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Temporal Stretching of Laser Pulses

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1. Introduction

Many lasers operate predominantly or only as pulsed sources and the pulse duration is determined by the duration of effective pumping, intra-resonator energy extraction rates, etc. However, in certain applications of the pulsed lasers, it is necessary to extend the duration of the laser pulses without reducing its pulse energy. The duration of laser pulses is increased by using laser pulse stretchers, which stretch the pulses temporally. An ideal laser pulse stretcher increases the duration of the laser pulse without introducing losses so the peak power of the laser is reduced without reducing its average power. The temporal stretching of laser pulses is vital for many applications of pulsed lasers. The temporal stretching of oscillator pulses of high beam quality is required in oscillator–amplifier systems for achieving high output power. The temporal stretching of pump laser pulses leads to an increase in energy conversion efficiency and tuning range along with a decrease in linewidth of the tunable dye lasers. While launching the laser pulses of high energy into optical fibers, the temporal stretching of laser pulses is done to reduce the peak power, without reducing the pulse energy, to save the input faces of optical fibers from damage. Thus the temporal stretching of laser pulses also increases the upper limit of transmission of pulse energy in the optical fibers. The optical pulse stretchers are used for removing laser-induced plasma spark generation in spontaneous Raman-scattering spectroscopy by reducing the peak power. In the guide star experiments, the pulse stretching of laser pulses is required to avoid saturation effects. The temporal pulse stretching is required in material processing because a stretched pulse is more efficient for heating the material. The temporal stretching of laser pulses is needed in optical microlithography to avoid degradation of semiconductor materials as well as optics. In the medical application of lasers, the pulse stretching of laser pulses is done to reduce the high peak intensities, which generally damage the tissues. The temporal stretching of laser pulses is done in holographic interferometry for removing the boiling effect, which is detrimental to the quality of the photographs. The ultrashort pulses are temporally stretched in the chirped pulse amplification (CPA) to avoid the nonlinear effects that lead to catastrophic damage. There are many more important applications, where temporal stretching of laser pulses is done. According to the type of the laser and the requirements of the application, various types of laser pulse stretchers, both passive and active, are developed for temporal stretching of laser pulses.

2. Techniques of temporal stretching of laser pulses

Based on the physics and technology, the techniques of temporal stretching of laser pulses can be broadly classified into four categories; (a) optical pulse stretching, (b) pulse stretching by intracavity nonlinear materials (c) electronic pulse stretching and (d) pulse stretching by dispersion.

2.1 Optical pulse stretching

The technique of optical pulse stretching uses a configuration of optical elements that split the amplitude of the incident laser pulse and introduce optical delays among them and also recombine the temporally delayed portions of the pulse to provide a temporally stretched laser pulse. These optical pulse stretchers are generally passive and configured external to the laser system for temporal stretching of nanosecond long laser pulses. Several types of optical components can be configured in different ways in optical pulse stretchers to obtain temporal pulse stretching. A typical optical pulse stretcher is an optical ring cavity formed by several 100% reflecting mirrors and at least one partially reflecting beam-splitter.
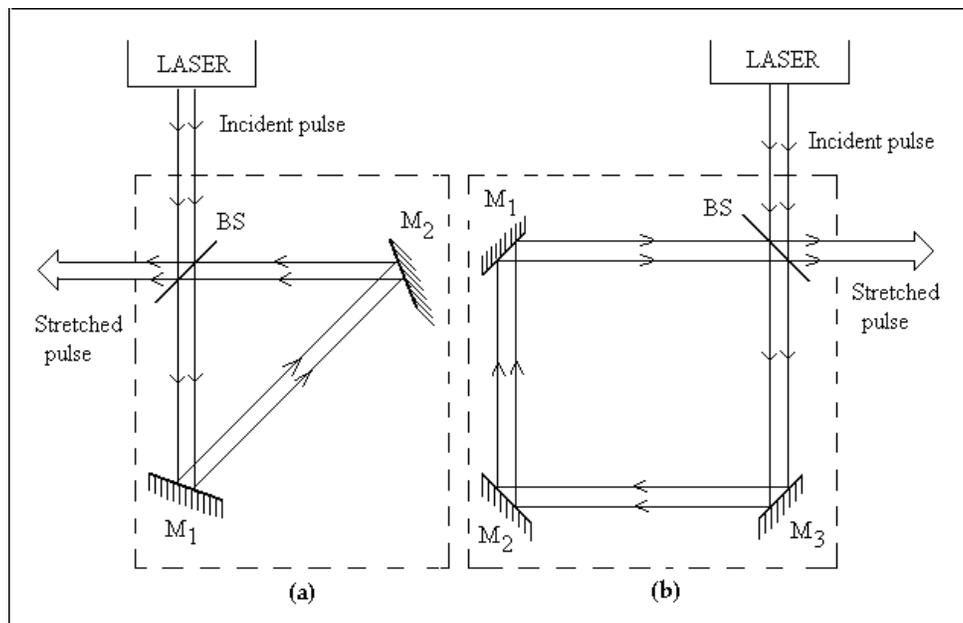

Fig. 1. Schematics of optical pulse stretchers of ring cavities with (a) three mirrors and (b) four mirrors. M_1, M_2 and M_3: 100% reflecting plane mirrors; BS: beam-splitter.

The optical ring cavity of a pulse stretcher, shown in Fig. 1(a), is a triangle ring cavity consisting of a beam-splitter, *BS*, and two 100% reflecting plane mirrors, M_1 & M_2. The optical ring cavity, shown in Fig. 1(b), is a square ring cavity consisting of a beam splitter, *BS*, and three 100% reflecting plane mirrors, M_1, M_2 & M_3. The beam-splitter and the 100% reflecting mirrors of the optical ring cavity can also be arranged in other shapes, like rectangle, etc. The laser pulse, which is to be stretched, is incident on the beam-splitter, *BS*. If the absorption losses of the beam-splitter are zero, then it splits the amplitude of the incident laser pulse into two parts such that one part is reflected while the remaining transmitted part is stored in the ring cavity to traverse an additional path. The stored part is then released in each roundtrip by the beam-splitter, *BS*, where it gets spatially superimposed on the reflected part as well as on the earlier released parts to form a single

pulse of longer duration. Thus the optical ring cavity divides an initially large amplitude laser pulse into many smaller amplitude pulses and recombines them after introducing optical delays among them. A spatial overlapping between the successive parts of the laser pulse at the beam-splitter is essential in an optical pulse stretcher. The optical ring cavity, shown in Fig. 1(a), is a right-angled triangle ring cavity because this configuration permits the optimum superposition of the input and output pulses upon exiting the cavity by use of a 45° incidence beam-splitter. The beam-splitter reflectivity, the optical cavity delay time, the laser beam pointing stability and the laser beam divergence are the key parameters, which affect the performance of a optical pulse stretcher. The optical ring cavity traps and stores a portion of the circulating laser pulse, subsequently releasing the stored pulse over a longer period of time as determined by the optical delay time and the intracavity leakage rate. The optical delay time, τ, is the roundtrip propagation time of the ring cavity and is given by

$$\tau = L/c \tag{1}$$

where c is the speed (i.e., group velocity) of light in air and L is the length of the ring cavity. Suppose the reflectivity of the *BS*, whose absorption losses are zero, is R% and p(t) is the instantaneous power of the pulse, which is incident on the pulse stretcher, then *BS* divides the pulse such that reflected part, Rp(t), goes out of the pulse stretcher and transmitted part (1−R)p(t), circulates inside the ring cavity. After 1st roundtrip, which is completed in time τ, *BS* transmits a part of pulse, $(1-R)^2 p(t-\tau)$, out of the cavity, which gets superimposed on the earlier reflected part. Now the reflected part of the pulse, $R(1-R)p(t-\tau)$, circulates inside the ring cavity. After 2nd roundtrip, which is completed in time 2τ, *BS* transmits another part of amplitude, $(1-R)^2 Rp(t-2\tau)$, out of the pulse stretcher and reflects the remaining part, $R^2(1-R)p(t-2\tau)$, to circulate inside the ring cavity. The process repeats and the ring cavity divides an initially large amplitude laser pulse into many smaller amplitude pulses such that the successive pulses exiting from the pulse stretcher are temporally shifted with respect to the initial pulse by τ, 2τ,..., $n\tau$, where n is an integer representing the number of round trips in the cavity. The integrated instantaneous power of the pulse, obtained as the output of the optical pulse stretcher is given by

$$
\begin{aligned}
P(t) &= Rp(t) + (1-R)^2 p(t-\tau) + R(1-R)^2 p(t-2\tau) + R^2(1-R)^2 p(t-3\tau) + R^3(1-R)^2 p(t-4\tau) \\
&\quad + R^4(1-R)^2 p(t-5\tau) + \cdots + R^{n-1}(1-R)^2 p(t-n\tau) + \cdots \\
\\
&= Rp(t) + \sum_{n=1}^{\infty} R^{n-1}(1-R)^2 p(t-n\tau)
\end{aligned}
\tag{2}
$$

