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Ultrashort Pulse Laser Sources

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ULTRASHORT PULSE LASER SOURCES

J. R. Taylor Imperial College London

INTRODUCTION

In the twenty five years since the introduction of the concept of mode locking, the mode locked laser has supplied the source of the shortest pulses available to researchers, which have found application, quite obvoiusly, in time resolved relaxation dynamics in all areas of scientific research. The concept of mode locking will have been introduced in an earlier series of lectures, and in the three lectures to be presented here, particular emphasis will be placed on sources of wavelength tunable, femtosecond pulses, in particular the dispersion compensated colliding pulse passively mode locked dye laser (the source of the shortest pulses, direct from any laser system), the synchronously pumped laser, and the application of optical non linearity in optical fibres in order to extend the available wavelength range of simple sources of femtosecond pulses.

THE CONCEPT OF MODE-LOCKING

In order to derive ultrashort pulses from a laser, the fluorescence or gain bandwidth of the amplifier must be sufficiently broad to support the pulse. For example, the ruby laser has a bandwidth of ~ 0.2nm, Neodymium glass ~10nm, an organic dye ~100nm and the recently developed Titanium doped sapphire laser ~400nm. This would infer that the minimum pulse durations directly obtainable from the lasers would approximately be 10 psec in the case of ruby to potentially 3 fsec from Titanium sapphire! The method of ultrashort pulse generation in lasers, "mode locking" has been used for the past twenty five years [1,2]. During that time, various refinements to the technique have led to the development of laser systems capable of operating in the femtosecond regime.

If one considers the most basic laser system, a gain medium placed between a pair of mirrors, then the range of frequencies over which the laser will operate, is determined by the gain bandwidth of the medium and the loss of the cavity. This is illustrated in figure 1. The frequencies which oscillate are determined by the resonator. These self reproducing field distributions are called the modes of the oscillator. If it is assumed that the laser can be made operate on the lowest order, fundamental, transverse field distribution or mode, then there exists an infinite set of longitudnal modes separated in frequency by c/2L associated with this, where c is the speed of light and L is the optical length of the laser cavity. The number of modes which actually contribute to the laser action is determined by the bandwidth $\Delta\nu_L$ of the laser gain which exceeds the resonator loss, see figure 1.

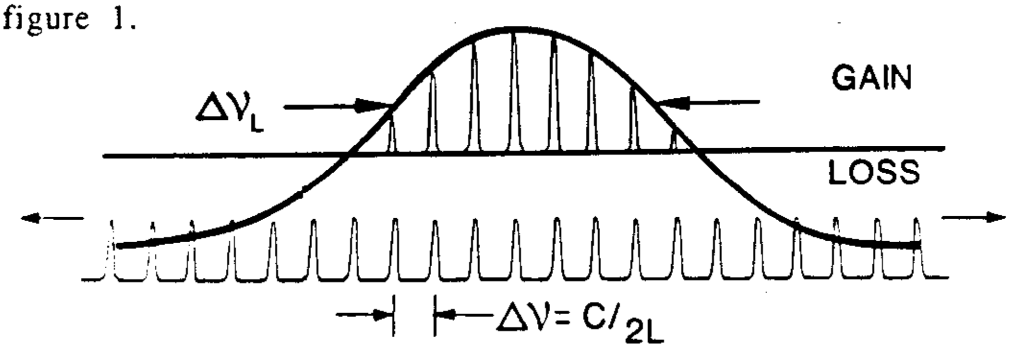

Figure 1 The resonator modes which experience a net gain contribute to the mode locking process

The resultant field of the laser is the integral of all of these modes. In general, the relative phase between the modes is varying randomly, and as such, although the average power of the laser remains relatively constant, the instantaneous intensity of the output will fluctuate randomly, having the characteristic of thermal noise. Figure 2(a) shows for example, the output intensity with time of a laser operating with 101 modes, having a Rayleigh distribution about a Gaussian mean with randomly distributed phases [3]. Under these operating conditions, the duration of the intense spikes is approximately the inverse of the laser bandwidth $\Delta \sim 1/\Delta\nu_L$. If however, the modes are forced to maintain a fixed phase relationship under the gain profile, then Fourier analysis reveals the laser output to consist of a single pulse (see figure 2(b)) of duration also given by the inverse of the bandwidth, occuring with a periodicity of 2L/c, and the laser is said to be "mode locked". Physically this would be equivalent to the situation where at any one time in the cavity, a single pulse would be propagating and the ratio of the cavity round trip time to the pulse width is approximately the number of locked modes.

If one considers a dye laser operating at 600nm, with a typical bandwidth of 5nm and a round trip time of 10ns, there are approximately $4X10^4$ modes which should contribute to a mode locked pulsewidth of approximately 200fs or less.

