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Original Article

Broadly Tunable Femtosecond Solid State Lasers

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ABSTRACT

Since the discovery of the laser, a significant level of scientific research has relied heavily on advanced laser technology. The remainder of laser usage falls into the commercial, industrial and medical categories. Whether using single frequency lasers for high resolution spectroscopy, femtosecond lasers for ultrafast spectroscopy, scientists in many fields of research benefit from the unique properties of lasers. Significant achievements have taken place in the generation and amplification of ultrashort optical pulses from the femtosecond to nanosecond time scales. The emergence of new ultrafast optical modulation techniques has opened the way towards a new femtosecond laser technology based on solid state gain media. Femtosecond laser systems have proven their potential in research laboratories in a variety of applications that were previously unthinkable, in fields as diverse as material processing, photonic device production, microscopy, and biomedicine. Laser power, wavelength, linewidth, pulse length, and beam profile must all be optimized for a particular application. In the future, they may be a critical component of space based remote sensing systems, communications systems and laser medicine.

***KEY WORDS:** Femtosecond, tunable, wavelength, solid state, frequency*

INTRODUCTION

The first frequency tunable source of coherent optical radiation a parametric light generator was constructed in 1$Oi9-965, five years after the ruby laser became operational. In the early 1970's tunable high pressure CO_2 lasers were put into operation. From the middle 1970's tunable lasers based on color centers in alkali halide crystals "solid state analogs" of lasers bases on solutions of dyes were undergoing intensive development. Tunable lasers brought about a real revolution in a number of very important fields of optics and experimental physics. This refers first of all to optical spectroscopy, nonlinear spectroscopy is wholly indebted for its achievements to tunable lasers, and to physics and technology of the action of optical radiation on matter. The prospects that were here opened up have for a long time attracted the attention of many research groups to the search for new "wide band" laser an nonlinear materials, and to the development of tunable lasers in different ranges of the optical spectrum. It should also be noted that beginning with the 1970's this research and development was also more and more stimulated by the requirements of picosecond and femtosecond laser technology. For the past few years, optical parametric generators and amplifiers have proved to be a convenient way to extend the tunability of femtosecond lasers in compact all solid state systems [1-6].

The development of femtosecond lasers has continued rapidly since the demonstration of femtosecond titanium doped sapphire (Ti:sapphire) systems in 1989. Recent research has yielded lasers which offer greatly enhanced performance in all areas [7]. In these systems a strong femtosecond pulse is used to amplify a portion of a white light continuum or parametric fluorescence. The amplified wavelength depends on the phase matching angle of the nonlinear crystal, and thus tunability can easily be accomplished. 100 femtosecond pulses can now be routinely generated by use of either the fundamental or the second harmonic of Ti:sapphire as the pump wavelength [8]. The generation of sub picosecond optical pulses has been an exciting area of research for many years and has been of influence in a wide range of research areas from ultra precise optical metrology to ultrafast data communications. Furthermore many Ti:sapphire lasers occupy a large footprint and require active cooling although recent research developments and commercial products have shown that compact cavities are possible. It still remains impossible to provide direct diode pumping of Ti:sapphire due to the lack of availability of high power green laser diodes and the overall purchase and operating costs of these lasers remains a barrier to wide scale applications outwith research laboratories. In addition to a by now quite traditional presentation of the principles and diagrams of tunable ultraviolet lasers contains new data on powerful wide band amplifiers based on KrF (with output energies up to 300 J) and on XeCl. Recently such amplifiers have attracted attention as output stages of femtosecond generators of ultraintense light fields [9].

The optical parametric oscillator has become one of the most effective methods of producing tunable coherent radiation. In an optical parametric oscillator the pump beam is used to generate a signal and idler beam in a three wave mixing process. The frequency of the signal and idler must sum to equal the frequency of the pump and this is the energy matching condition. The signal and idler frequencies are determined by the need to phase match the interaction and this is the momentum matching condition. Tuning of the optical parametric oscillator is accomplished by altering the phase matching by either orientation of the crystal or by changing the temperature of the crystal. The operation of an optical parametric oscillator is intimately connected with the coherence properties of the pump beam since this directly effects the signal and idler frequencies [10]. Although optical parametric oscillators do provide wide tunability their major limitation is that they require very well controlled pump lasers and that they do not store energy. A typical schematic diagram of a vibronic laser is very similar to that of a dye laser. The pump laser excites high in the excited state band. The system relaxes rapidly due to photon interactions. Laser action is produced by emission from the bottom of the upper level which has a lifetime of some microseconds down to the unpopulated ground state band. The energy difference is made up by phonons. The pump bands are therefore very broad and emission is also broad. This means that vibronic laser provide wide tunability and are capable of producing very short pulses. The most widely accepted vibronic laser system is Ti:sapphire. The laser tunes from about 680 nm out to 1100 nm. Ti:sapphire is usually pumped with an argon ion laser operating in the green region. Ti:sapphire has been pumped by a doubled diode system the power is low and the tuning very limited [11, 12]. Such outstanding achievements as the construction of a laser based on alexandrite tunable over the range of 710-820 nm, and in particular of a laser based on sapphire with titanium ions, the tuning range of which stretches from 660-1060 nm, radically alters the status of solid state lasers based on paramagnetic ions within the wide ranging family of tunable lasers [2, 11].