In Eq. (2), the 1st term is initial reflection of *BS*, the 2nd term is transmission of *BS* after 1st roundtrip, the 3rd term is transmission of *BS* after 2nd roundtrip, and so on. There are infinite numbers of terms in the expression, however only first few terms are effective because the pulse amplitude, oscillating in the ring cavity, becomes negligibly small after few roundtrips. Several configurations of passive optical pulse stretchers are developed. A passive optical pulse stretcher of square ring cavity configuration was used in a copper vapor laser MOPA system, where it stretched the oscillator pulse of duration of about 34 ns to about 50 ns (Amit *et al.*, 1987). A similar optical pulse stretcher of rectangular ring cavity was set up to stretch the pulses of a copper vapor laser from 60 ns to 72 ns at base (Singh *et al.*, 1995).

The technique of optical pulse stretching is suitable for temporal stretching of pulses of durations of few tens of nanoseconds. A very compact optical ring cavity would be required for temporal stretching of pulses of very short durations. A Fabry–Perot interferometer, which consists of two closely spaced parallel mirrors of high reflectivity, is a compact optical cavity and can also be used for temporal stretching of subnanosecond pulses. The degree of pulse stretching depends on the spacing between the two mirrors and their reflectivity. A Fabry-Perot interferometer with mirrors of reflectivity 98% was used for temporal stretching of 290 ps pulses of a mode-locked Nd:YAG to two to five times by changing the mirror spacing (Martin, 1977). If the pulse duration of the pulse, to be stretched by the optical pulse stretcher, were smaller than the roundtrip time of the ring cavity then a series of separated pulses would be obtained rather than a single stretched pulse. An optical pulse stretcher, consisting of three 100% reflecting plane mirrors and a beam-splitter of reflectivity 40% in a rectangular ring cavity of length 3.3 m (roundtrip time = 11 ns), applied to a Q-switched Nd:YAG laser to stretch its 7 ns pulses, generated a series of separate pulses instead of a single stretched pulse (Beyrau *et al.*, 2004). If a series of separate pulses are not desired, then a laser pulse stretcher with multiple optical ring cavities can be used to obtain a single stretched pulse. In this arrangement, several basic ring cavities are arranged in tandem such that the output of the first ring cavity is used as the input to the second ring cavity and so on. This configuration of multiple ring cavities not only increases the stretching factor but also recombines all the pulses in such a way that a single stretched pulse with longer temporal width is obtained. The roundtrip time of the shortest ring cavity, the number of ring cavities and the ratio of roundtrip times of different ring cavities of the pulse stretcher are chosen in such a way that the a stretched pulse is single and smooth. It is shown that a pulse stretcher, which consists of multiple ring cavities such that the roundtrip times of subsequent cavities decrease in geometric progression and the roundtrip time of the shortest cavity equals to the pulse width (FWHM) of the original pulse, is the best to recombine multiple pulses into a smooth single output pulse (Kojima *et al.*, 2002). The advantage of pulse stretcher with multiple ring cavities is that each additional cavity further stretches the original pulse, however it also increases the optical propagation distance. An optical pulse stretcher, consisting of three triangular ring cavities with roundtrip times of 35.2 ns, 16.7 ns and 9.03 ns (in the ratio of ~ 4:2:1) temporally stretched a 8.4 ns laser pulse of a Q-switched Nd:YAG laser to a 150 ns long (FWHM = 75 ns) single pulse with a peak power reduction of $0.10\times$ and 83% efficiency (Kojima *et al.*, 2002). The configuration of multiple ring cavities in the pulse stretcher is such that the removal of the beam-splitter from the path of laser beam makes that ring cavity ineffective. Therefore the beam-splitters of the ring cavities of the pulse stretcher can be mounted on linear translation stages to have different combinations of the ring cavities to operate to provide stretched pulses of different lengths without disturbing the whole optical layout. An optical pulse stretcher, consisting of two ring cavities of 12 and 6 m long, not only stretched the 24 ns pulses of the 193 nm ArF excimer laser but also allowed a fast switching between different pulse lengths (24, 60, 63, and 122 ns) by operating the motorized translation stages on which the beam splitters were mounted (Burkert *et al.*, 2010).

In the optical pulse stretchers, discussed so far, plane mirrors are used and consequently the size of that part of the beam, which traverses longer path length, becomes larger at the beam-splitter due to finite beam divergence of the laser beam. The gradual growth of beam diameter in each roundtrip results in imperfect spatial overlapping between different parts of the laser beam at the beam-splitter. This also causes requirement of large diameter optics
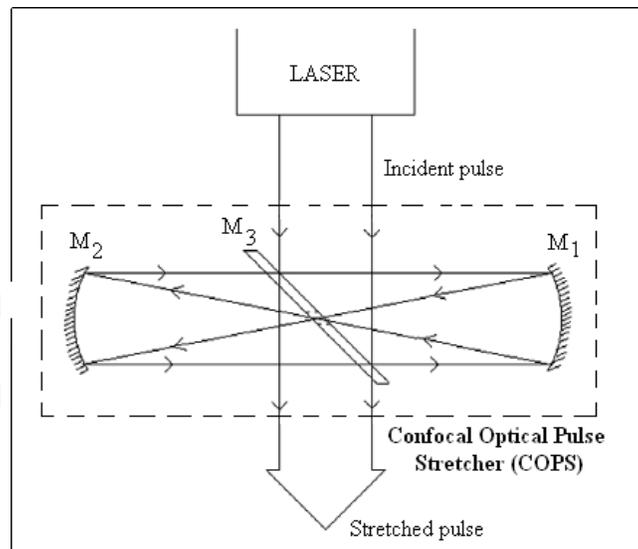
Fig. 2. Schematics of the confocal optical pulse stretcher (COPS). M_1, M_2: 100% reflecting concave mirrors of equal focal lengths; M_3: partially reflecting plane mirror with a hole at the center (scraper beam-splitter).

because the size of the laser beam exiting from the pulse stretcher becomes significantly larger than the original size. The large size of the temporally stretched beam requires an additional telescopic optics for reducing the size of the beam to inject it in the amplifier in typical oscillator–amplifier experiments. To overcome these problems a confocal optical pulse stretcher (COPS) was designed where the increase of the beam size due to beam divergence was compensated by the confocal nature of the pulse stretcher (*Khare et al.*, 2009). Irrespective of the beam divergence of the laser beam, the sizes of the successive parts of the beams remain same at the beam-splitter in the COPS, which ensures perfect spatial overlapping of laser pulses and also removes the requirement of additional telescopic optics. The optical configuration of the COPS is shown in Fig. 2. Two 100% reflecting concave mirrors M_1 and M_2, of equal focal lengths, *f*, are used to form confocal cavity of COPS. A partially reflecting plane mirror with a hole at the centre (scraper beam-splitter), M_3, is used as a beam-splitter in the COPS. The central hole of M_3 is made at an angle of 45° with respect to normal to the surface and M_3 is configured at the common focal plane at an angle of 45° with respect to the axis of the confocal cavity of the COPS. The COPS is configured such that the laser beam falls on M_3 at angle of 45° with respect to the normal to the surface. Thus the axis of COPS becomes perpendicular to the direction of propagation of the laser beam. The beam-splitter, M_3 splits the incident laser beam in two parts such that the transmitted part goes out of the COPS while the reflected part traverses towards M_1. The concave mirror, M_1, reflects and focuses the beam. The focused beam passes fully through the hole of M_3 without obstruction because M_3 is configured at an angle of 45° to the axis of COPS at the focal plane and the hole is also made at an angle of 45° with respect to normal to the surface of M_3. The hole removes the problems of mirror damage by the focused beam. After passing through the hole of M_3, the beam diverges and falls on M_2, which reflects and collimates the beam. The scraper beam-splitter, M_3, reflects a part of the beam out of COPS, which gets combined with the earlier transmitted beam. The part of the laser beam, which was transmitted by M_3, falls on the mirror M_1 again and the process repeats. The optical delay time, τ, is the round-trip propagation time of COPS and is given by