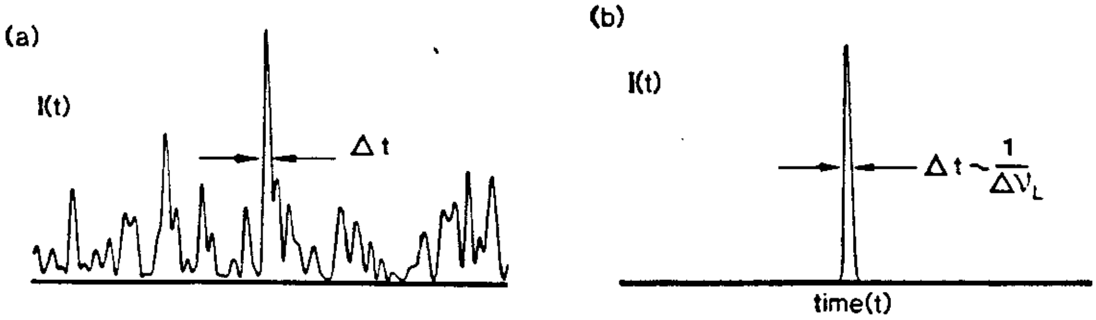

Figure 2 Output intensty with time of a laser operating with, (a) modes exhibiting randomly distributed phases and (b) with a fixed phase relationship between the modes. Note The intensity scales are different.

ACTIVE MODE-LOCKING

The ideal device to mode lock the laser would be one which placed intra cavity, opened at the cavity repetition rate for a time equivalent to the pulsewidth required. Devices of this type operating on a femtosecond time scale have yet to be devised! However, the basic technique used in mode locking has been previously applied to radio and microwaves. If one considers a carrier frequency $\nu_0$and modulates this at a frequency $\Delta\nu$, then sidebands are generated at ν_0 +/- $\Delta\nu$ in phase with the carrier. These cascade out generating further sidebands at ν_0+/- $2\Delta\nu$, and up to ν_0+/- $n\Delta\nu$, with a fixed phase relation. The constructive and destructive interference of these phase locked waves is analagous to the mathematical interference of the components of a Fourier series in the construction of a repetitive pulse train.

In laser cperation, the equivalent situation can be obtained by the introduction of an amplitude or phase modulator into the laser cavity, operating at a frequency equal to, or a sub multiple of, the cavity round trip time. Infact either gain or loss modulation can be applied. The most common element to be used intra cavity is the acousto-optic amplitude modulator [4], which is shown schematically in figure 3(a). In these devices a sinusoidal r.f. drive is applied to a transducer, bonded for example to a quartz block. Often, an intra cavity optical tuning element is used, for example a prism. This launches an ultrasonic wave into the block and a standing wave is set up due to reflection off the opposite face. The standing wave amplitude which is zero twice every ultrasonic period, acts as a Bragg reflector to the laser radiation. When twice the frequency of the applied r.f. is equal to the cavity round trip time then mode locking will build up with a single pulse circulating in the cavity. The pulse evolution takes place around the point where the cavity loss is at a minimum (see figure 3(b)).

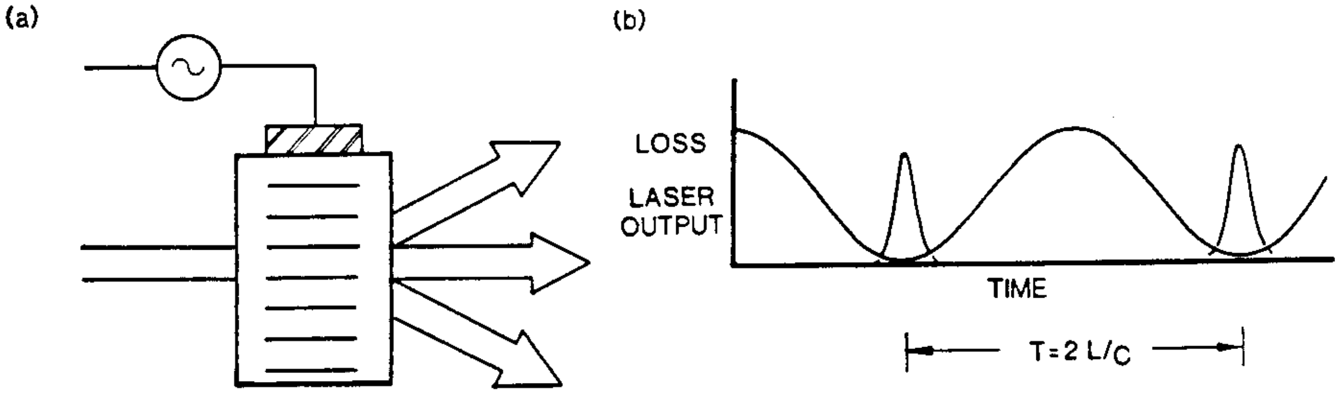

Figure 3 Schematic of (a) the construction and (b) the operation of an acousto-optic amplitude modulator.

Because the sinusoidal modulation gives rise to a weak pulse shaping mechanism, the pulse durations obtained from an actively loss modulated laser are relatively long. Kuizenga [5] has shown that the generated pulse duration is given by

$$\tau_p = \left[\frac{2^{1/2}\ln 2}{\pi}\right]^{1/2}\left[\frac{g_0}{\delta}\right]^{1/4}\left[\nu_m \Delta\nu_L\right]^{-1/2}$$

g_0 is a gain term, δ a modulation term given by $\frac{1}{2}\ln\left[\frac{1}{1-\eta}\right]$ where η is the single pass modulation depth, ν_m the modulation frequency and $\Delta\nu_L$ the laser spectral bandwidth. Clearly the shortest pulses are obtained for wide bandwidth, high frequency, high modulation depth operation. However, typical pulsewidths obtained using this method are of the order 10-100psec and other techniques need to be used to generate pulses of femtosecond durations.

