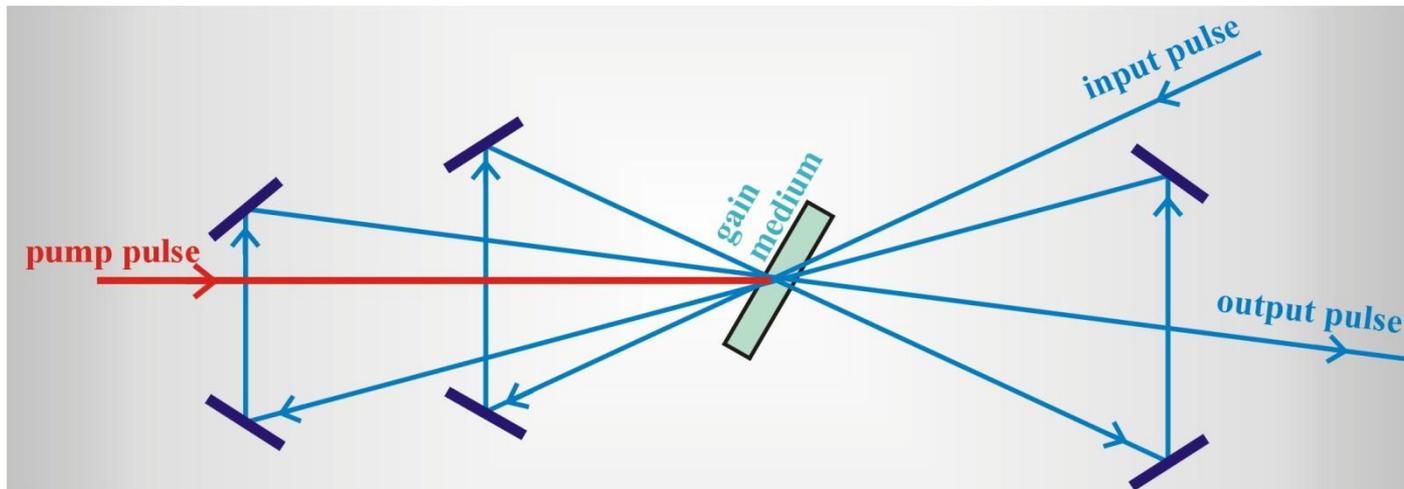


Fig. 6.4 Multipass amplifier

AMPLIFIERS (regenerative amplifier)

Regenerative amplifiers (fig. 6.5) are generally employed for ultrafast system with relatively low output energies from femtosecond oscillators (a few nJ) to achieve the output energy from the amplifier of around 1 mJ at 1 kHz. Higher energy can be obtained from combination RGA/MPA methods that can deliver energy greater than 3.5 mJ per pulse and higher at repetition rates of 1 kHz. Regenerative amplifiers are also used to produce powerful picosecond pulses from a train of low-energy pulses of modelocked lasers. The regenerative amplifiers have originally been pumped by flash lamps or by cw arc lamps. More recently, the Nd:YAG, Nd:YLF or Nd:glass amplifiers are pumped by diode arrays.

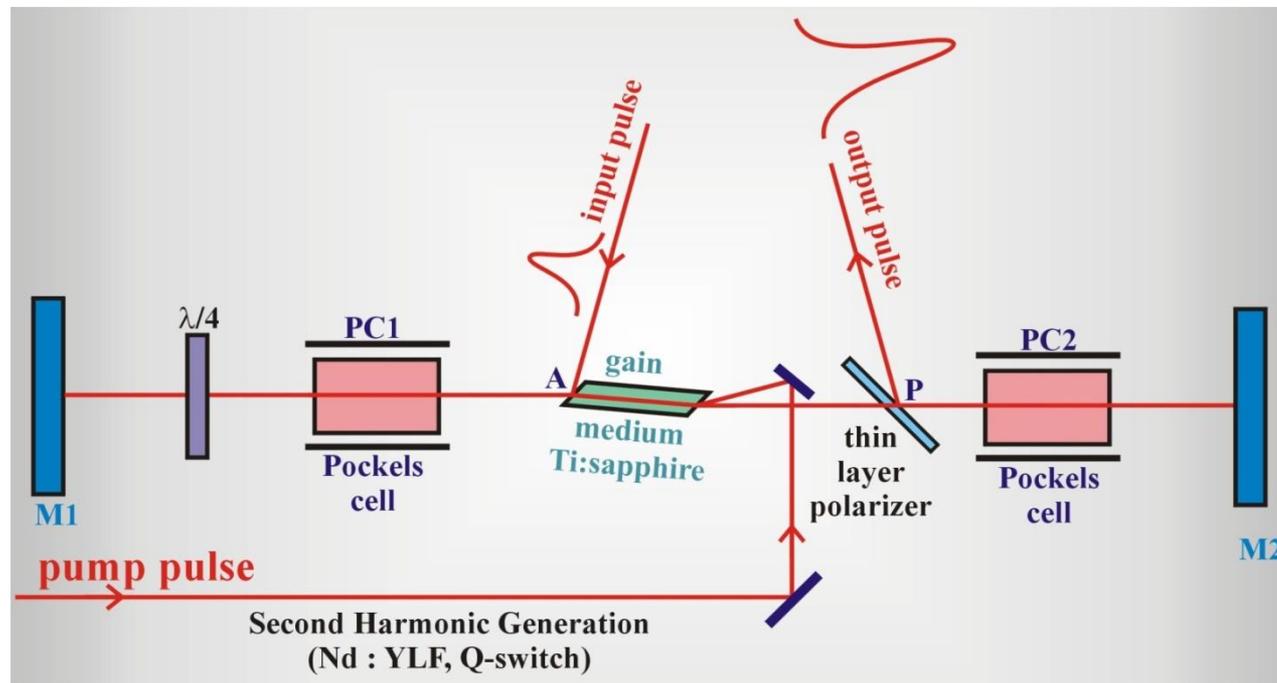


Fig. 6.5 Regenerative amplifier

AMPLIFIERS (CPA)

Amplification of ultrashort pulses leads to enormously large peak powers that may be far above the damage threshold of the active medium employed in the amplifier. To avoid this problem the chirped-pulse amplification (fig. 6.6) was developed.