$$\tau = 4f/c \qquad (3)$$

where c is the speed (i.e., group velocity) of light in air. The intracavity leakage rate of COPS depends on reflectivity of M_3 only, if absorption losses of M_3 are zero. Suppose the reflectivity of M_3, whose absorption losses are zero, is R% and p(t) is the instantaneous power of the pulse, which is incident on COPS, then M_3 divides the pulse such that transmitted part (1–R)p(t), goes out of COPS and reflected part, Rp(t), circulates inside COPS. The process repeats and the COPS divides an initially large amplitude laser pulse into many smaller amplitude pulses such that the successive pulses exiting from the COPS are temporally shifted with respect to the initial pulse by τ, 2τ,. . ., nτ, where n is an integer representing the number of round trips in the cavity. The integrated instantaneous power of the pulse, obtained as the output of the COPS is given by

$$
\begin{aligned}
P(t) &= (1-R)p(t) + R^2 p(t-\tau) + R^2(1-R)p(t-2\tau) + R^2(1-R)^2 p(t-3\tau) + R^2(1-R)^3 p(t-4\tau) \\
&\quad + R^2(1-R)^4 p(t-5\tau) + \cdots + R^2(1-R)^{n-1} p(t-n\tau) + \cdots \\
&= (1-R)p(t) + \sum_{n=1}^{\infty} R^2(1-R)^{n-1} p(t-n\tau)
\end{aligned}
\qquad (4)
$$

In Eq. (4), the 1st term is initial transmission of M_3, the 2nd term is reflection of M_3 after 1st roundtrip, the 3rd term is reflection of M_3 after 2nd roundtrip, and so on. The temporal stretching of pulses by COPS of fixed length is determined by the reflectivity of M_3. The reflectivity of M_3 is chosen such that more number of terms of Eq. (4) are effective such that energy content of the successive pulses, exiting from COPS, are significant to contribute effectively to have maximum temporal stretching. A simple reasoning indicates that the temporal stretching of the pulse would be a maximum for that value of R of M_3, which splits the pulses such that the energy content of the later split pulses are more than the earlier spilt pulses. In case of COPS, the condition that the 2nd split pulse has more energy than the 1st split pulse is given by

$$R^2 > (1-R) \implies R^2 + R - 1 > 0 \implies R > 0.62 \qquad (5)$$

The condition that the 3rd split pulse has more energy than that of the 2nd split pulse is given by

$$R^2(1-R) > R^2 \qquad (6)$$

However, Eq. (6) cannot be satisfied for any value of R lying in the range 0 < R < 1. In fact, it is evident from Eq. (3) that the nth split pulse cannot have more energy the (n–1)th pulse for all values of n except for n = 1. The value of R, which provides maximum energy in the 3rd split pulse, is given by

$$\frac{\partial}{\partial R}\left[R^2 (1-R) \right] = 0 \implies R = 0.67 \qquad (7)$$

The value of R, which provides maximum energy in the 4th split pulse, is given by

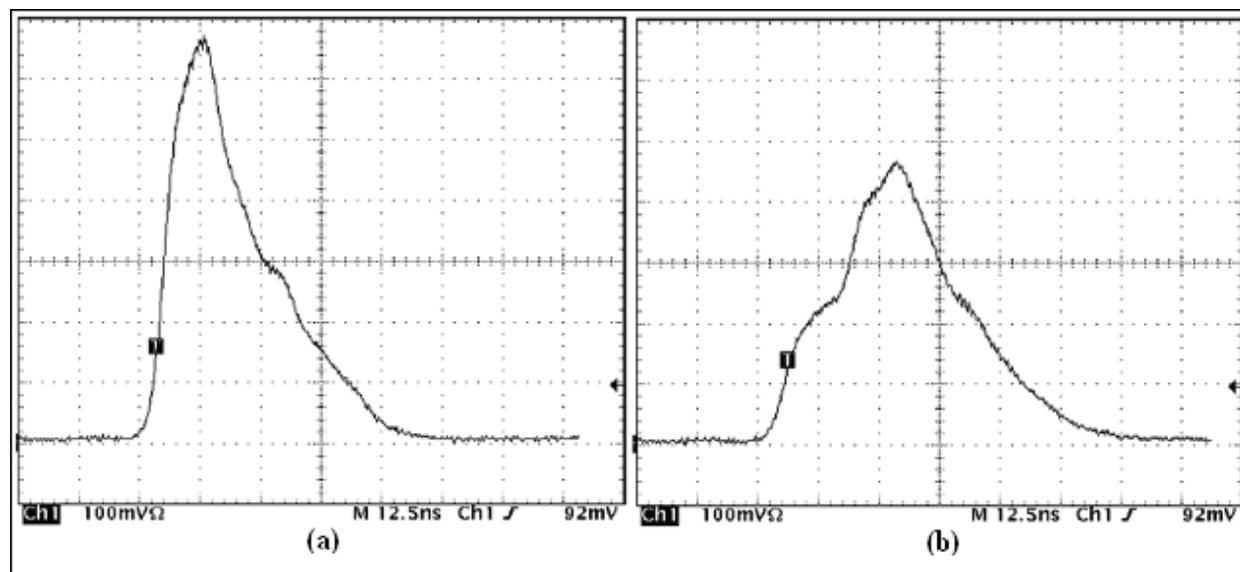$$\frac{\partial}{\partial R}\left[R^2 (1-R)^2 \right] = 0 \implies R = 0.5 \qquad (8)$$

Fig. 3. Incident pulse (a) and stretched pulse (b) of the copper vapor laser by the COPS.

The value of R, given by Eq. (8) clashes with earlier requirements, given by Eq. (5). Therefore a value of R = 0.5 would not allow the 2nd split pulse to have more energy than 1st split pulse and the 3rd split pulse would have only 12.5% of incident pulse energy. Furthermore in this case, the energy of the 4th split pulse would be only 0.0625% of incident pulse energy, which would not contribute significantly in the process of pulse stretching. Consequently the value of R = 0.5 would not result in optimum stretching of the incident pulse. The value of R = 0.67 of M_3 would provide maximum stretching of incident pulse by COPS. Fig. 3 shows the performance of a COPS, consisting of two 100% reflecting concave mirrors of focal lengths 1.0 m each and a scraper beam-splitter of 70% reflectivity, which stretched a 40 ns pulse of a copper vapor laser to 55 ns, without loss of pulse energy (Khare *et al.*, 2009).

The ABCD matrix of the COPS for each roundtrip is given by

$$\begin{pmatrix} 1 & f \\ 0 & 1 \end{pmatrix}\begin{pmatrix} -1 & 2f \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 1 & f \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad (9)$$

The RHS of Eq. (1) is a unit matrix with a negative sign. Thus the size of the beam remains unchanged in COPS in each round trip but the spatial profile is inverted. A two fold 1:1 imaging at the beam splitter of the pulse stretcher can be implemented by using 4f confocal arrangement of four concave mirrors of equal focal lengths, aligned in the off axis configuration and a partially reflecting plane mirror as the beam splitter. This configuration ensures complete true-sided overlap of the spatial profile of the delayed pulses with the original pulse at the beam splitter. A 4f confocal pulse stretcher, consisting of four concave mirrors of focal lengths 1.5 m and a beam splitter of reflectivity 60%, stretched the 24 ns pulse of an ArF excimer laser to 60 ns (Burkert *et al.*, 2010).

Most of the optical pulse stretchers use beam-splitters and mirrors in an optical ring-cavity to obtain a temporally stretched laser pulse. The optical fibers, which are very convenient tool for transmission of laser beams, can also be used in place of beam-splitters and mirrors to design a passive optical pulse stretcher. The optical fibers of different lengths are bundled together at both ends. In this configuration of optical fibers, a single laser pulse, injected at

one end of the fiber bundle would be split spatially into many parts among the various fibers and each fraction would traverse a different length of optical fiber to reach at the other end. At the other end of the bundle, the optical fibers are grouped together and the parts of the laser pulse are recombined spatially into a single beam. Therefore a laser pulse, which is injected at one end of bundle of optical fibers, would emerge from the other end as a temporally stretched pulse. This optical pulse stretcher is flexible and its efficiency is limited primarily by the core-to-cladding ratio of the fibers and packing density of the bundle. Two optical pulse stretchers consisting of a bundle of 80 optical fibers of core diameter of 200 μm and outside diameter of 230 μm, with lengths varying from 0.5 to 4.0 m and 0.5 to 8.0 m at an increment of 0.5 m, provided a temporal stretching of 15 ns and 30 ns respectively with 40% transmission efficiency (Hanna & Mitchell, 1993).