PASSIVE MODE-LOCKING

The technique which has been most extensively developed for the generation of femtosecond pulses is passive mode locking. As the name suggests, no external signal need be applied to the system, negating problems of synchronization of the r.f. drive signal and the radiation propagating in the cavity, which is associated with active mode locking. Most commonly a solution of an organic dye has been used as the passive mode locking element, although gases and solids, in particular semi-conductor multiple quantum well materials, have also been used. The mode locking process requires saturable absorption to take place. This is shown schematically in figure 4(a)-(c).

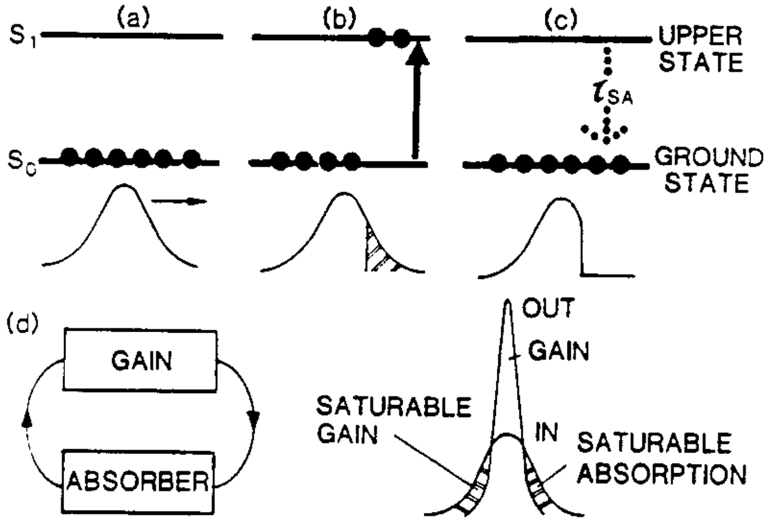

Figure 4 (a)-(c) Schematic of the process of saturable absorption and (d) The mechanism of saturable absorption plus saturable amplification leads to pulse comression.

A burst of radiation is incident on the solution of the dye which is in equilibrium, in the ground state. On absorbing energy from the leading edge of the radiation burst, at a wavelength which corresponds to the ground state to first excited state transition, electrons are promoted into the excited state and the ground state absorption decreases. The dye becomes more transmissive for the intense region of radiation, returning to the ground state with a characteristic relaxation time τ_{SA}. The operation of the material is non linear, with low light levels being absorbed while with saturation the more intense signals are preferentially transmitted. Therefore, when placed intra cavity, a saturable absorber can be visualized as a loss mechanism, automatically adjusting the modulation frequency to the round trip of the laser. Naturally, the relaxation time τ_{SA} has to be less than the cavity round trip time and with no other pulse shaping mechanism taking place, the duration of the generated pulses is primarily determined by the relaxation time of the absorber. Solvent and environmental factors can effect the absorption recovery time of organic dyes in solution, but typically these lie in the range 1-1000psec, depending on dye structure etc. [6].

However, in ultrashort pulse generation from lasers, other processes can contribute to the pulse shortning mechanism. If one considers the gain process, organic dyes have a gain cross section σ $\sim 10^{-16} cm^2$ consequently the saturation fluence $h\nu/\sigma$ is of the order of $mJ.cm^{-2}$. For a solid state laser such as Nd:Glass the saturation fluence is $\sim Jcm^{-2}$. Consequently, gain saturation can readily occur in dye lasers. Considering the pulse shaping mechanism, if after encountering the the saturable absorber, transmitted radiation experiences gain in the laser amplifying medium (see figure 4(d)), the peak of the pulse will see gain. As gain saturation takes place, the trailing edge will see relatively no gain and as a result the pulse will effectively shorten. New[7] first quantified this process, demonstrating that it is essential that saturable absorption occurs before saturable amplification and that for specific ratios of the loss to gain cross sections, stable, short pulse operation occurs. This is defined by New's parameter S defined as $S=R\sigma_A/\sigma_G$ where σ_G and σ_A are the dye gain and absorber cros sections respectively and R is the ratio of the beam areas in the gain and absorber media. For stable mode locking, S must be greater than 2. Consequently, the choice of the parameters of the absorbing dye is critical for short pulse generation, but clearly femtosecond pulses can be obtained with absorbers with relaxation times in the picosecond to nanosecond regime, due to the combined effects of saturable gain and saturable absorption. The first cw pumped passively mode locked dye laser was reported in 1972[8], using Rhodamine 6G as the active laser dye and the cyanine dye 3,3'-diethyloxadicarbocyanine iodide (DODCI) as the saturable absorber. This combination had been previously successfully demonstrated in a pulsed flashlamp pumped system[9]. A typical laser cavity arrangement is shown in figure 5(a).