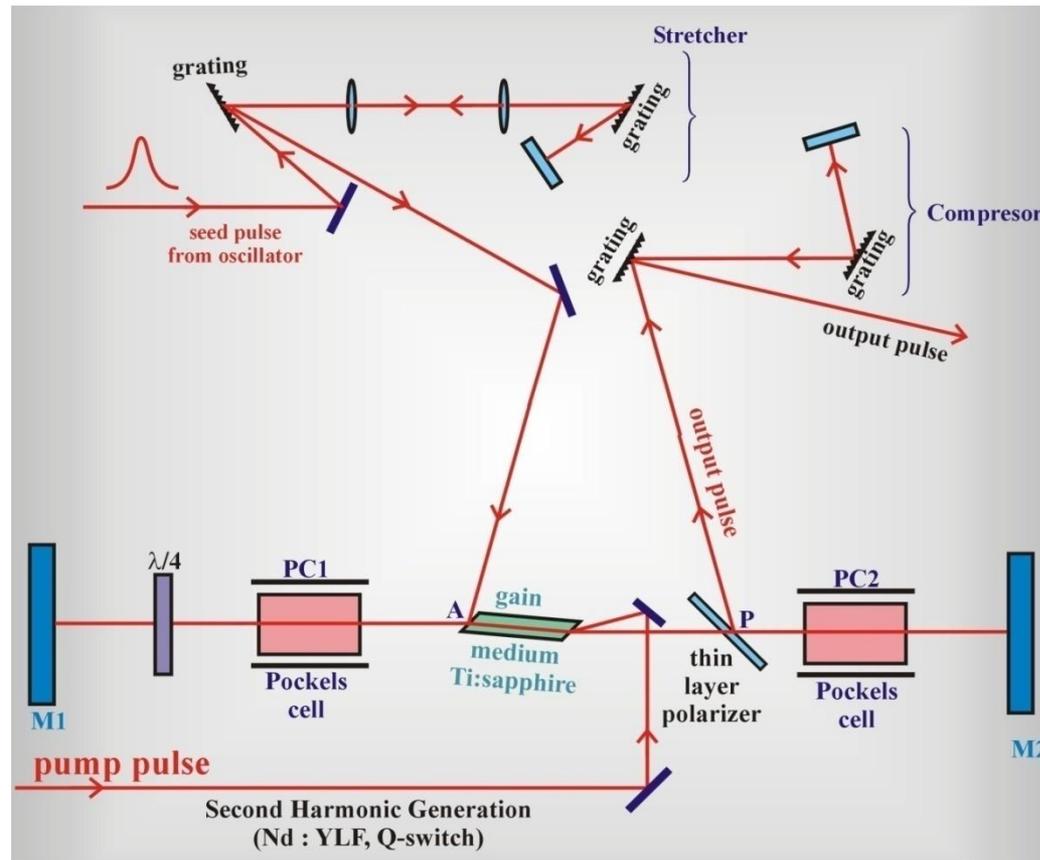
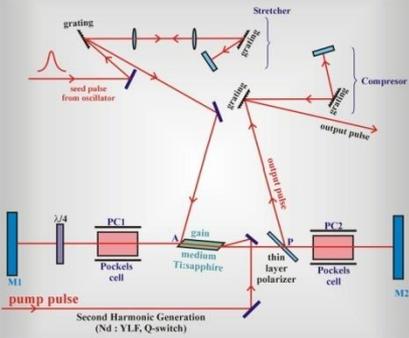


Fig. 6.6 Chirped pulse amplifier (CPA)



AMPLIFIERS (CPA)

- The configuration of the typical chirped pulse amplifier is presented in fig. 6.6. One can see that it consists of the regenerative amplifier and the stretcher and the compressor. The stretcher placed before the regenerative amplifier expands the pulse duration by many orders of magnitude (from femtosecond to hundreds picosecond) and thereby reduces peak power.
- Employing the stretcher solves the problem of high intensities in the amplifiers for ultrashort pulses that are above the damage threshold of the active medium of the amplifier. For example, Ti:sapphire crystal has a high saturation fluence and a large gain-bandwidth needed to generate relatively high energies for sub-picosecond pulses. Self-focusing in the crystal is a desirable effect when employed in modelocking, but it has also its dark sides. Beam focusing due to the Kerr lens focusing can lead to catastrophic beam collapse that may destroy the crystal, which makes it necessary to limit the intensity present in amplifiers to reasonable magnitude less than 10 GW/cm^2 . This obstacle can be removed by the technique called *chirped pulse amplification (CPA)*.

Now we will explain how the regenerative amplifier operates. One can see from fig. 6.5 that the typical commercially available regenerative amplifier consists of an active medium (Ti:sapphire crystal), two Pockels cells (PC1 and PC2), $\lambda/4$ plate and thin-film polarizer placed between two mirrors M1 and M2.