Prisms, instead of mirrors, can also be configured to introduce an optical delay in a passive optical pulse stretcher. When a laser beam falls on a prism, a part of the beam is reflected and the remaining part is transmitted through it. The prisms can be arranged in such a way that the transmitted parts of laser beam traverse a closed path and then join the earlier reflected as well as transmitted parts. This configuration of prism generates partial pulses from the original laser pulse and introduces optical delays between them to provide a temporally stretched pulse. The reflectivity of the prism surfaces, the angle of incidence of the laser beam on the prism, polarization selectivity of the glass/air, the physical dimensions of the prisms and their separation are the key parameters, which determine the stretching factor. Here the dispersion characteristics of the prism, which play an important role in dispersive pulse stretchers, are not used. The 100 ps pulses of a mode locked Nd:YAG laser were stretched to 200 ps by a passive optical pulse stretcher using a pair of prisms, which formed a unidirectional light loop based on total internal reflections and polarization selectivity of the glass/air interface (Tóth, 1995).
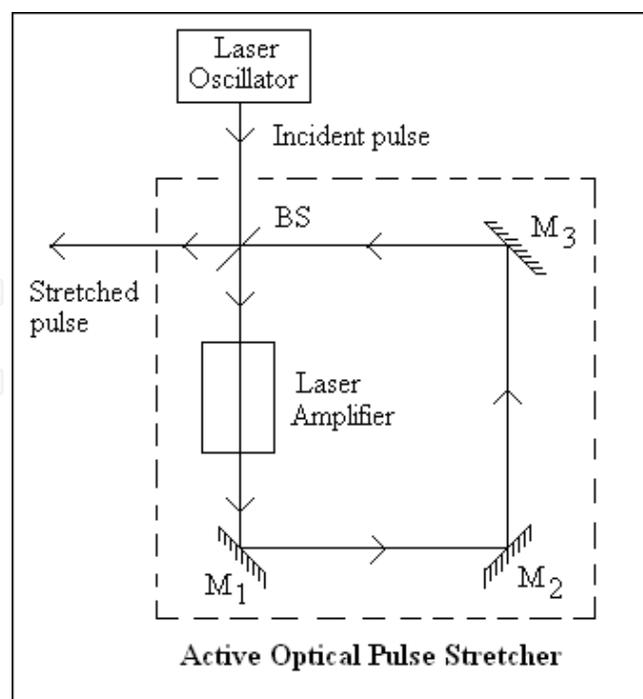

Fig. 4. Schematics of the active optical pulse stretcher. M_1, M_2, M_3: 100% reflecting plane mirrors; BS: Beam-splitter.

Generally the optical pulse stretchers operate in the passive mode, however the optical pulse stretchers can be configured in active mode also by providing gain inside the ring cavity. The optical configuration of an active pulse stretcher that incorporates a laser amplifier is shown in Fig. 4. Thus the ring cavity of the active pulse stretcher divides the initial large amplitude laser pulse from the laser oscillator into many smaller amplitude laser pulses and releases them over a longer period of time in such a way that each part is amplified by the laser amplifier. The amplified pulses, which are released over a longer period of time, are recombined at the beam-splitter. The active pulse-stretchers are more effective in comparison to passive pulse stretchers in temporal stretching of incident pulses due to inherent amplification of each part during successive roundtrips in the ring cavity. An active optical pulse stretcher of cavity length of 6 m, applied to copper vapor laser MOPA system, temporally stretched the 18 ns (FWHM) oscillator pulse of 510.6 nm to 80 ns (FWHM), while a similar passive optical pulse-stretcher under identical conditions provided temporal stretching to 50 ns only (*Kundu et al.*, 1995).

2.2 Pulse stretching by intracavity nonlinear materials

Temporal pulse stretching by intracavity nonlinear materials are used in Q-switched lasers for incresaing the duration of laser pulses. The Q-switched lasers emit pulses of durations of several tens of nanoseconds. In these nonlinear materials, the absorption of light increases more than linearly with increasing intensity of light. The absorption as a function of laser intensity of a typical nonlinear absorber is shown in Fig. 5. If such a nonlinear material is inserted in the cavity of a Q-switched laser, the intracavity losses increase nonlinearly with building up of photon flux, which prevents rapid depletion of inverted gain population. The existence of gain for a prolonged period in a Q-switched laser leads to temporal pulse stretching of the laser pulses with reduced peak powers. The optical process, which gives rise to nonlinear absorption in the material depends upon the material used and the intensity of the laser within the cavity. The nonlinear mechanism increases the nonlinear losses with increasing intracavity power and thus limits the power and lengthens the pulse duration, whereas the output energy remains constant under ideal conditions. There are several nonlinear optical mechanisms, such as two-photon absorption, excited-state absorption, harmonic generation, parametric oscillation, polarization ellipse rotation, stimulated scattering processes including Rayleigh, Raman and Brillouin, etc., which introduce nonlinear absorption in the materials.
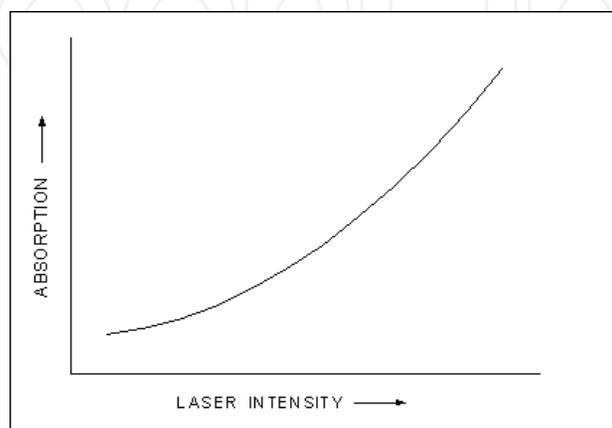

Fig. 5. The absorption characteristics of a nonlinear absorber.

The two-photon absorption (TPA) is a nonlinear optical process in which two photons are absorbed simultaneously, such that the energy of the photons adds up to the energy of the excited atom or molecule. The rate of TPA is proportional to the square of the radiation intensity. The pulse duration of a Q-switched laser has been increased by insertion of a two-photon absorbing semiconductors in the laser cavity. An important advantage of the two-photon nonlinearity in semiconductors is its localized nature and instantaneous response, which not only lengthens a pulse but also smoothens out its spatial and temporal inhomogeneities. A theoretical and experimental investigation confirmed that the pulse stretching of a Q-switched ruby laser by insertion of a CdS crystal in the cavity was due to the two-photon absorption in CdS (Hordvik, 1970). The pulse durations were increased by one to two orders of magnitude by two-photon absorption in the nonlinear optical crystals of GaAs and CdS in the laser cavities of Q-switched Ruby and Nd-glass lasers respectively (Schwartz et al., 1967). The pulse stretching depends on the nature of the nonlinear losses and on the rate of Q-switching. The insertion of nonlinearly absorbing semiconductors CdP_2 and ZnP_2 into the resonators of ruby and neodymium lasers increased the pulse durations by different amounts. The 20 ns pulses of ruby laser were increased to 360 ns and 290 ns by CdP_2 and ZnP_2 respectivly while the 25 ns pulses of neodymium laser were increased to 190 ns and 150 ns repectively (Lisitsa et al., 1974). The pulse duration of 30 ns of Q-swiched ruby and neodymium lasers were stretched to continuously variable duration up to 350 ns and 400 ns respectively by insersion of two-photon absorbing semiconductor plates, cut from single crystals of CdS and CdSe, at Brewster angle in the respective cavities (Arsen'ev et al., 1972). The use of readily available semi-insulating form of GaAs as a two photon absorber in a Q-switched Nd:YAG laser stretched the pulses from 30 ns to 150 ns while high-purity n-type GaAs stretched the pulses up to 1.5 μs (Walker & Alcock, 1976). The solution of Rhodamine 6G was used as a two-photon absorber in the cavity of a Q-switched Nd:glass laser and a pulse stretching of about 8 times (FWHM ~ 350 ns) of 45 ns pulse was obtained (Bergamasco et al., 1993). A crystal of ZnSe was used as a two-photon absorber in a Q-switched alexandrite laser (λ = 750 nm) to achieve temporal stretching of pulse-widths (FWHM) up to 1.7 μs of 5 ns pulses (Rambo et al., 1999). The excited state absorption (ESA) is a nonlinear optical process in which the absorption cross-section of an excited state is more than that of the ground state and the rate of ESA increases nonlinearly with the radiation intensity. Insertion of a single crystal of GaAs at the Brewster angle in the cavity of a Q-switched Nd:glass laser produced temporal pulse stretching with greater spatial homogeneity due to ESA (Schwarz et al., 1967).