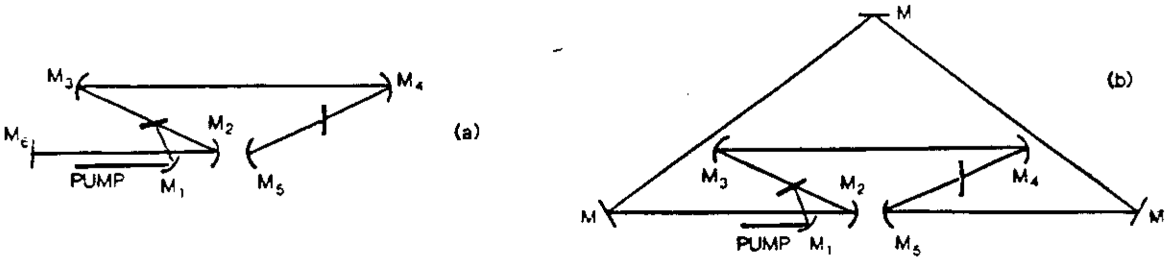

Figure 5 Geometry of cw pumped passively mode-locked dye laser cavities (a) linear and (b) colliding pulse

Pumped by the all lines radiation of a cw Argon ion laser, the pump radiation is focussed into a jet stream of laser dye of about 100 µm thickness placed at the common focal point of the mirror folded section M_2M_3. Both the active and passive dyes are contained in nearly identical jet streams. To ensure preferential saturation of the absorber, generally the spot size in the absorber jet between mirrors M_4M_5, should be smaller than that in the gain medium. The laser cavity is formed by mirror M_6 and the retroreflection off mirror M_5. Using a linear geometry, typical operational pulsewidths are in the range 150fs to 200fs. Up until 1986 however, only the Rhodamine 6G/DODCI combination was used in cw passively mode locked laser systems, severely limiting the wavelength range of operation to around 620nm. Over the past few years the Femtosecond Optics Group at Imperial College have through the characterization of various active/passive dye combinations demonstrated completely tunable operation of cw pumped passively mode locked dye lasers from 480nm to 840nm. These combinations are shown in figure 6 [10], with their tuning ranges indicated and it should be noted that all have the capability to generate sub 100 fs pulses.

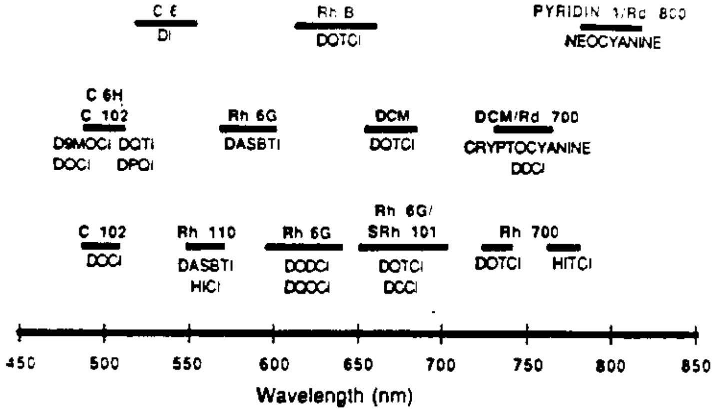

Figure 6 Spectral coverage of cw pumped passively mode-locked dye lasers currently available, showing the individual active and passive dye combinations.

COLLIDING PULSE MODE LOCKED LASERS

Since 1972, the pulse durations obtainable from passively mode locked cw dye lasers have decreased by almost two orders of magnitude. This reduction in the pulse duration has been principally due to improvements in the laser resonator design and to an increased understanding of the limiting processes on femtosecond pulse propagation in the laser cavities. One of the major steps in the development was the introduction of the "colliding pulse mode locked" (CPM) ring laser configuration by Shank and coworkers at Bell Telephone Laboratories in 1981 [11]. A typical CPM cavity arrangement is shown in figure 5(b). The cavity components are similar to those of the linear system , shown in figure 5(a). However, in the CPM configuration pulses travel in both directions around the cavity. Where these oppositely travelling pulses collide at the saturable absorber jet, the energy loss in the system is at a minimum. This scheme is in effect self synchronizing. On the other hand, it is necessary to place the absorber jet approximately one quarter of the cavity round trip time from the gain jet. This ensures the counterpropagating pulses see approximately the same gain, since after the passage of the pulse, the gain has approximately the same time (one half of a round trip) to recover before another pulse encounters gain. The simultaneous collision of the pulses in the absorber while encountering the amplifier at different times gives rise to an effective increase in the mode locking S parameter by a factor of 2. In addition, coherent scattering has also been shown to contribute to the overall pulsewidth reduction.

The colliding pulses set up an absorption grating which coherently scatters light from one pulse into the other. This has been shown to give rise to an increase in the S parameter of 1.5 times. Therefore the CPM laser has an overall enhancement over the identical linear system by a factor of 3. The introduction of the CPM technique allowed for the first time the reliable generation of sub 100 femtosecond pulses. Naturally, all the laser systems listed in figure 6 can operate in CPM configurations.