The gain medium is pumped with the second harmonic of the solid-state laser Nd:YLF, Q-switched with pulses durations of 250 ns and the average energy of 8 W at the Brewster's angle.

The regenerative amplifier selects an individual pulse from a train of modelocked pulses (called a seed pulse). The seed pulse is trapped in an amplifier where it is amplified at each pass in the crystal. The pulse passes many times (usually about 10-20 times) through the gain medium to get more energy. Once its energy increases by as much as 10^6 , the amplified pulse is removed from the amplifier as the output pulse that can be used for further applications.

The number of passages in the regenerative amplifier depends on the round-trip time between the M1 and M2 mirrors in the amplifier. If the round-trip time is 10 ns and the pumping pulse duration is 250 ns, a typical time evolution of the pulse energy in a regenerative amplifier is given in fig. 6.7. The amplified pulse shape follows the shape of the pumping pulse originating from the depletion of the excited-state in the gain medium. It is obvious from fig. 6.7 that the pulse should be switched out from the amplifier after around 20 passages where there is a gain maximum and the energy of the amplified pulse is the highest.

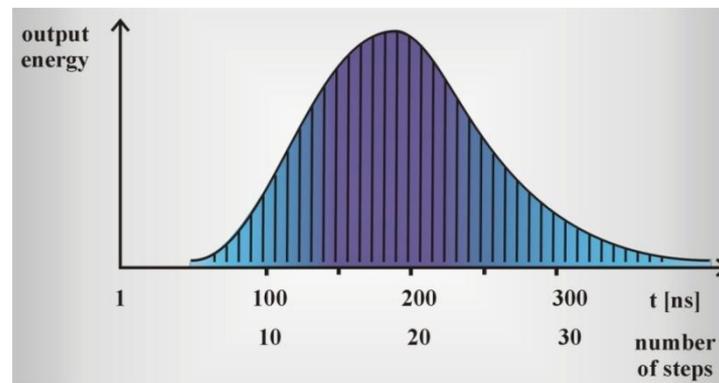
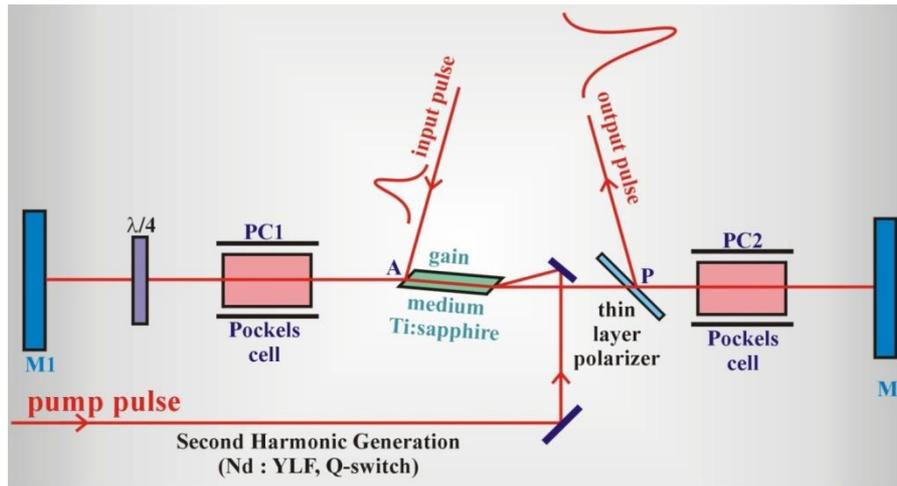


Fig. 6.7 Time evolution of the amplified pulse energy versus time and the number of passages in the regenerative amplifier



Now we have to understand how the input pulse is trapped in the amplifier. We will show that it is trapped on the polarization basis. Let us recall that:

- $\lambda/4$ plate changes the polarization from linear to circular,
- $\lambda/2$ plate rotates the linear polarization by $2a$, where a is the angle between the polarization vector and the optic axis,
- thin layer polarizer acts as a reflective polarizer that at the Brewster's angle reflects the polarization perpendicularly to the plane of reflection, and transmits the polarization parallel and perpendicular to the plane of reflection,
- Pockels cell acts like a $\lambda/4$ or $\lambda/2$ plate depending on the external voltage applied.

Pockels Cell

The Pockels cell plays an important role as an electro-optic Q -switch. Now we will explain its operation. The Pockels cell consists of a nonlinear optical material with the voltage applied to the material. The electric field can be applied along the direction of the optical beam (fig. 6.8a) or perpendicular to it (fig. 6.8b). The crystal becomes birefringent under the influence of the applied electric field. The crystals used for parallel configuration (fig. 6.8a) are uniaxial in the absence of an electric field with the optic axis along z direction. The ellipsoid of the refraction index projects as a circle on a plane perpendicular to the optic axis (fig. 6.9a).