The second harmonic generation (SHG) is a nonlinear optical process, in which a radiation interacts with a nonlinear material to generate a radiation with twice the frequency of the incident radiation. The nonlinear crystal inside the cavity of the Q-switched lasers acts as a variable output coupler due to the nonlinear power conversion from the fundamental wave to the second harmonic. The second harmonic generation by the intracavity nonlinear crystal introduces nonlinear power dependent internal loss, which leads to temporal pulse stretching of the laser pulses. In applications where the desired output is the second harmonic of the pumping laser, this approach is particularly advantageous because the pulse stretching is achieved at no expense in output energy (Murray & Harris, 1970). A lithium iodate ($LiIO_3$) crystal was placed inside the cavity of a Q-swiched Nd:YAG laser, operating at 0.946 μm, to provide both output coupling and an easily adjustable, nonlinear loss mechanism for stretching pulses in the range of 200 ns to 1 μs at 0.473 μm at constant

energy (Young *et al.*, 1971). A temporal pulse stretching in the range of 100 ns to 2 μs was obtained in a Q-switched Yb:YAB laser by self frequency doubling in the Yb:YAB crystal itself (Dekker *et al.*, 2005). The temporal pulse stretching to durations (FWHM) 650 ns and 3.2 μs was achieved without significant loss of pulse energy in a Q-switched Nd:YLF laser by using the effect of overcoupled intracavity second harmonic generation with intracavity KTP crystals of lengths 5 and 10 mm respectively while the pulses were stretched to 600 ns and 1.5 μs by the intracavity LBO crystals of lengths 10 and 20 mm respectively in the same set-up (Kracht & Brinkmann 2004).

The polarization ellipse of a laser beam rotates as the laser beam propagates through a nonlinear medium (Maker & Terhune, 1965). The rotation arises from the tensor nature of the third-order nonlinear susceptibility and the magnitude of the rotation increases with increasing laser intensity. The induced optical birefringence and ellipse rotation is used for intensity-dependent intracavity loss in Q-switched lasers to slow down the release of optical energy from the laser cavity. The field-induced loss limits the cavity intensity and consequently the excess energy stored in the inverted population appears in the form of a longer pulse. To use the rotation of polarization ellipse as an inducible loss in the laser cavity, a nonlinear device, consisting of an optical nonlinear medium through which intensity-dependent ellipse rotation can occur, a polarizer followed by a retardation plate to elliptically polarize the beam before it enters the nonlinear medium, and an analyzer after the nonlinear medium to observe the ellipse rotation in the nonlinear medium, is used. These elements are arranged in such a way that the cavity loss is a minimum without ellipse rotation. As ellipse rotation increases with the cavity field intensity, transmission through the analyzer decreases, leading to an increase in the cavity loss. A nematic liquid crystal is a transparent liquid that causes the polarization of light waves to change as the waves pass through the liquid. The extent of the change in polarization depends on the intensity of the applied electric field. Pulse stretching was demonstrated in a Q-switched ruby laser by using a nematic liquid crystal EBBA (p-ethoxy-benzylidene-p-butylaniline) as the nonlinear optical ellipse rotation medium in the cavity to introduce intensity dependent cavity loss due to rotation of polarization ellipse (Murphy & Chang, 1977). Stretching of pulses of 70 ns duration by a factor of 4 has been observed by placing liquid crystal MBBA (n-p-methoxybenzylidene-p-butylaniline) in the cavity of a Q-switched ruby laser along with other polarizing elements for self-induced ellipse rotation (Hsu & Shen, 1982).

A light scattering process is said to be stimulated if the fluctuations in the optical properties that cause the light scattering are induced by the presence of the light field. Stimulated light scattering is much more efficient than spontaneous light scattering. The stimulated scattering causes a nonlinear loss at the laser frequency since part of the laser energy is transferred to a different frequency. Stimulated Rayleigh-Wing scattering (SRWS) is the stimulated scattering process resulting from the tendency of anisotropic molecules to become aligned along the electric field direction of an applied optical wave. SRWS leads to the generation of a wave shifted in frequency by approximately the inverse of the orientational relaxation time of the anisotropic molecules (Miller *et al.*, 1990). The 40 ns pulses of a Q-switched ruby laser were temporally stretched to 150-400 ns by introduction of a benzene cell, which acted as a Rayleigh-wing scatterer, into the laser cavity (Callen *et. al.*, 1969). The stimulated Brillouin scattering (SBS) is a third-order nonlinear effect, which arises from the interaction of light with propagating density waves or acoustic phonons. Intracavity stimulated Brillouin scattering (SBS) in hexafluorethane (C_2F_6) was used for

temporal stretching of 60 ns Q-switched pulses from a phase-conjugated Nd:YAG laser to 300 ns (Seidel & Phillipps, 1993).

2.3 Electronic pulse stretching

The technique of electronic pulse stretching is based on electronic feedback circuits, which control the electro-optical devices of Q-switched lasers in such a way that the laser pulses are temporally stretched. This is an active pulse stretching technique, where the electronic feedback loop modifies the switching of the electro-optic shutter to control the temporal losses in the Q-switched lasers. In several Q-switched lasers, an electronic circuit is used to switch voltages to the electro-optical device (Pockels or Kerr cell), placed inside the laser resonator, to produce controllable birefringence. At the beginning of the Q-switching process, the optical resonator is closed (high losses) by applying a high voltage to the electro-optical device for population inversion to reach to a level far above the threshold for normal lasing action. Then the voltage applied to the electro-optical device is removed to restore the high Q of the cavity and consequently the stored energy is suddenly released in the form of a very short pulse of high energy. This short pulse of high energy can be temporally stretched by applying a negative feedback to the electro-optical shutter, used for Q-switching, in such a way that its reopening does not remain rapid and the stored energy is released for a longer duration. This is the basic principal of operation of the electronic pulse stretchers. The block diagram of a simple feedback controlled electro-optical circuit for electronic pulse stretching of a Q-switched laser is shown in Fig. 6. The Q-switched laser consists of a gain medium, G, polarizing optics, PO, and the electro-optical device, EO. The mirrors M_1 (100%) and M_2 (partially transmitting) form the optical cavity of the laser. The gain medium is optically pumped by a flashlamp. A beam-splitter, BS, is inserted in the optical cavity of the Q-switched laser to direct a small part (5% to 10%) of the intracavity photon flux into a photodiode, PD. R is the load resistor. Negative feedback on the circulating power is applied through the action of the photodiode derived voltage on the electro-optical device, EO. In this way the stored energy in the gain medium, G, is released at a controlled rate.
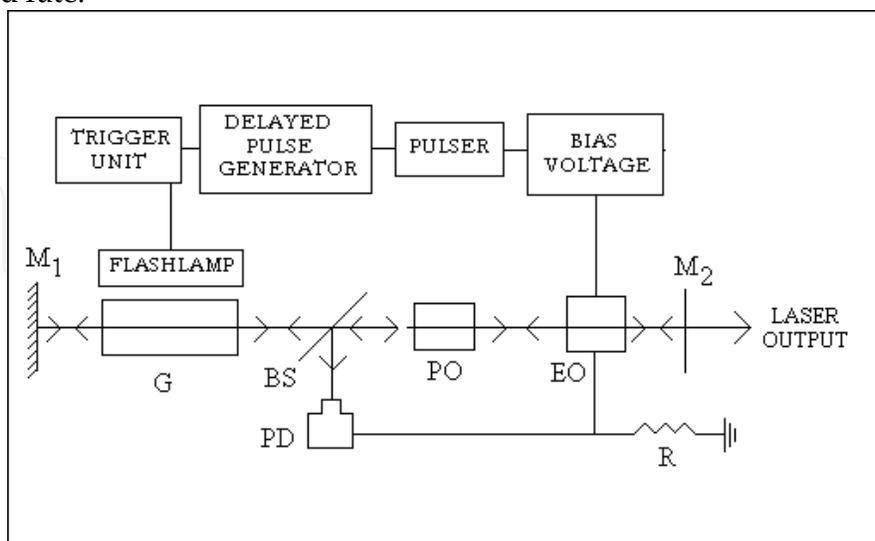

Fig. 6. Block diagram of an electronic pulse stretcher. G: gain medium of the Q-switched laser; PO: polarizing optics; EO: electro-optical device; M_1, M_2: resonator mirrors; BS: beam-splitter; PD: photodiode; R: resistor.