The actively mode locked continuous wave neodymium doped yttrium aluminum garnet (Nd:YAG) laser and the passively mode locked, flashlamp pumped Nd:glass laser were the standard sources of picosecond optical pulses for several years. In actively mode locked lasers the amplitude or frequency modulation proved too inefficient to exploit the available bandwith for ultrashort pulse production. For passively mode locked solid state lasers the pulse shortening down to the limit set by the gain bandwidth was prevented by the finite response time of the available saturable absorbers and their excessive bleaching during the final period of pulse evolution [13]. The ultimate limitation preventing feedback controlled Nd:glass lasers from femtosecond pulse generation has been the picosecond relaxation times of the resonant nonlinearities used. Ti:sapphire and Nd:glass, mode locked pulses of tens of picoseconds could be compressed to less than 1 picosecond without soliton like pulse shaping in the external cavity [14]. This sub picosecond pulse formation is based on the coherent addition of a weak nonlinear phase shifted pulse returning from the coupled cavity to the main cavity pulse. This technique has been called additive pulse mode locking, coupled cavity mode locking, and interferential mode locking. The disadvantage of additive pulse mode locking implemented with a coupled cavity is that stable pulse train formation requires the external cavity length to be stabilized to the main cavity length to within a fraction of a wavelength. Nevertheless, strong gain saturation compared to other solid state lasers are likely to play an essential role in femtosecond pulse formation in these systems.

Another interesting feature distinguishing continuous wave passively mode locked solid state lasers from their dye forerunners is that femtosecond pulse generation requires a net negative dispersion in the cavity. It demonstrated 100 femtosecond pulse generation from an all diode pumped solid state laser for the first time [15, 16]. The experiments presented in this area clearly demonstrate the close relationship between radio frequency spectral characteristics of the free running laser and the feasibility of self starting passive mode locking. Passive mode locking experiments must therefore always be preceded by a careful inspection of the optical setup for spurious reflections inside and outside the cavity. The large number of modes in continuous wave broad band in homogeneously broadened systems implies a reduced lifetime of the mode beating fluctuations and may require additional bandwidth limitation for self starting passive mode locking. By contrast, homogeneously broadened lasers support a comparatively low number of longitudinal modes under free running conditions, resulting in long lived mode beating fluctuations and thereby a comparatively low threshold for self starting passively mode locked operation. The ultimate femtosecond performance is not at all affected by the smaller initial number of free running modes because after their locking the loss modulation becomes sufficiently strong to generate a large number of further locked modes enhancing ultrashort pulse production [13]. The techniques of coupled cavity mode locking and self mode locking in which intensity induced nonlinear effects are exploited have been reviewed for broad band gain media. Particular emphases have been placed upon the archetypical colour centre and Ti:sapphire laser configurations in which these techniques were first demonstrated and subsequent refinements are set in context. A femtosecond optical parametric oscillator pumped by a self mode locked Ti:sapphire laser has also been described as an exemplar of a practical means of extending the source tunability into the mid infrared spectral region [17].

Femtosecond laser systems have proven their potential in research laboratories in a variety of applications that were previously unthinkable, in fields as diverse as material processing, photonic device production, microscopy, and biomedicine. Up to now, the application of these lasers outside research laboratory environments has been very limited because of their complexity and difficulty of operation and because of the high prices of commercially available laser systems. Cr^{2+}:ZnSe remains the most extensively studied member of this class of lasers and over the last decade has emerged as a versatile source of broadly tunable laser radiation in the mid infrared region between 2 and 3 μm. This gain medium possesses many favorable spectroscopic characteristics that enable efficient lasing. These include a four level energy structure and absence of excited state absorption which allow low threshold continuous wave operation, a broad absorption band that overlaps with the operating wavelength of many laser systems for optical pumping a phonon broadened emission band that gives rise to wide tunability and near unity fluorescence quantum efficiency at room temperature [18]. Undoubtedly it will be welcomed with interest by specialists involved in the development of tunable lasers, by physicists and engineers involved in work in the field of laser spectroscopy, the physics of selective action of radiation on matter, and by specialists in picosecond and femtosecond laser technology.