The attainment of even shorter pulses directly from CPM laser systems came through the realization of the significance of group velocity dispersion and the non linearity, self phase modulation, on the pulse shaping of ultrashort pulses in laser cavities. With the generation of femtosecond pulses, even rather modest pulse energies correspond to high peak powers and at the gain and absorber jets the intensity in the focal region is sufficient to give rise to non linear effects. The main contribution arises from the non linear refractive index. Overall the refractive index can be written as

$$n = n_0 + n_2 I$$

where n_0 is the zero intensity index which is normally experienced, n_2 is the non linear coefficient and I the intensity. The non linear coefficient is dependent on the material, but for the solvents most commonly used in the jets it has a value of order of magnitude 10^{-16}-10^{-15} cm^2W^{-1}. The additional refractive index change gives rise to a phase change

$$\begin{aligned} \Delta\phi &= dn\, K\, L \\ &= n_2 I\, K\, L \end{aligned}$$

where K is the wavenumber $2\pi/\lambda$, and L the thickness of the jet. This time dependent phase shift gives rise to a frequency shift

$$\begin{aligned} \Delta\omega &= -d/dt\,(\Delta\phi(t)) \\ &= -n_2\, K\, L\, dI(t)/dt \end{aligned}$$

Figure 7 shows the frequency shift which is asociated with an input Gaussian pulse, assuming that the response time of the nonlinearity is less than the pulse duration.

The frequency shift is simply governed by the time differential of the intensity profile, such that the front edge of the pulse is frequency down shifted, (wavelength upshifted) while the rear is frequency upshifted. In the central region of the pulse there exists a relatively linear frequency (wavelength) sweep or chirp.

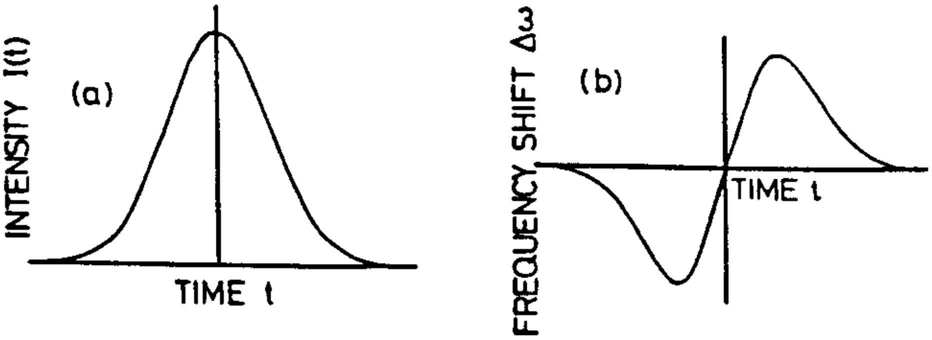

Figure 7. (a) Input pulse and (b) the associated frequency shift due to self phase modulation

The effect of dispersion on pulse duration can be clearly visualized, refering to figure 7(b). Where dispersion is normal, long wavelengths exhibit higher group velocities than shorter wavelengths, consequently the pulses will temporally broaden as the frequency downshifted front of the chirped pulse moves away from the the slower moving frequency upshifted rear.

This intensity dependent spectral broadening is often refered to as self phase modulation, since it can also be seen by reference to figure 7(b), that any one wavelength is present at two times and this gives rise to interference (modulation) effects. Although the nonlinearity gives rise to spectral broadening, hence the potential to support shorter pulses, unless dispersion control is introduced into the cavity, temporally broader pulses will result.

Dispersion control was implemented through the introduction of an intracavity prism sequence into the cavity[12,13]. Clearly it is negative dispersion which is required to counteract the Kerr nonlinearity, ie the shorter wavelength components must exhibit higher gvd such that the temporal profile will tend to compress. Martinez [12] has shown that a prism pair arranged with an entrance and exit face parallel, ie see figure 8, operating at minimum deviation and Brewsters angle in the laser system, can introduce negative group velocity dispersion.

Spectral dispersion occurs in the plane A, which is undone by using the identical mirror image prism pair. However, by placing an aperture in the plane A, tuning of the laser can be achieved. The prism pair provides a fixed amount of negative dispersion, due to the angular displacement and an adjustable positive (or normal) dispersion is added by varying the amount of intracavity glass path, through translating one prism along the axis perpindicular to its base.

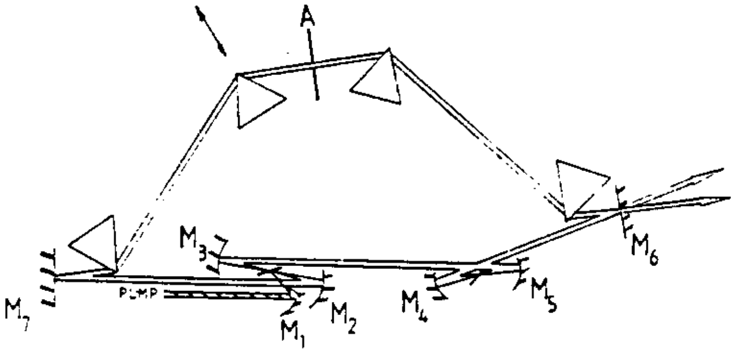

Figure 8. Schematic of the dispersion-compensated, colliding-pulse, mode-locked cw pumped dye laser.