Several designs of electronic circuits with sophisticated feedback loops have been designed to regulate the voltages on the electro-optical devices for temporal stretching of pulses of the Q-switched lasers. A feedback circuit connected to the Kerr cell of a Q-switched ruby laser was used to temporally stretch pulses of 5 ns duration to 5 μsec (Thomas & Price, 1966). The most promising of this kind of active pulse stretching techniques use a compound feedback circuit with negative and positive feedbacks to have stretched pulses of desired shapes. This allows the laser oscillation to build up, and a sustained laser action is ensured by the balance between the negative and positive feedbacks. These techniques are quite sophisticated and circuit parameters are highly optimized because the net high voltage applied to the Pockels or Kerr cell must follow precisely a prescribed waveform. A 40 ns pulse of a Q-switched ruby laser was stretched to a flat-top pulse of 240 ns by using a compound control circuit having negative and auxiliary positive feedback loops having a photodiode, a KD*P (potassium dihydrogen phosphate) Pockels cell, a Krytron switch, and the optimized values of inductance and shunt capacitance (Lovberg et al., 1975). An electronic feedback circuit with controllable parameters of resistance across the photodiode, Pockels cell bias voltage, Pockels-cell open time, and delay time of the delay pulse generator resulted in stretching the 200 ns pulses a Q-switched Nd: glass laser to 50 μs pulses of smooth near-rectangular shape and otherwise stretchable up to 400 μs (Panarella & Brdley, 1975). The pulses of a Q-switched Nd:YAG laser with an intracavity polarizer, a quarterwave plate, and a Pockels cell driven by a high voltage planar triode were temporally stretched from 30 ns to 650 ns with flatness within ±7% for 505 ns by a dual feedback circuit, which provided sufficient feedback to put the cavity above threshold, but keeping the cavity Q low enough to generate a pulse with a moderate growth rate (Schmid, 1980). A compound feedback circuit and a clamping circuit, comprising of a vacuum photodiode and thyristors as switching elements, were used to control the voltage on a Pockels cell of a flashlamp pumped Q-switched ruby laser oscillator for stretching its 30 ns pulses to flat pulses of durations up to 100 μs by varying the oscillator voltage, Pockels cell voltage, clamping circuit voltage and the delay between firing of the flashlamp and opening of the Pockels cell (Harigel et al., 1986). A closed loop controller circuit with feedback and feedforward portions was designed to apply voltages of appropriate waveforms to the opposite sides of the Pockels cell of a Q-switched ruby laser to stretch its pulses of 30 ns (FWHM) duration to fairly flat pulses with adjustable duration between 200 ns to 16 μs (Verluyten et al., 1990). A pulse stretching circuit, consisting of a pin photodiode, a transimpedance amplifier, a derivative element, a push–pull amplifier, and field effect transistors in the feedback loops, controlled the net voltage on the Pockels cell of a Q-switched ruby laser to stretch its pulses to durations from 200 ns to 1 μs (Pflüger et al., 1996).

2.4 Pulse stretching by dispersion

In case of ultrashort pulses, the technique of pulse stretching by dispersion is used. A dispersive pulse stretcher is suitable for temporal stretching of ultrashort pulses because the spectral bandwidth of the ultrashort pulses is very large. The dispersive pulse stretcher is a configuration of dispersive optical elements that introduce wavelength dependent optical delays to introduce frequency chirp for temporal stretching of ultrashort laser pulses. The term frequency chirp means temporal arrangement of the frequency components of the laser pulse.
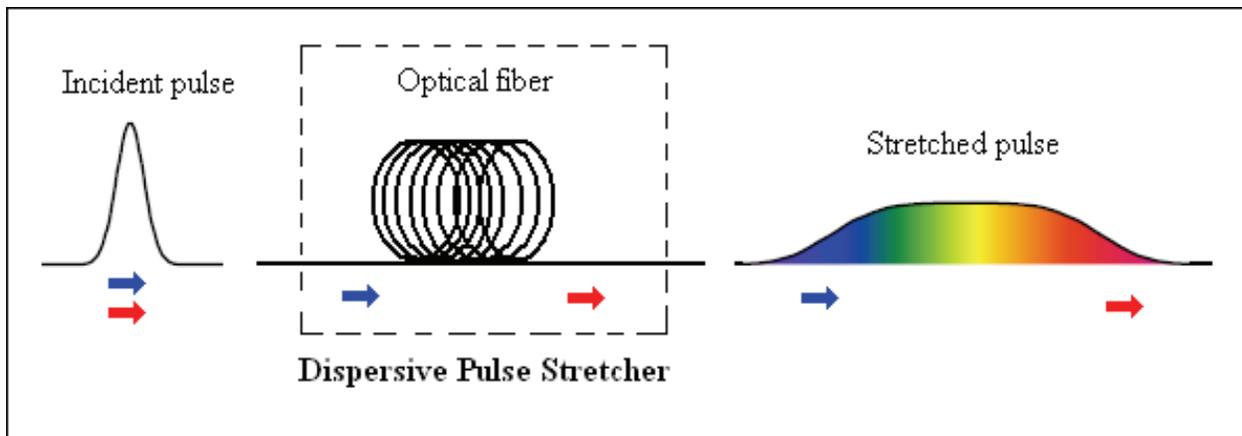
Fig. 7. Schematics of a dispersive pulse stretcher using an optical fiber.

Generally optical fibers or diffraction gratings are used for frequency chirping. In a medium with positive dispersion, the higher frequency components of the pulse travel slower than the lower frequency components and the pulse becomes positively-chirped or up-chirped, increasing in frequency with time. In a medium with negative dispersion, the higher frequency components travel faster than the lower ones and the pulse becomes negatively chirped or down-chirped, decreasing in frequency with time.

A dispersive pulse stretcher using an optical fiber is shown in Fig. 7. In this configuration, the long-wavelength (red) components of the pulse propogate faster than its short-wavelength (blue) components and the pulse is temporally stretched. The effect of pulse stretching in a dispersive pulse stretcher is generation of a 'temporal rainbow' with longer pulse duration and lower peak power. A 1.3 km long single mode silica fiber of 9 μm core was used to temporally stretch 55 ps pulses of Nd:YLF laser to 300 ps across a 3.5 nm bandwidth for chirped pulse amplification (Maine *et al.*, 1988). A multimode optical fiber with length of 50 m and core of 200 μm diameter was used to temporally stretch laser pulse of 160 fs duration of a mode-locked Ti:sapphire laser to nearly 300 ps for combined laser-SR (synchrotron radiation) spectroscopy (Azuma *et al.*, 2001).

Diffraction gratings provide large stretching factors and by using diffraction gratings based dispersive pulse stretchers, ultrashort optical pulses are stretched to more than 1000 times to their original duration. The dispersive pulse stretcher, shown in Fig. 8, is based on parallel configuration of a pair of gratings, G_1 and G_2. The ultrashort pulse, incident on the first grating, G_1, is separated into its component wavelengths. The beams of different wavelengths propagate along different directions in the space between the two gratings. After diffraction by the second grating, G_2, the beams of different wavelengths become parallel but they have traversed different distances. The pulses of longer wavelengths (red) have traversed longer distance in comparison to pulses of shorter wavelengths (blue). Thus the pulses of higher frequency arrive earlier than lower frequency pulses in this configuration of parallel gratings.