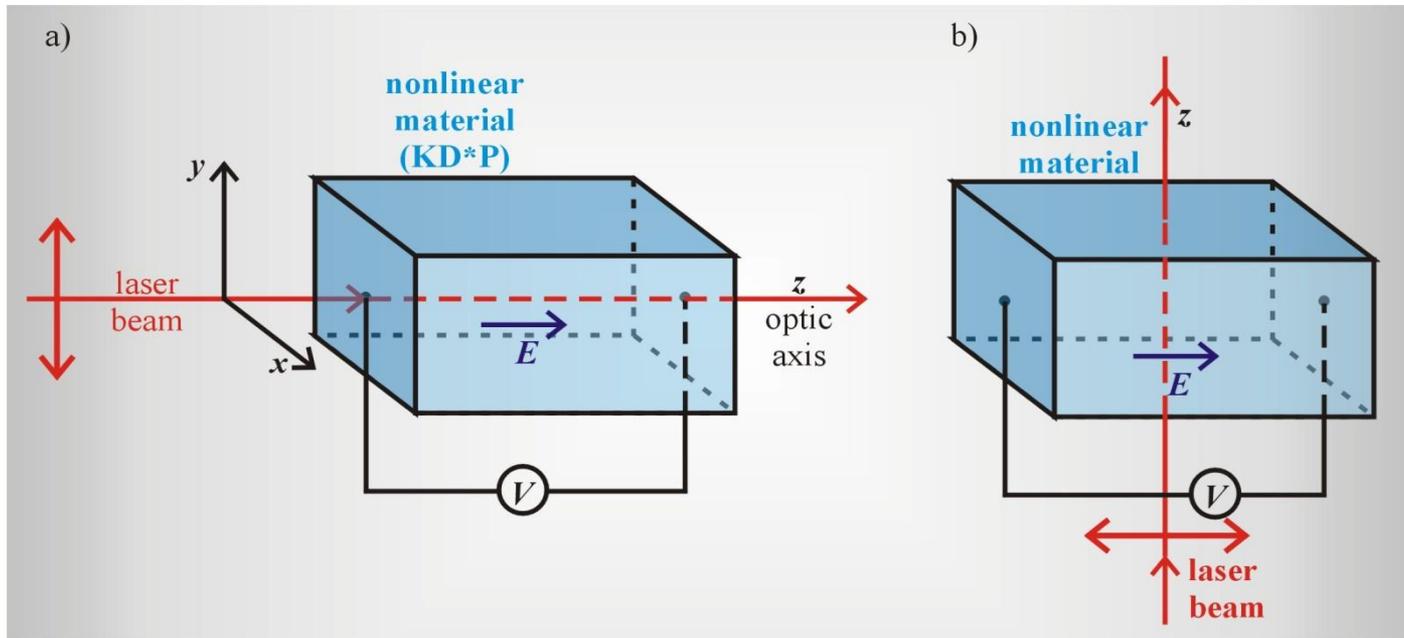


Fig. 6.8 The Pockels cell, the electric field can be applied along the direction of the optical beam (a) or perpendicular to it (b)

Pockels Cell

So, the laser beams having polarizations along x or y directions propagate with the same velocities along the z axis because the crystal is not birefringent in the direction of the optic axis. For the situation presented in fig. 6.9a, the laser beam linearly polarized along y passes through the KD^*P crystal unchanged when no voltage is applied. When an electric field is applied parallel to the crystal optic axis z , the ellipsoid of the refractive index projects as an ellipse, not a circle, on the plane perpendicular to the optic axis with the axes x' and y' rotating by 45° with respect to the x and y crystallographic axes (fig. 6.9b). The angle of 45° is independent of the magnitude of the electric field. Therefore, when a voltage is applied, the KD^*P crystal becomes birefringent along the z axis, and divides the laser beam into two components (along x' and y') that travel through the crystal at different velocities.

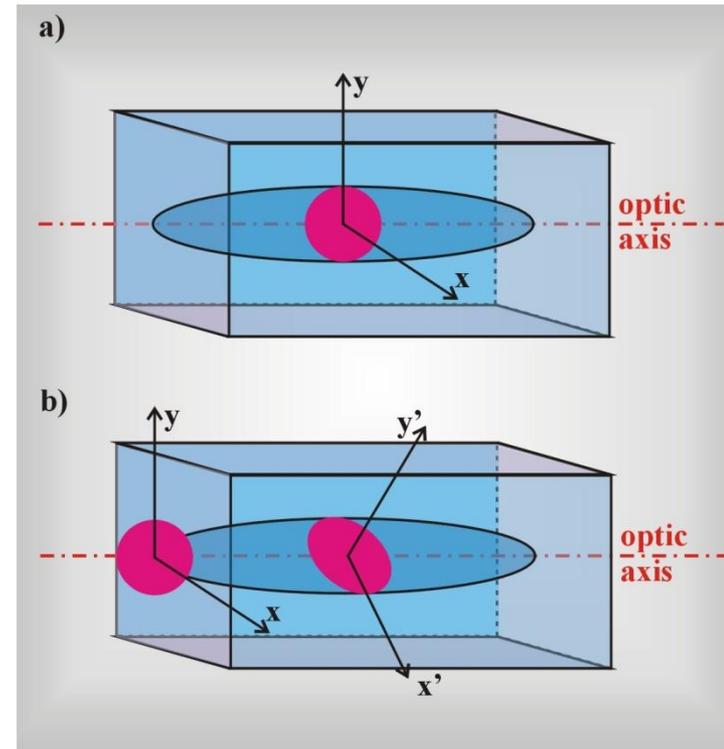


Fig. 6.9 Change of the refractive index in a KD^*P crystal, x , y , z – the crystallographic axes a) without an electric field, b) when an electric field is applied ($E \neq 0$), x' , y' , z – the electrically induced axes

Pockels Cell

- The polarization of the output beam depends on the phase difference between the two orthogonally polarized components – ordinary and extraordinary rays, which depends on the applied voltage

$$\delta = \frac{2\pi}{\lambda} l \Delta n \quad (6.19)$$

- ,
- where Δn is the difference in the indices of refraction for the ordinary and extraordinary beams, l is the crystal length.