With femtosecond pulses, dispersive reflection off multiple layer dielectric mirrors is also particularly relevant to the design and operation of the ultrashort pulse capability. To obtain the minimum pulsewidths, single stack, dielectric reflectors used near normal incidence are required. Used at an angle, the mirrors can give rise to chirp and introduce spectral limiting and hence broader pulses.

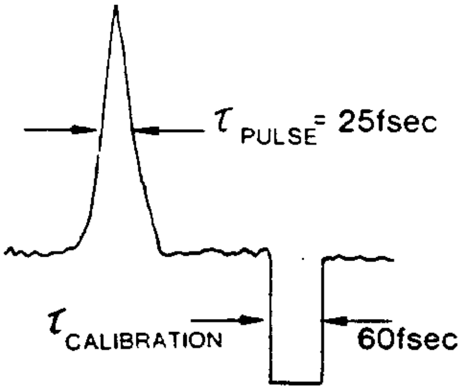

Figure 9. Autocorrelation measurement of a 25 fsec pulse generated in a CPM dye laser (see text).

In a fully optimized and dispersion compensated CPM laser system, pulses as short as 25 fsec can be generated. Figure 10 -

shows an autocorrelation (pulsewidth) measurement of a 25fsec pulse obtained from a laser with rhodamine 6G and Kiton red as the active dyes and DODCI and Malachite Green as the mixed saturable absorbers.

If one wishes to generate pulses which are shorter than those from a particular laser system, that are essentially limited by the amplification bandwidth of the laser or by some other intra cavity bandwidth limiting device, then the operational bandwidth needs to be enlarged and this is generally done by making use of non linear optical phenomena. The most common method is to make use of the fibre-grating compressor and its many variations, which has been described elsewhere in this series of lectures.

SYNCHRONOUS MODE-LOCKING

Probably the most common subpicosecond laboratory laser system is the synchronously pumped dye laser. These provide c.w. trains of subpicosecond pulses, tunable throughout the visible and the near infrared. The technique utilizes a mode locked laser as an optical pumping source. Often an actively mode locked argon ion, krypton ion or frequency doubled Nd:YAG laser act as the master pump source. In recent years, the temporally compressed pulses from the mode locked Nd:YAG and its frequency doubled output, have been used to readily achieve subpicosecond operation with numerous dye laser systems. The technique requires the precise matching of the slave and master laser cavity round trip times. The short pump pulse provides a rapid modulation of the gain and pulse formation is a consequence of both active and passive modulation mechanisms. The leading edge of the dye laser pulse is shaped by the rising gain generated by the short pump pulse, while saturation of the gain, by the generated pulse gives rise to pulse shaping effects on the trailing edge. A schematic of the pulse formation dynamics is shown in figure 10, below. This technique gives rise to substantially shorter pulses than are obtained from weak or sinusoidally modulated sources. The actual pulse durations generated using the synchronous pumping technique are dependent upon the mismatch in the round trip pasage time of the pump and slave cavities and also upon the actual duration of the pump pulse. One advantage of the synchronously mode locked laser is that operation can be achieved in species with extremely short upper state lifetimes (the order of picoseconds) in which true cw laser operation is precluded.

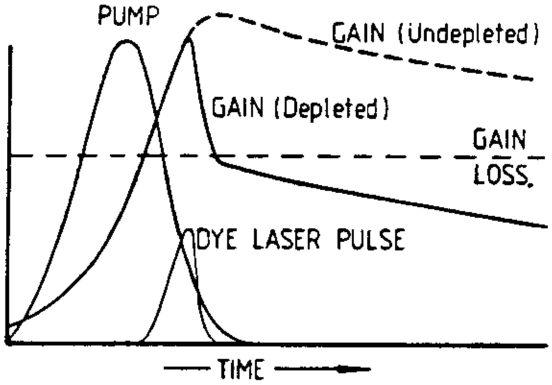

Figure 10 Schematic of the principle of operation of a synchronously-pumped, mode-locked dye laser

Although synchronous mode locking has several advantages, the principal disadvantge is that the pulses tend to be less stable and exhibit significant temporal jitter, relative to what can be obtained using, for example, passive techniques. It has been shown that spontaneous emission plays a dominant role in the dynamics of the synchronously mode locked laser. In particular, when the cavity length is adjusted to achieve the optimally shortest pulse profiles, the pulses are vulnerable to large scale perturbations originating in the weak background noise. At optimum, the circulating pulse advances through the background signal. Phase and amplitude fluctuations of the noise are amplified on the leading edge of the pulse and drift backwards in time through the peak. This results in a noise burst with a Gaussian envelope, which manifests itself in autocorrelation traces as the characteristic cusp-shape profile. These autocorrelations reflect the time average of the continuously fluctuating autocorrelation function.

Lately it has been realized that by injecting into the synchronously pumped laser, a coherent low level signal, which is strong enough to swamp the noise background but weak enough so as not to directly effect the pulse forming dynamics of the laser, then stable low jitter pulses can be achieved. Both theoretical and experimental evidence has confirmed this mechanism [14 -16].