The dispersive pulse stretcher, shown in Fig. 9, consists of two reflection gratings, two achromatic lenses and a retro-mirror pair. In this arrangement the two gratings, G_1 and G_2, are aligned in anti-parallel configuration. Between the gratings, the two lenses, L_1 and L_2, of equal focal lengths, *f*, are placed at a distance *2f* from each other to form a telescope of magnification 1. The telescopic arrangement is used to ensure that the dispersing radiation returns parallel after passing the two dispersive gratings. The telescope reverses the sign
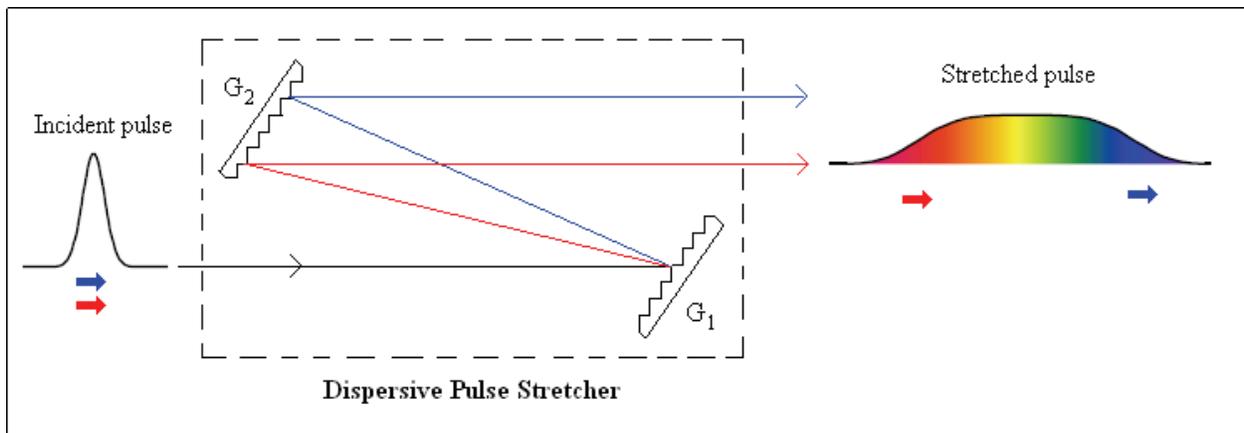
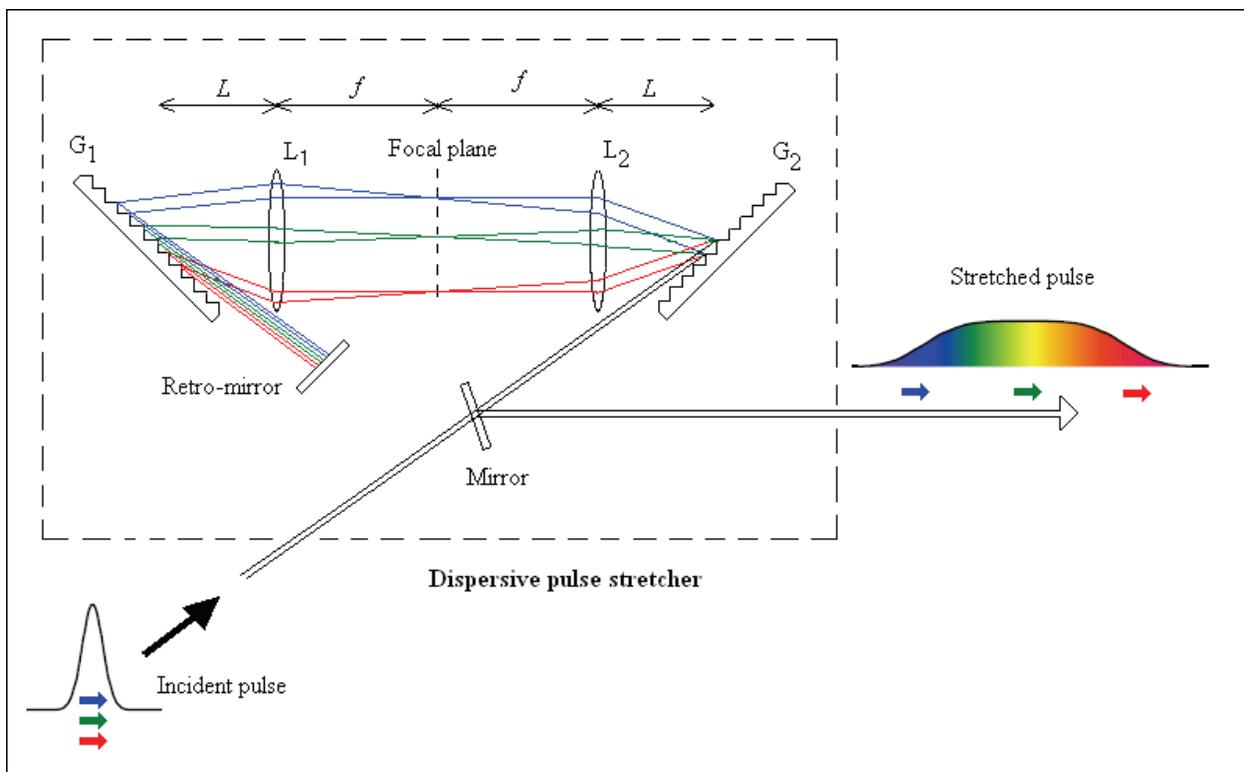Fig. 8. Schematics of a dispersive pulse stretcher with a pair of parallel gratings. G_1, G_2: gratings.

Fig. 9. Schematics of a dispersive pulse stretcher with a pair of anti-parallel gratings. L_1, L_2: lenses of focal lengths f; G_1, G_2: gratings.

of the angles so that the beams will meet the second grating at the same angle as they leave the first one. This arrangement provides positive dispersion if the lenses are placed at a distance L from the gratings such that $L < f$ (Martinez, 1987). In this configuration of gratings, the pulses of longer wavelengths (red) traverse shorter distances in comparison to pulses of shorter wavelengths (blue). The retro-mirror is used for retro-reflecting the dispersed beam back in the optical arrangement for removing the lateral walk and also to retain the beam shape. The double pass arrangement increases the pulse stretching by two-fold. This type of dispersive pulse stretcher was used to temporally stretch laser pulses of

duration 250 fs (FWHM) from a Nd:flouro phosphate glass oscillator to 240 ps (FWHM) by placing a pair of identical holographic gratings (groove density = 1740 l/mm) symmetrically outside of two identical achromatic lenses (focal length = 500 mm) at a distance of 250 mm and using a retro-reflector to obtain a linear chirp of 44 ps/nm at central wavelength of 1054 nm (Sharma *et al.*, 2005).

3. Significance of temporal stretching of laser pulses

The temporal stretching of laser pulses plays a significant role in many applications of pulsed lasers. The necessity of temporal pulse stretching in certain applications of pulsed lasers along with use of different laser pulse stretchers is discussed.

Temporal pulse-streching of the laser beam from master oscillator is required in master oscillator power amplifier (MOPA) systems, which are used to obtain high power with good beam quality and good efficiency. In the MOPA system, the beam quality (linewidth, divergence, coherence, etc.) of the laser beam is controlled by the master oscillator while the amplifier is used to increase the power of the beam. Generally the pulses of the oscillator are temporally shorter than the amplifier pulses and this leads to incomplete overlap of oscillator pulses with the duration for which gain is available in the amplifier. Consequently the MOPA system suffers from poor extraction efficiency along with generation of amplified spontaneous emission (ASE), which degrades the beam quality of the amplified output. Thus a laser pulse stretcher is generally configured in a MOPA system for achieving maximum extraction efficiency and elimination of amplifier ASE. A passive optical pulse stretcher was used in the MOPA system, which increased the output from 18 W to 25 W along with elimination of ASE because of increase of duration of oscillator pulses from 34 ns to 50 ns (Amit *et al.* 1987). A passive optical pulse stretcher was configured in a MOPA chain, consisting of an unstable oscillator and two amplifiers, to obtain an output of 50 W due to stretching of pulses of the copper vapor laser to 72 ns (Kumar *et al.* 1995).

In dye lasers pumped by pulsed lasers, the temporal stretching of pump laser pulses increases the energy conversion efficiency and tuning range of the dye laser along with a decrease in its linewidth. The linewidth of the dye laser output depends mainly on the passive linewidth of the resonator and the number of roundtrips taking place in the resonator (Khare *et al.*, 1995). The number of round-trips depends upon the pulse duration of the pump laser. A passive optical pulse stretcher was configured in a copper vapor laser pumped dye laser system to stretch the pulses of copper vapor laser from 60 ns to 72 ns, which resulted in increasing the pulse duration of dye laser from 20 ns to 28 ns and this led to increasing the energy conversion efficiency and spectral tuning range of the dye laser from 8% to 10%, and 37 nm to 47 nm respectively along with decreasing the linewidth from 0.08 cm^{-1} to 0.06 cm^{-1} (Singh *et al.*, 1995). The temporal stretching of the pump laser by a passive optical pulse stretcher in a copper vapor laser pumped dye amplifier, not only increased the extraction efficiency of the amplifier but also smoothened the pulse shapes due to increase in tolerance on synchronization between pump and signal pulses (Singh *et al.*, 1994).