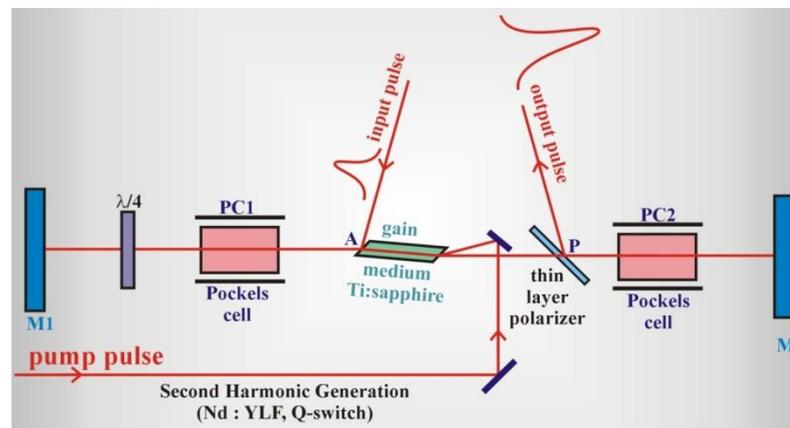
- It has been shown that Δn can be expressed as

$$\Delta n = n_0^3 r_{63} E_z \quad (6.20)$$

- ,
- where r_{63} is the element of the electro-optic tensor of the third rank that is the response to the applied field E in the z direction (E_z), n_0 is the index of refraction for the ordinary ray. Employing the relation between the voltage V and the applied electric field E_z , and inserting (6.20) in eq. (6.19) one gets

$$\delta = \frac{2\pi}{\lambda} n_0^3 r_{63} V_z \quad (6.21)$$

- .
- When the applied voltage V_z is adjusted to generate the phase difference $\delta = \pi/4$ or $d = \pi/2$ the Pockels cell operates as a quarter-wave or half-wave plate.
- The Pockels cell belongs to the fastest all-optical switching devices, and is highly reliable. Typical commercially available Pockels cells employ KD*P crystals with $l/4$ voltage between 3.5 and 4 kV at 0.69 mm and 5 to 6 kV at 1.06 mm . As a particular example, Pockels cells are used to select and retain high-peak-power pulses in regenerative amplifiers.



- Knowing how the Pockels cell operates let us return to fig. 6.5 to explain the mechanisms of trapping the seed pulse from a train of modelocked pulses inside the amplifier. The operation of a regenerative amplifier presented in fig. 6.5 can be divided into the following steps:
- A seed pulse arrives in the amplifier at the Brewster's angle by reflecting from the surface of the active medium ($\text{Ti}^{+3}:\text{Al}_2\text{O}_3$). The polarization of the seed pulse is perpendicular to the plane of drawing. The polarization of the pulse passing through the Pockels cell PC1, which is initially switched off is unchanged, but double passing through $\lambda/4$ (before and after reflection from M1) changes the polarization by 90° . So, the beam reflected from M1 is not reflected from the crystal surface at A point but is refracted and passes the crystal leading to its amplification by the stimulated emission induced in the crystal ($\text{Ti}^{+3}:\text{Al}_2\text{O}_3$) in which the population inversion is generated by the pumping source. The pulse passes through the thin-layer polarizer and the Pockels cell (PC2), inactive at the moment. The pulse is reflected from the mirror M2.
- When PC1 (and PC2) is still switched off, the beam passes twice $\lambda/4$ plate and the pulse is removed out of the amplifier by reflection from the crystal surface at the point A.
- When PC1 is switched on (as a $\lambda/4$) before arriving the seed pulse, the total effect of the $\lambda/4$ plate and PC1 is $\lambda/4 + \lambda/4 + \lambda/4 + \lambda/4 = \lambda$, which means that the polarization is unaffected and the pulse is trapped inside, not reflected from the surface of the active medium.
- Each pass of the pulse through the active medium results in the pulse amplification. When the pulse has been amplified to the desired level ($\sim 10^6$ times), the voltage $l/4$ is applied to the Pockels cell PC2. The pulse going to the mirror M2 and returning through PC2 ($\lambda/4 + \lambda/4 = \lambda/2$) changes its polarization and is removed from the amplifier at the P point by reflection from the thin layer polarizer.

Pulse compressor

The group velocity dispersion (GVD) is the most important factor affecting the temporal pulse broadening.

Due to the GVD each frequency component that comprises the spectrum of the pulse travels through the medium with different group velocity. For so called positive GVD materials, the red components travel faster than the blue components. As we have shown a pair of prisms can be used to compensate for the excess GVD that results in the pulse compression. The same can be achieved with the diffraction gratings