ADDITIVE PULSE MODE-LOCKING

Over the past few years, the technique of "additive pulse mode locking", which was developed both experimentally and theoretically by Blow et al [17,18], has come into prominence. It has been extensively investigated and exploited as a simple method of generating femtosecond pulses, in particular from lasers with low gain cross sections and long upper state lifetimes. Such lasers when mode locked using passive techniques do not exhibit saturable gain and so the generated pulsewidths are essentially limited to the recovery time of the saturable absorber. With additive pulse mode locking dramatic pulse compression can be obtained. A schematic of a typical experimental arrangement is shown in figure 11.

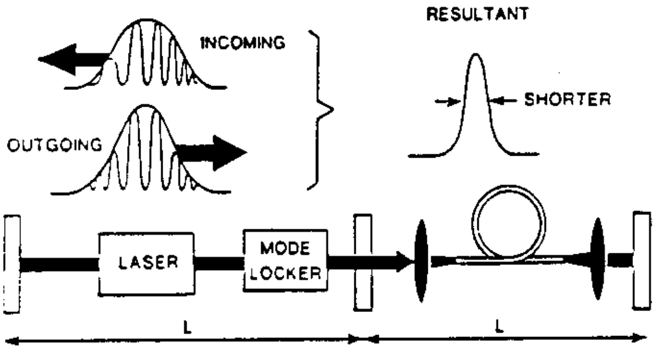

Figure 11 Schematic and basic principle of the additive pulse mode-locking technique.

If one considers for example a laser system mode locked using an acousto-optic mode locker. The pulses generated, typically of the order of 100psec, can be considerably longer than the minimum pulse duration potentially supportable by the laser amplifier bandwidth. If the output from the actively mode locked laser is coupled into a single mode fibre and retroreflected, it will experience self phase modulation, giving rise to a phase shift across the pulse. If the optical length of the external fibre cavity is equal to that of the laser cavity, then the phase distorted, returning pulse will overlap with the next outgoing pulse from the laser. The phase can be adjusted such that the phases of the peaks of the outgoing undistorted and incoming distorted pulses are constructive. The phases in the wings then will be destructive due to the shift caused by the nonlinearity. This interference will result in a temporally shorter pulse which will be amplified, and the process will continue. Clearly the relative phase between the laser and the fibre cavities have to be maintained to an interferometric accuracy. This is carried out by having the non common outside mirror of the fibre cavity mounted on a piezoelectric stack with feedback control. This method has allowed the generation of pulses as short as 70fsec from colour centre lasers [19], but unfortunately, the method is not applicable to dye lasers. As well as phase shifting, non linear polarization rotation can be utilized as an effective mechanism for generating short pulses using the additive pulse mode locking technique.

Recently, additive pulse mode locking has been shown to operate in a passive manner, generating mode locked pulses from a purely cw pumped Ti sapphire laser, coupled to an external fibre cavity. The generated pulses were 1.4 psec in duration and exhibited a chirp which when compensated for using a grating pair external to the laser [22] yielded pulses of 200 fsec. It has also been demonstrated recently that pulses as short as 60 fsecs can be generated directly from a dispersion compensated Titanium doped sapphire laser in the absence even of an external cavity. The technique makes use of the interference of two distinct transverse mode operation in a conventional cw pumped Titanium sapphire laser , generating a mode locked pulse train at the cavity round trip period [21].

FEMTOSECOND RAMAN GENERATION IN FIBRES

For relatively long (the order of 10's-100's picoseconds) pulses of moderate power levels propagating in single mode fibres, stimulated Raman scattering has been shown to be a dominant loss mechanism, with Stokes frequencies being generated with high efficiency. For silica based fibres, the peak of the Raman gainis at a frequency shift of around 440 cm^{-1} [22], with a gain bandwidth of several hundred wavenumbers, such that relatively high Raman gain is possible for substantially smaller frequency shifts. As a result of the gain bandwidth, subpicosecond pulse generation is possible, although dispersion does tend to limit the minimum available pulsewidths. Kafka et al [23] have shown that by including a negatively dispersive grating pair to compensate for the inherent dispersion of the fibre, subpicosecond pulses can be directly obtained from a synchronously pumped fibre Raman ring laser.

The need for a compensating grating pair can be negated through operating in the region of anomalous dispersion, such that soliton shaping takes place. The first proposal for the use of stimulated Raman for the generation of solitons was made by Vysloukh and Serkin [24]. One of the simplest developments of this technique is the single pass soliton Raman generation mechanism [25].

For a pump pulse in the region of the dispersion minimum of an optical fibre, the interaction distance between the pump and the first Stokes can be considerable, giving rise to high Raman conversion efficencies, and pump pulse depletion readily occurs. With the pump pulse in the anomalously dispersive regime, modulational instability [26] can play a major role in the pulse development process. The requirements for modulational instability are similar to those for soliton generation. i.e. nonlinearity, the intensity dependent Kerr effect and anomalous dispersion. For a long duration pump pulse, which is essentially a very high order soliton, modulations in amplitude or phase on top of an essentially continuous background exhibit an exponential growth. The modulations which can be visualised as a four wave mixing mechanism, with two carrier photons generating Stokes and anti Stokes side bands, behave as solitons. On propagation, the modulations are amplified and consquently temporally narrow. As these soliton like structures temporally compress, their bandwidth increases and the high frequency components can provide Raman gain for the low frequency components, i.e. inter pulse Raman scattering or the soliton self frequency shift as it is known [27]. The frequency shifting gives rise to an increase in the central wavelength. The soliton structures which are intensity dependent, naturally form initially at the peak of the pump pulse. As a result of the frequency shift, these components relatively slow up, moving to the rear of the pump pulse , where they collide with other solitons in the early stages of their formation.