The temporal stretching of the pump laser pulses is done in the experiments of pulsed amplification of a continuous-wave (cw) laser, which combines the power of the pulsed laser with the spectral qualities of the cw laser. The temporal stretching of the duty cycle of

the pump laser pulses reduces the linewidth of the amplified pulses. In the pulsed amplification of cw He–Ne laser by a frequency doubled Nd:YAG laser, a reduction in the linewidth of the amplified pulses is obtained by temporal stretching of duration of pump laser pulses (Black & Valentini, 1994). The pulse stretching of the pump laser pulses from 8 ns to 12 ns in the pulsed amplification of cw ring dye laser by a frequency doubled Nd:YAG laser, reduced the bandwidth of the amplified pulses to 130 MHz from 180 MHz (Lee & Hahn, 1996).

The optical fibers are very convenient and useful tool for transmission and delivery of high power laser beams. The key problem in fiber-optic transmission is that the high peak-power beams cannot be coupled into fiber optics because of the damage of the end faces. (Seidel & Phillipps, 1993). The light intensities of Q-switched pulses focused to a diameter of 600 μm reach to 10^{11} W/cm^2 and are beyond the damage threshold of optically polished glass and fused silica (Lowdermilk & Milam, 1981). The material of the optical fiber can be prevented from intensity dependant damages by temporal stretching of laser pulses. The temporal stretching of laser pulses of a Q-switched ruby laser by an electronic pulse stretcher increased the upper limit of transmission of pulse energy by a factor of 4 and pulses of 300 mJ were transmitted in quartz fibers with a 600 μm core diameter without fiber damage (Pflüger et al., 1996). Another disadvantage of high peak-power systems is the reduced applicability for material cutting because high peak power produces plasma on the surface, which absorbs most of the incident energy. A temporally stretched pulse containing the same output energy becomes more efficient for heating the material (Seidel & Phillipps, 1993). Thus the use of stretched pulses permits delivery of full pulse energy at reduced peak power, which not only avoids the damage of the optical fiber but also controls the laser-material interactions for improvement.

Excimer lasers provide nanosecond pulses in the ultraviolet spectral range with high pulse energies. Excimer lasers are widely used for optical microlithography however its high peak power degrades the optical material of the projection lens and adversely affects its imaging property. The high peak intensities lead to breakthrough in gases and damages in optical materials such as lenses and beam splitters. A cumulative damage mechanism is known in fused silica in addition to the well-known single pulse damage threshold (*Burkert et al.*, 2007). Sufficiently high pulse energies far below the single pulse damage threshold can lead to a densification of the glass, which is called compaction (*Liberman et al.*, 1999). Such density variations in a lens cause beam aberrations. Excimer lasers in combination with pulse stretchers provide pulses with lower peak intensity at the same pulse energy. Gas breakthrough and damages in optical materials can be reduced or at least retarded by pulse stretching. The temporal stretching of lasers pulses reduces the peak power and increases the lifetime of the scanner lens (Pätzel & Stamm, 2005).

The Spontaneous Raman-scattering (SRS) spectroscopy with pulsed lasers provides a quantitative measurement of major chemical species concentrations and temperatures in turbulent and chemically reacting flow processes such as combustion. To collect high-quality SRS data in gas phase flows, high-energy pulsed lasers are required to compensate for the weak signal levels generated by the Raman effect. However, high-energy Q-switched lasers often suffer from laser-induced plasma spark generation at the focused probe volumes. The strong optical emission from the plasma spark overwhelms the weak Raman-

scattering signal, making spatially resolved measurements with high-energy Q-switched lasers difficult. The SRS signal is linearly proportional to the total energy of the laser pulse and not the intensity. Thus the SRS signals are measured by reducing the peak-power of the Q-switched laser in such a way that the total pulse energy is maintained. Hence temporal stretching of laser pulses was done in spontaneous Raman-scattering spectroscopy for removing laser-induced plasma spark generation by reducing peak power (Kojima & Nguyen, 2002). Temporal stretching of laser pulses is done by configuring a passive optical pulse stretcher in the coherent anti-Stokes Raman spectroscopy to increase signal-to-noise ratio and to improve precision of the determined temperatures and concentrations while avoiding window damage and laser-induced breakdown (Beyrau *et al.*, 2004).

One of the important applications of lasers is its use in medical sciences. In ophthalmology, the pulses of a Q-switched laser operating in the green spectral region is temporally stretched to obtain microsecond long pulses, which are most suited for to selectively target dysfunctional retinal pigment epithelium (RPE) while preserving the adjacent tissues, especially the photoreceptors and the neuronal retina (Kracht & Brinkmann 2004). The high peak intensities of shorter pulses of Q-switched lasers generally damage the tissues and thus the pulses were temporally stretched by using intracavity pulse stretcher with two-photon absorber (Rambo *et al.*, 1999). The pulse durations are stretched and optimized for lithotripsy (kidney stone fragmentation) and other medical applications.

Pulsed lasers are used in the studies of holographic interferometry. Pulse stretching of Q-switched ruby laser was required to reduce instantaneous power at constant energy to avoid the boiling of the chamber liquid, which adversely affected the quality of the photographs, taken to record high-energy neutrino interactions in bubble chamber holography (Harigel *et al.*, 1986). A remarkable asset of stretched pulses is the considerably increased coherence length compared with the Q-switched operation (Harigel *et al.*, 1986). The lasers are used in creating artificial guide stars for adaptive optics for ground-based astronomy by permitting correction of the optical aberrations due to the atmosphere. Pulse stretching of dye laser pulses was required in the sodium guide star experiment for correcting the adaptive optics system of large astronomical telescopes, which were used to study the effects of atmospheric turbulence. The optical pulse-stretcher stretched the 40 ns (FWHM) pulses of dye laser by a factor of 15 to lower the laser flux and avoid saturation effects in the sodium guide star experiment (Friedman *et al.*, 1992).

The chirped-pulse amplification (CPA) is the most important technique to amplify ultrashort pulses (*Salin et al.*, 1992). In the amplifiers, the peak intensities associated with the ultrashort pulses becomes so high that excessive nonlinear pulse distortions and optical damage take place. Dispersive pulse stretchers are used for temporal stretching of the ultrashort pulses in CPA, where the stretched pulses are amplified to moderate peak power levels to prevent damage of the amplification medium and then the amplified stretched pulses are compressed to its Fourier-transform limit to obtain high peak power pulses.

4. Conclusion

The physics and technology of a wide variety of techniques, developed for temporal stretching of laser pulses, is described. The significance of temporal stretching of laser pulses and their applications in different fields are discussed.

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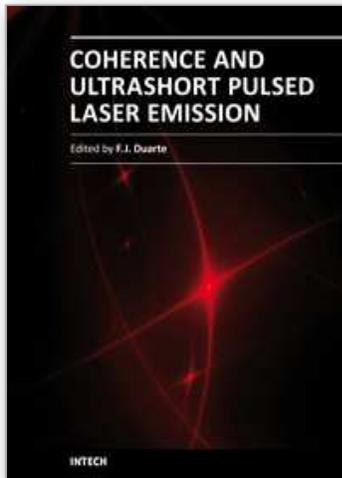
Coherence and Ultrashort Pulse Laser Emission

Edited by Dr. F. J. Duarte

ISBN 978-953-307-242-5

Hard cover, 688 pages

Publisher InTech

Published online 30, November, 2010

Published in print edition November, 2010

In this volume, recent contributions on coherence provide a useful perspective on the diversity of various coherent sources of emission and coherent related phenomena of current interest. These papers provide a preamble for a larger collection of contributions on ultrashort pulse laser generation and ultrashort pulse laser phenomena. Papers on ultrashort pulse phenomena include works on few cycle pulses, high-power generation, propagation in various media, to various applications of current interest. Undoubtedly, Coherence and Ultrashort Pulse Emission offers a rich and practical perspective on this rapidly evolving field.

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