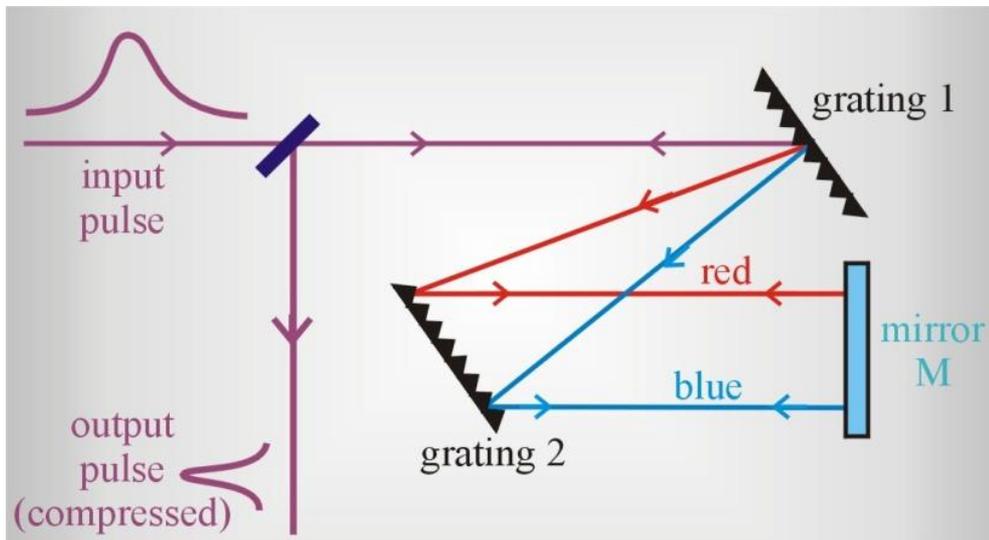
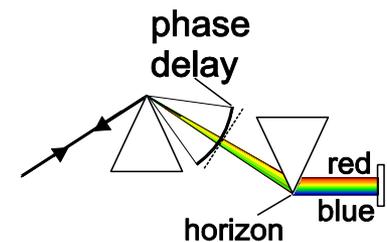
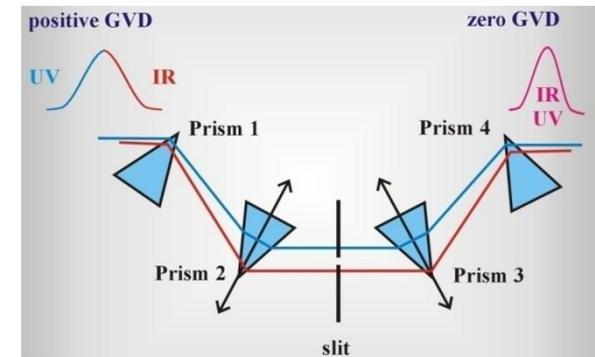
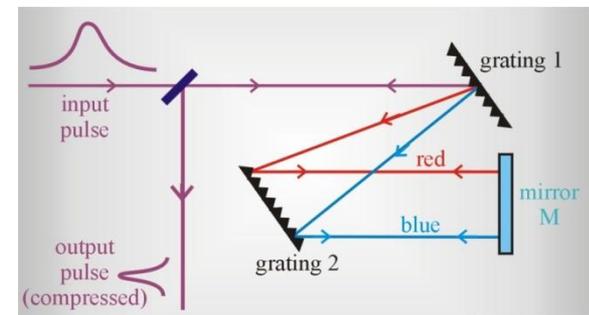