TUNABLE SOLID STATE LASERS

In the last decade tunable solid state lasers have become an increasingly significant component of quantum electronics. While they have only recently emerged from being a laboratory curiosity to playing key roles in varicty of electro optics systems. Until recently, was the most widely used tunable system, the liquid medium dye laser, solid state laser media offer unlimited operating and “shelf” lifetimes along with the capability to store energy and thus generate high peak powers via Q-switching. In addition, for some systems one can obtain either a broader tuning range than a given dye or an extension to longer infrared wavelengths. Current applications of tunable solid state lasers include basic scientific investigations in atomic, molecular and solid state spectroscopy, laboratory studies of new semiconductor and fiber optic devices, generation of ultrashort pulses and amplification of such pulses to high peak powers. Future applications now under development include aircraft and space based remote sensing lidars, submarine communication systems and laser medicine.

Solid state lasers operate on stimulated transitions between electronic levels of ions contained in solid crystalline or glassy hosts. To date, ions of practical significance have been positively charged ions from the rare earth or 3d transition metal groups of the periodic table. While all solid state lasers can operate over some range of wavelengths, and thus are tunable, it is common to consider “tunable” lasers as those capable of covering a wavelength range greater than several percent of the laser central wavelength. In the following we discuss some basic laser concepts and consider the mechanisms important for making a laser “tunable”.

1. Linewidth, cross section, and lifetime: The physical characteristic determining tuning range is the linewidth of the laser transition. Two other quantities of general interest to laser design are the gain cross section and the lifetime of the upper laser level. The population of the upper laser level, in the absence of laser action, decays at a rate determined by the combined effects of radiative or spontaneous emission and other nonradiative processes considered below. In simple systems; the rate is constant, which leads to an exponential decay of the population after the pumping is turned off, and a characteristic lifetime given by the inverse of the decay rate. Lifetimes for levels used in solid state lasers are in the range from 10^{-8} to 10^{-2} sn. The upper level lifetime is important in determining how much pumping power is required to generate the necessary population of ions for laser action [19].

For tunable systems with large linewidths, large gain cross sections are possible only if the lifetime is short. Conversely, for constant lifetimes, the gain cross section is inversely related to the linewidth. If one assumes a fixed length of laser material and certain level of gain needed for laser operation, one can readily show that the pumping, power required to obtain steady state laser operation is proportional to the linewidth. These kinds of considerations led early investigators to search for solid state laser materials with narrow linewidths. As techniques for optical pumping improved, including the use of another laser as the pump source operation on systems with large linewidths became possible. Even though the progress in ultrafast dye laser technology pushed research with mode locked solid state lasers into the background, work continued on the development of new solid state laser materials, leading to the emergence of a number of a new gain media. The characteristics of some of the most intensively investigated and most widely used solid state laser materials are shown in Table 1.

Table 1. Spectroscopic parameters laser materials for ultrashort optical pulse generation [13].

	Nd:YLF	Nd:glass	Ti:sapphire	Cr:LiSAF
Peak emission cross section (x10^{-20} cm^2)	18	4.2	30	4.8
Gain bandwidth (cm^{-1})	12	200	3200	1900
Fluorescence peak (μm)	1.047	1.053	0.78	0.83
Upper state lifetime (μm)	480	350	3.2	67

2. Single frequency operation: Solid state tunable laser gain media make ideal single frequency narrow linewidth lasers. A unidirectional ring with active stabilization in a well designed Ti:sapphire laser cavity will have in linewidth of around 100 kHz. This can be reduced to about 1 kHz fairly readily since all the frequency fluctuations are at relatively low frequency. Laser systems have been designed with beam ranges under electronic control of up to 40 GHz [20, 21].

Although many of the materials for diode pumping including Nd:YAG are homogeneously broadened gain media there has been little success in achieving single frequency operation in any other standing wave configurations even when using intercavity etalons to reduce the effects of spatial hole burning. The use of unidirectional ring laser oscillators to completely eliminate spatial hole burning has proved the most successful approach to high average power single frequency diode pumped all solid state lasers. Unidirectional operation of the ring is commonly achieved by using the Faraday effect. It is well known that the Faraday effect produces a non reciprocal polarisation rotation. Faraday rotation can be combined with cancel in the opposite direction. The inclusion of such a device in a cavity with polarising elements such as the Brewster surface of a laser rod results in low loss in only one direction and hence unidirectional laser operation.

In solid state systems the situation is quite different. Firstly, the passive amplitude modulation introduced by an all optical modulator using a nonresonant nonlinearity is usually less efficient than that caused by the combined action of saturated gain and absorption in dye laser. Secondly, the significantly longer amplifier medium and higher intracavity power lead to a strong self phase modulation in the amplifier host [13]. Interacting with positive dispersion in the cavity [22], self phase modulation prevents broad band solid state lasers from producing femtosecond pulses, and stops pulse shortening typically beyond 1 picosecond. However, with a net negative dispersion in the cavity the same system generate pulses of sub 100 femtosecond duration [23]. This tremendous improvement in ultrashort pulse performance clearly demonstrates the essential role of passive phase modulation in femtosecond solid state lasers.