This gives rise to increased power and increased spectral broadening and the overall result is a spectral ensemble of many solitons. The actual number of solitons and the spectral extent of the soliton Raman continuum thus generated are not particularly controllable. There is a weak dependence on pump power, but because of the essential noise evolution of the process, this can not be defined. It is possible through spectral filtering to select single solitons of defined wavelength, peak powers in the kilowatt regime, and pulse durations as short as 80 fsec, see figure 12. However, the dynamics of the formation process gives rise to an inherent jitter in the soliton pulse repetition rate under the gain envelope, which precludes these pulse from applications demanding strict timing stability, but they do find useful application in for example, pump-probe experiments. As described above , the spectral extent is dependent on the pump power, but for readily available pump powers, from for example a mode locked Nd:YAG laser at 1.32 μm in a 500 m fibre, the soliton Raman continuum can extend up to 1.7 μm.

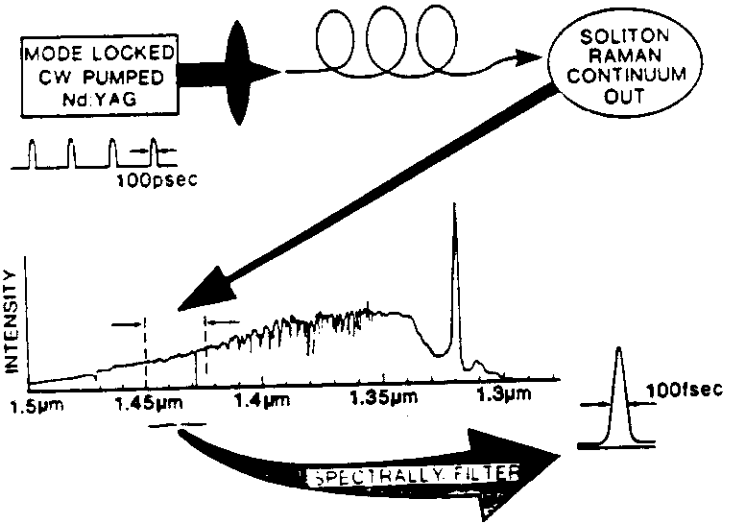

Figure 12 Femtosecond pulse generation via the soliton Raman continuum.

REFERENCES

[1] Mocker,H.W. et al. App.Phys.Lett. 7, 270 (1965)
[2] DeMaria,A.J. et al. App.Phys.Lett. 8, 22 (1966)
[3] New, G.H.C. et al. Proc. IEEE 62,313 (1974)
[4] Hargrove L.E. et al. App.Phys.Lett. 5, 4 (1964)
[5] Kuizenga, D.J. et al. IEEE J.Quant. Elect. QE-6, 694 (1970)
[6] Taylor J.R. et al. IEEE J.Quant. Elect QE- 17, 500 (1981)
[7] New, G.H.C. IEEE J.Quant. Elect. QE-10, 115 (1974)
[8] Ippen E.P. et al. App. Phys. Lett. 21, 348 (1972)
[9] Schmidt, W. et al. Phys Lett. 26A, 558 (1968)
[10] French, P.M.W. et al. Revue Phys. App. 22, 1651 (1987)
[11] Fork, R.L. et al. App. Phys. Lett.38, 671 (1981)
[12] Fork, R.L. et al. Opt. Lett. 9, 150 (1984)
[13] Valdmanis, J.A. et al. IEEE J.Quant Elect. QE-22, 112 (1986)
[14] Beaud, P. et al. Ultrafast Phenomena VII , 23 (1990)
[15] New, G.H.C., Opt. Lett. 15, 1306 (1990)
[16] Hodel, W. et al. To appear in Opt. Commun. (1990)
[17] Blow, K.J. et al. J.Opt. Soc. Am. B5, 629 (1988)
[18] Blow, K.J. et al. Opt. Lett. 13, 1026 (1988)
[19] Sibbett, W. et al. Opt. Lett. 14, 1192 (1989)
[20] Goodberlet, J. et al. Opt. Lett. 15, 1125 (1989)
[21] Sibbett, et al. Paper CPDP 10 CLEO (Anaheim) 1990
[22] Stolen, R.H. et al. App. Phys. Lett. 22, 276 (1973)
[23] Kafka, J,D. et al. Ultrafast Phenomena V, 51 (1986)
[24] Vysloukh, V.A. et al. JETP Lett. 38, 199 (1983)
[25] Gouveia-Neto, A.S. et al. Opt.Lett. 12,1035 (1987)
[26] Tai, K. et al. Phys. Rev. Lett. 56, 135 (1986)
[27] Mitschke, F.M. et al. Opt. Lett. 11, 659 (1986)

COPIES OF SOME OF THE MORE IMPORTANT OVERHEADS TO BE USED IN THE LECTURE COURSE FOLLOW.