Fig. 6.10 Illustration of the principle of the pulse compression

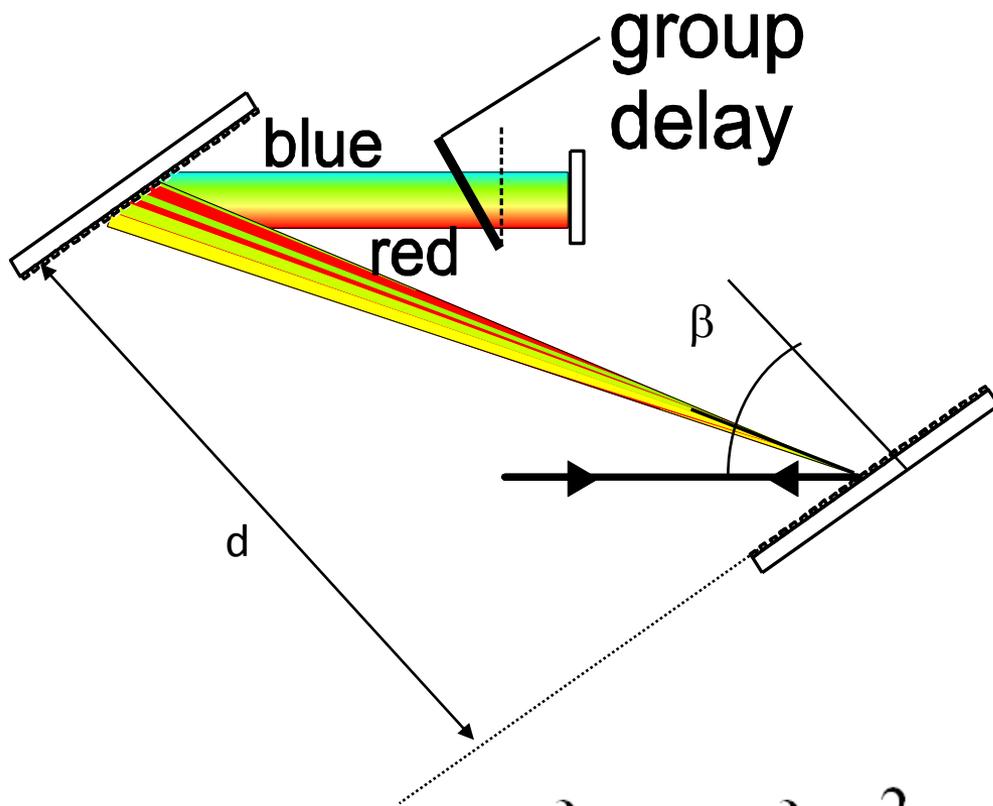


Pulse compression



- The pair of parallel gratings shows a simplified pulse compressor, which demonstrates the concept of compression. One can see that the optical path through the grating pair is longer for the longer wavelengths than for the shorter ones. The mirror M reflects the beam back into the grating pair recovering the spatial distribution, but still increasing the difference in the optical paths for the red and the blue components. Thus, the pair of the parallel gratings provides the negative group-velocity. If the input pulse that is positively chirped travels through the gratings, the output pulse becomes shorter due to partial cancellation of the positive GVD effect by the negative GVD of the gratings in the configuration presented in Fig. 6.10. Pulse stretching is essentially the reverse of the pulse compression. The gratings can be configured in such a way so the bluer components have to travel longer path through the stretcher than the redder components. The result is that the stretcher generates a *positive GVD effect* that results in that the redder components travel even faster than for the input pulse and exit the stretcher with the temporal pulse significantly longer.

The grating compressor



Λ : grating period

$$\text{GDD}(\lambda) = -\frac{\lambda}{2\pi c^2} \left(\frac{\lambda}{\Lambda}\right)^2 d \left[1 - \left(\frac{\lambda}{\Lambda} - \sin\beta\right)^2\right]^{-3/2}$$



Pulse stretcher

One can see that the main difference between the compressor (fig. 6.10) and the stretcher (fig. 6.11) is that a telescope is added between the gratings to invert the sign of the dispersion from the negative in fig. 6.10 to the positive in fig. 6.11.

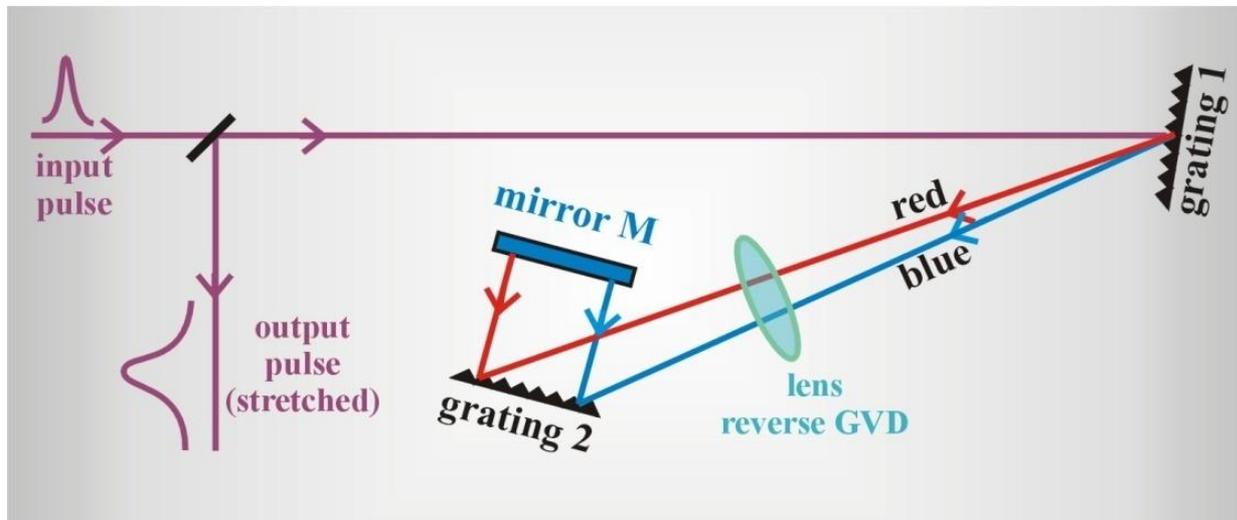


Fig. 6.11 Illustration of the principle of pulse stretching

Pulse stretcher – another configuration

In practical applications some other configurations are used. For example, instead of using a pair of gratings, a single grating combined with the curved mirror can be used as presented in fig. 6.12. One can see that this multi-pass configuration reduces the complexity and ensures four-pass the grating that is necessary for the spatial reconstruction of the stretched beam.

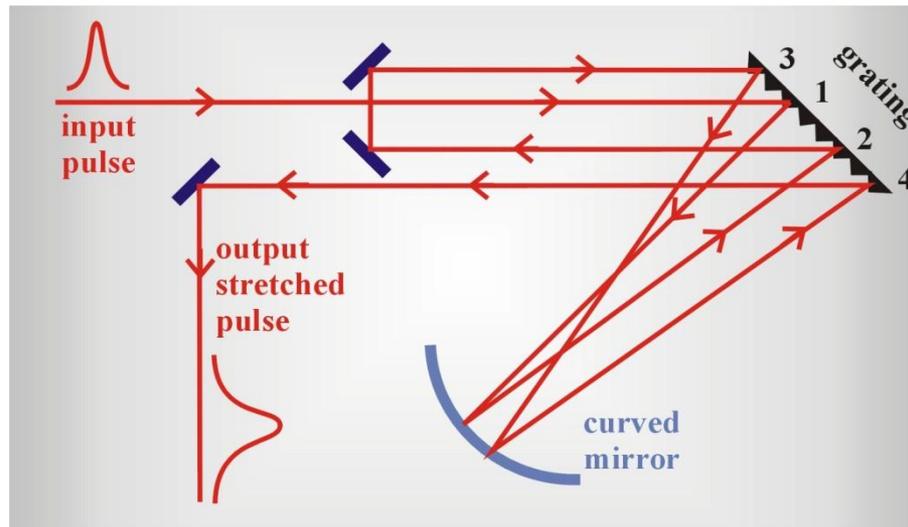
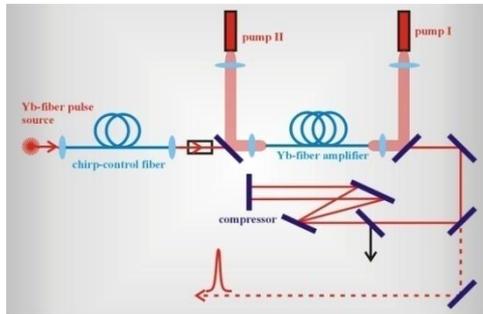