Intensive efforts of some researchers has led to a fundamental understanding of the pulse shaping mechanisms and to a continuous improvement of mode locking parameters over 20 years. As a result of this development (Figure 1) sub picosecond synchronously pumped dye lasers and sub 100 femtosecond passively mode locked dye laser became part of the standard equipment of ultrafast research laboratories by the mid 1980's. It is worth mentioning that picosecond pulses have also been produced by self Q-switching in distributed feedback dye lasers. The adverse effect of spurious reflections on passive mode locking has recently been demonstrated experimentally and studied theoretically [24]. Actually, this is the case in almost all solid state lasers producing ultrashort pulses in the 100 femtosecond regime.

3. Broad linewidths: The first consider the mechanisms giving rise to the finite gain linewidth of a solid state laser. Unlike gas lasers, the Doppler effect due to the motion of the ions in the host is not of significance. Vibrational frequencies range up to 10^{13} Hz, but the ions are constrained to tiny displacements by the strong forces holding the host medium together and the resultant maximum velocities and Doppler shifts are relatively small.

The most fundamental cause of a finite linewidth is the finite lifetimes of the upper and lower laser levels, since the uncertainty relation requires that the linewidth of any level is the inverse of the level lifetime. In calculating the value to be used for the lifetime of the level it must consider processes which not only cause decay out of the level, but also processes which change the phase. For all but the lowest temperatures the latter ocur at a much higher rate than the former, and are due to interactions with the phonons of the host medium. In many common fixed wavelength solid state lasers, the linewidth is related to finite level lifetimes, values at room temperature range from 100 GHz and on up [19].

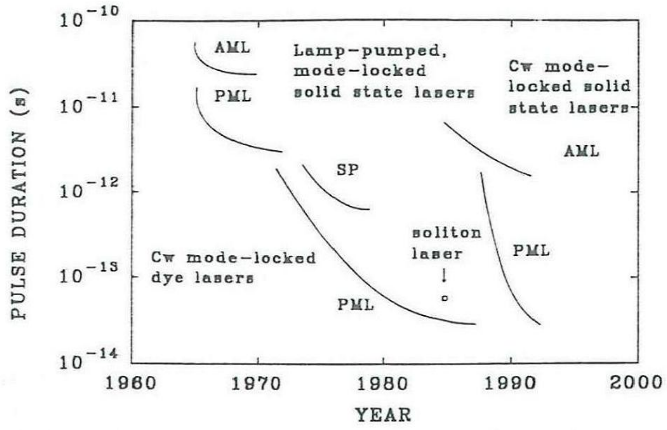

Figure 1. Graphic representation; based on pulse duration of the ultrashort pulse lasers (SP=shortest pulses, PML=passive mode locking, AML=active mode locking). Pulse durations direct from lasers are now approaching 10 femtosecond [13].

Lifetime broadening is homogeneous, that is all the ions in the host are subject to the same broadening mechanism. For disordered host materials such as glasses, another type of broadening occurs because each ion is in a slightly different environment from another. Since the energy levels of the ion depend to some extent on the surroundings, a distribution of ion energy levels results. The enermous number of ions that interact with a typical optical beam effectively create a smooth distribution of energies, and transitions between levels have a broadened lineshape. This type of broadening is referred to as inhomogeneous since the properties of ions vary from one to the other. The mechanism giving rise to the large linewidths of nearly all broadly tunable solid state lasers is different from the two mentioned above, and comes about because of even stronger interaction between ions and the host than previously described. The energy versus distance relation is in the form of a parabola, a quadratic approximation to the manner in which the atoms of the crystal react to a change in spacing. The host vibrations we referred to earlier occur about the lowest energy point of the parabola, the equilibrium position. For this discussion we consider a simple mode of vibration in which all the atoms surrounding the laser active ion move in and out at the same time the "breathing" mode.

4. Mode locked Ti:sapphire: The broad bandwidth and high power available from Ti:sapphire has meant that there has been considerable efforts to induce mode locking. Early attempts based to active mode locking were very disappointing. The technique Kerr lens mode locking (KLM) was discovered in Ti:sapphire and works exceptionally well. A schematic diagram of a KLM Ti:sapphire laser is shown in Figure 2.

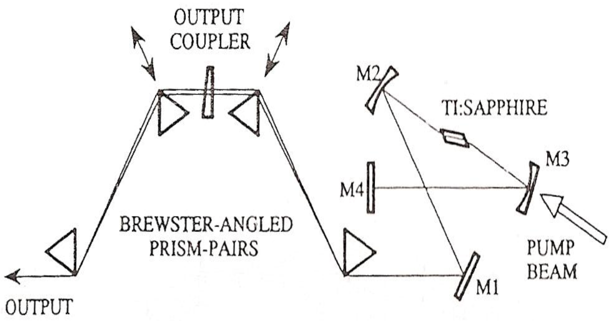

Fig 2. Femtosecond "bulk" solid state oscillator (Kerr lens mode locked Ti:sapphire) [13].

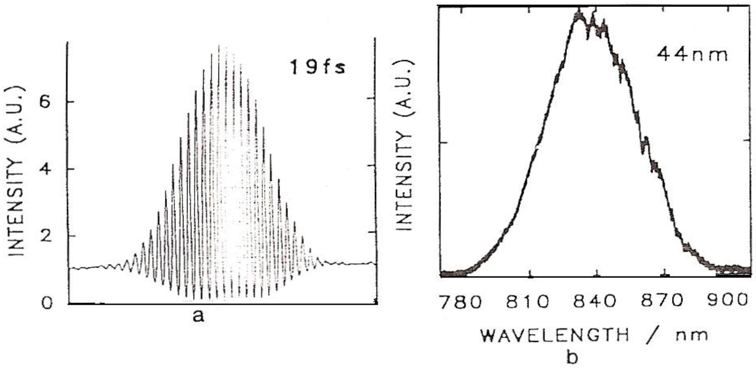

Fig 3. Optical spectra (Autocorrelation Kerr lens mode locked Ti:sapphire) [13].

The gain medium is at a focus and provides the Kerr lens. There is provision for two intracavity prisms. Prisms arranged in this way provide anomalous dispersion. It is well known that the combination of anomalous dispersion and self phase modulation are required for soliton like effects. By careful choise of low dispersion prisms and by use of external cavity chirp removal using prisms, pulses of less than 20 femtosecond have been reported [13]. Figure 3 shows a colinear autocorrelation of a 19 femtosecond optical pulse together with its spectrum. The optical fringes in an autocorrelation can be used calibration.

In many cases, the condition for spontaneous starting of passively mode locked lasers is not satisfied because of a weak nonlinearity, low intracavity power or excessive beat note linewidth. The start up process can be effectively supported by some active modulation. In general, active techniques are much more efficient in initiating the mode locking process than passive mechanisms. This is easily understood if one compares the magnitude of the gain window in the passive and active mode locking systems at the beginning of pulse evolution. Special care has to be taken when selecting and operating active starting mechanisms in femtosecond lasers [13].

The temporal shift imposed on a short pulse when traversing a loss modulator is proportional to the temporal derivative of the modulator loss and the inverse square of the pulsewidth [25]. Even if the passively mode locked pulse train can be kept synchronized to the externally driven modulation, significant jitter and thus amplitude noise may be expected in the femtosecond regime. The latter effect is especially undesirable since it may seriously impair the pulse energy stability compared with that of the purely passively mode locked laser.

These amplitude fluctuations can be reduced in three different ways:

1. Employing active modulation with an efficiency comparable to that of the passive mechanisms to reduce jitter and thus amplitude noise,

2. Dropping the requirement for synchronization and decreasing the modulation depth as far as possible,
3. Using another passive technique with an enhanced gain window for startup [26].

The nonlinear polarization evolution is finally transformed into a passive amplitude modulation by the polarizer. By proper adjustment of the relative phase delay between the two polarization modes in the fiber an artifical saturable absorber "of ultrafast response time" can be simulated. Since the pulse is subjected to a strong self phase modulation in the all optical modulator and the gain medium can be simply incorporated in the modulator by using an active fiber, the setup in Figure 4 has to be completed only with a dispersive delay line (Figure 5) to include all the essential pulse shaping mechanisms of a solitary system. Passive mode locking can also be started by loss or frequency modulation, where the adjustable radio frequency drive power provides a convenient means of optimizing the mode locking performance. If the passive amplitude modulation is strong enough to keep the mode locked state stable against environmental perturbations the starting modulator can even be switched off after reaching the steady state.

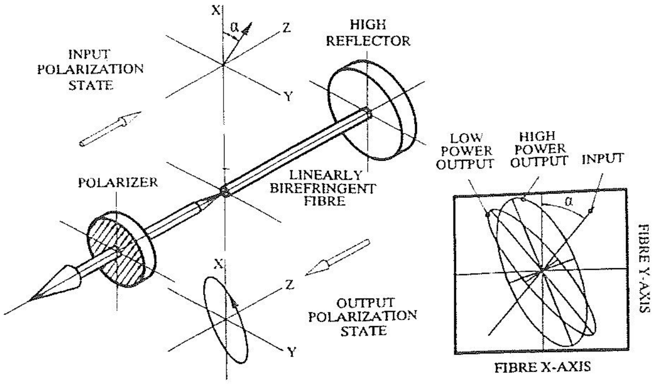

Fig 4. Operation principle of an all optical modulator based on nonlinear polarization evolution in a weakly birefringent optical fiber (adapted [13]).