Fig. 6.12 The pulse stretched with a single grating – curved mirror combination

- The recent decade have witnessed the dramatic improvement in amplification of ultrashort pulses. Amplification of the femtosecond pulses using the chirped pulse amplification (CPA) technique is now commercially available. Amplification of ultrashort pulses to mJ, corresponding to multiterawatt peak powers becomes a routine task. CPA technique is used both in the multipass configuration and regenerative amplification. Quite often these configurations are combined together to reach terawatt powers. Usually the regenerative amplifier is used as a first stage of amplification followed by multi-pass configuration used for the output power-boost stage.
- Generally, the multipass amplifiers are used for very short pulses (<50 fs). They need much lower amount of optical material for amplification that reduce nonlinear distortion of the pulse that usually comes at the expense of rather complicated alignment procedure and higher level of ASE (amplified spontaneous emission). The regenerative amplifiers are usually used for pulses longer then 50 fs. They have many advantages including much smaller ASE and a simple operation and maintenance. No realignment is necessary to adjust the number of passages through the amplifier since the beam follows the some path in the cavity.

FIBER TECHNOLOGY-OPTICAL AMPLIFIERS



- So far we discussed the conventional configurations based on bulk-optic-solid-state amplifiers. The development of optical communication created a growing market for higher-power *optical amplifiers* based entirely on the fiber technology. The development in double-cladding fibers technology and multi-mode diode pumping has increased *cw* fiber lasers output to the level comparable with the solid-state lasers. However, achieving a few watts of average power from fiber-based ultrashort laser systems, routinely produced by the solid-state femtosecond systems, is not so straightforward. Limitations come from large effective nonlinearities (SPM and GVD) described in chapter 5 that can destroy short femtosecond pulses produced in the fiber core. The obstacles related to pulse amplification can be reduced by using fibers with larger core. The typical core of a single-mode fibers are less than $10\ \mu\text{m}$, larger cores operate usually in multimode regime. However, it has been found that it is possible to obtain a single mode operation for a careful large-core fiber design. Increasing an active area of the core enables an efficient pumping at shorter length of the fiber reducing nonlinearities. Moreover, fibers exhibiting a positive GVD rather than negative GVD are used for high-power amplifications. The soliton-like behavior (described in chapter 5) obtained when the SPM and negative GVD offset each other at the properly chosen fiber lengths does not apply at high powers.

Optical amplifier

The system consists of a fiber-based ultrashort laser (Yb-doped fiber laser) that emits a seed pulse for further amplification. The seed pulse (1050 nm, 2 ps, 300 mW, 50 MHz) passes through a piece of single-mode fiber exhibiting a positive GVD to stretch the seed pulse. Then, the stretched linearly positively chirped seed pulse is amplified in a fiber amplifier. The fiber amplifier (Yb-doped fiber, 4.3 m length, 25 μm -diameter core) is pumped from both ends with two fiber-bundle-coupled laser-diode operating at 976 nm and 14 W. The seed pulse is amplified to 13 W and the width increases from 2 ps to 5 ps. Then, the pulse is recompressed down to 100 fs passing through a conventional diffraction grating compressor (negative GVD designed) achieving 5 W output at 1050 nm.

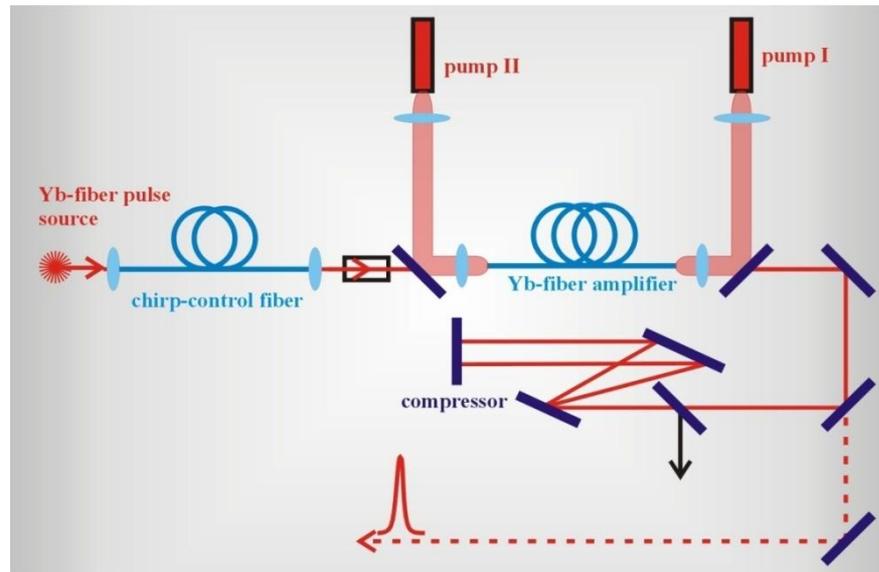


Fig. 6.13 Fiber amplification system