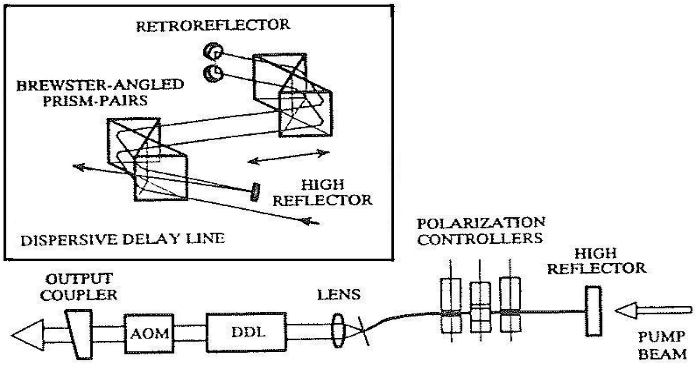

Fig 5. Femtosecond fiber laser oscillator (Nd doped silica fiber) [13].

5. Laser performance of Ti:sapphire: The dominant issue in optical pumping of Ti:sapphire lasers are the short upper state lifetime. In order to develop the highest possible excitation level under pulsed pumping conditions. The pump pulse duration must be equal to or less than the upper state lifetime. The xenon flashlamps for solid state laser pumping operate with pulsewidths of 100 μsn and greater. If one tries to operate flashlamps at pulsewidths at less than or equal to the 3.2 μsn lifetime of Ti:sapphire several problems arise. Firstly, electrical coupling to the lamp becomes much less efficient because of problems related to the dynamics of the gas discharge process. Secondly, much of the lamp emission energy shifts from the visible to the ultraviolet, decreasing the fraction of lamp energy absorbed (Figure 6) by the laser crystal. Finally, lamp lifetimes at a given energy input decrease with pulsewidth due to increased loading on the lamp walls, with the limit that at sufficiently short pulsewidths there is high probability that the lamp will explode on the first pulse [19].

The problems with direct flashlamp pumping, many pulsed Ti:sapphire systems are operated with longitudinal pumping by a short pulse laser. From Figure 6, the absorption band of Ti:sapphire can be accessed by frequency doubled, Q-switched Nd lasers, and that system is commonly used as a pump source. When the Ti:sapphire laser is pumped by a Q-switched laser pump pulse the Ti:sapphire laser operates in a gain switched mode. If the pump pulse is over before the output of the Ti:sapphire laser reaches a peak the laser generates only a single short pulse, similar to that produced by Q-switching. Pulse duration in the nanosecond range is readily generated.

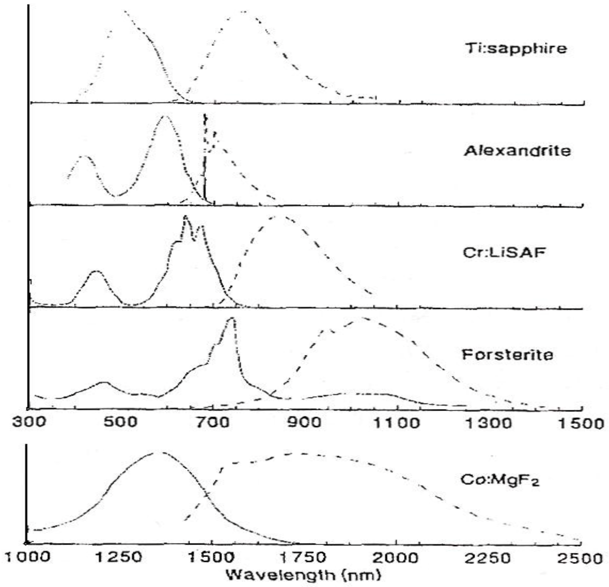

Figure 6. Absorption (solid line) and emission (dashed line) shapes as a function of wavelength for several combinations of laser active ions-host crystal (The sharp line in the alexandrite emission curve).

The highest energies produced by Nd laser pumped Ti:sapphire lasers have been achieved with flashlamp pumped pum lasers. Other pulsed sources for Ti:sapphire lasers include continuous wave lamp pumped, repetitively Q-switched Nd lasers which provide low pump energies but high “kHz range” pulse rates [27]. The highest energy laser pumped system to date has employed a single shot, flashlamp pumped, 495 nm dye laser to generate 2 J of energy for 10 J of pump input. The Ti:sapphire laser pulse was not a single gain switched pulse; as the pump pulse was 4 μsn in duration, but consisted of a burst of short pulses over a 3-4 μsn duration [28]. For unstable resonator cavity lasers, which have a low Q-switching, seeding by a continuous wave source insures that the laser will operate on no more than two longitudinal modes, but to reliably obtain true single frequency operation some control over the exact Ti:sapphire resonator length is required.

The Ti:sapphire laser has found wide applications in basic scientific research as a source for the high resolution spectroscopy, Raman scattering and frequency standards. In more applied research, it has found use in the characterization of photonic devices and as a laboratory substitute for semiconductor diode lasers in the pumping of fiber amplifiers and solid state lasers. With the recent development of mode locked lasers with 100 femtosecond duration pulses the Ti:sapphire laser will likely be applied to the study and characterization of high speed electronic and optoelectronic devices. Applications of high energy pulsed systems under development include atmospheric studies of global water vapor and oxygen concentration and temperature. Ti:sapphire lasers, combined with frequency doubling are a possible source for communication with submerged submarines. Ti:sapphire oscillator amplifer chains are sources of femtosecond duration high peak power pulses for research into the interaction between intense optical fields and various form of matter and can be the basis for the generation of short pulse X-rays.

DIODE PUMPED FEMTOSECOND LASERS

Femtosecond pulse sources that are tunable throughout the telecommunications window centred at 1550 nm have a great deal of potential for use with ultrafast data communications systems. They offer potential for data transmission, switching window control and precise clock distribution. The first demonstration of chromium doped yttrium aluminum garnet (Cr:YAG) lasers showed their potential in this wavelength regime (Figure 7) [29].

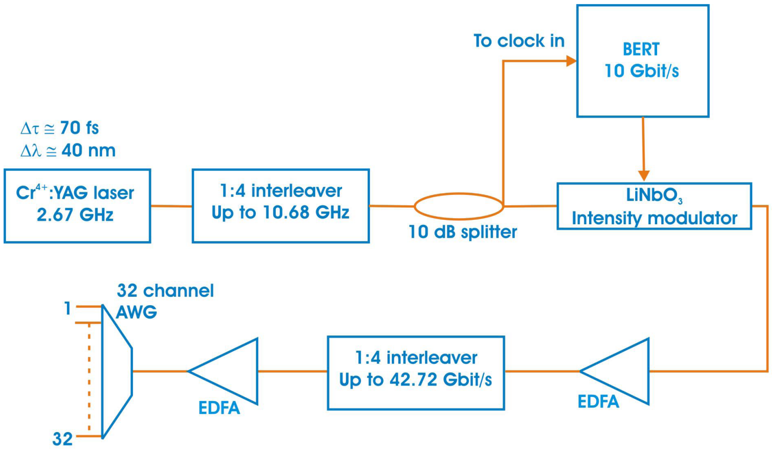

Fig7. Experimental arrangement of the spectral slicing experiment with a Cr:YAG laser [29].

In order to produce the performance required for use within communications applications, high pulse repetition frequencies must be generated. For a fundamental frequency mode locked laser, this produces the requirement for a very small cavity. In this respect, the highest pulse repetition frequencies have been delivered using two and three element cavity designs. Yb^{3+} ion based solid state femtosecond lasers have developed rapidly over past few years due to their ability to be efficient, low cost, relatively compact and robust. From the point of view of the development of new Yb doped crystals for reliable and efficient femtosecond lasers. Materials are preferred that possess high cross sections together with broad gain spectra and good physical and mechanical properties.

The recently developed Yb:YVO_4 crystal is another good candidate gain medium for incorporation into diode pumped, femtosecond lasers for the 1 μm spectral region due to its strong and broad absorption peak (FWHM of ~8 nm) at around 985 nm, the extremely low quantum defect, a relatively broad and smooth (glasslike) emission spectrum and a good thermal conductivity [30]. Applying a soft aperture Kerr lens mode locking technique, they have demonstrated a low threshold and efficient femtosecond Yb:YVO_4 laser pumped with a single mode laser diode.

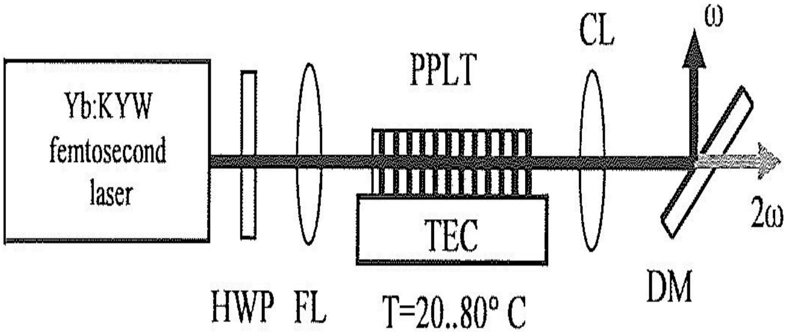

Fig 8. Experimental setup (HWP=half wave plate, FL=focusing lens, TEC=thermo electric cooler, CL=collimating lens, DM=dielectric dichroic mirror.

The femtosecond lasers that operate efficiently at wavelengths around 1 μm represent a route towards the provision of compact, efficient and high peak power ultraviolet and visible sources. Ultrafast lasers producing high peak intensity ultraviolet and visible outputs are especially relevant to a range of applications that include time resolved spectroscopy and studies in biology and photomedicine. Recently, they reported the efficient generations of femtosecond green pulses by extracavity single pass frequency doubling in periodically polled $LiTaO_3$ crystal of the output of a diode pumped, passively mode locked ytterbium doped double tungstates-Yb:KY(WO_4) (Yb:KYW) laser (Figure 8) [31]. The maximum second harmonic power was measured to be 150 mW at around 525 nm when the grating period of 7.35 μm was selected and used at a temperature of 80 ºC. During this measurements the Yb:KYW laser has produced 140 femtosecond pulses at 1049 nm with a corresponding spectral width of 8.7 nm, repetition frequency of 86 MHz and an average output power of 360 mW.

Mode locking of pulsed alexandrite lasers to generate pulses in the picosecond range has been demonstrated. Saturable absorbes have been used to yield pulses as short as 8 picosecond, while active locking of a system with an acousto optic modulator produced pulses as short as 160 picosecond. The use of alexandrite as the final stage amplifier in a chirped pulse high power laser system has allowed for the possibility of generating 100 femtosecond duration pulses of 50 mJ in energy [32].

Recently, a novel technique for the direct writing of waveguides and photonic circuits, exploiting refractive index modifications induced by focused femtosecond pulses has emerged [33-35]. The basic physical mechanisms underlying this process can be outlined as follow:

When the femtosecond pulse is tightly focused in a transparent material, a combination of nonlinear effects such as multiphoton absorption and avalanche ionization allows it to deposit energy is in a small volume around the focus. The photogenerated hot electron plasma rapidly transfers its energy to the lattice, giving rise to high temperatures and pressures, and possibly leading to melting; this localized absorption produces by mechanisms still under investigation, an increase of refractive index over a micrometer sized volume of the material. This photoinduced refractive index gradient allows one to produce by moving the laser focus inside the glass substrate, a wide variety of devices both active and passive.

Femtosecond micromachining shows compared with traditional waveguide fabrication techniques, a number of distinct advantages:

1. It requires simpler and less expensive device production equipment, avoiding clean room facilities.
2. It enables rapid device prototyping, because the device pattern can be easily changed by simple software control, with significant cost reduction in comparison with standard techniques using photolithographic steps and requiring the production of a mask.
3. It is intrinsically a three dimensional technique, because refractive index changes can be induced in any point in the bulk of the material within a given depth (100 μm to 1 mm) from the surface; this characteristic can be exploited to implement novel device functionalities, which are impossible with standard fabrication methods.

These simple measurements give experimental evidence of the serious consequences of small reflections from interfaces “lying nearly normal to the resonator axis” to the buildup of short pulses in mode locked oscillators [24]. In the light of these findings and considering the great number of such interfaces in our fiber oscillators, the broad beat note lines observed typically in the fiber systems are not surprising. Clearly, monolithic designs are expected to perform better in this respect. In fact self starting passive mode locking was recently achieved in monolithic, homogeneously broadened erbium fiber oscillators [36]. The experimental results are in close agreement with the predictions of the underlying theory of self starting passive mode locking.

Advanced Semiconductor Components for Femtosecond Lasers

In this section we will outline recent progress made in the development of semiconductor components for femtosecond operation. In particular we examine the use of quantum dot based materials in both active and passive configurations.

Femtosecond laser based using a GaInNAs: One option to initiate and stabilize mode locking within a femtosecond laser cavity is to use a semiconductor based saturable absorber. Typically these devices contain quantum wells to provide the saturable absorption behaviour with mirror based on semiconductor Bragg stack. The quantum well introduces and intensity dependent loss into the cavity. As the pulse duration shortens and the laser pulse becomes more intense, so the absorption losses in the quantum well becomes saturated resulting in lower round trip cavity losses for a laser operating in the femtosecond pulsed mode. In general mode locked operation using these devices in generally self starting.

Femtosecond laser based on quantum dot: An attractive option for use within advanced femtosecond quantum dots [37]. This is because of the broad operating band that can be obtained when dot layers with a range of size distributions are used. It may also be possible to grow long wavelength gain materials on the well established GaAs substrate technology. In addition dots also have similar saturation behaviour to quantum wells making them an attractive choice as saturable absorbers for femtosecond lasers based on vibronic crystals. The broad spectrum and the ultrashort pulse durations measured here demonstrate the potential of the simple two section quantum dot laser for the generation of pulses with durations in the femtosecond domain in near future.

CONCLUSION

More than two decades after the first operation of a laser producing picosecond light pulses, we have witnessed the emergence and evolution of a new generation of ultrashort pulse lasers based exclusively on solid state components. Novel ultrafast optical modulation techniques utilizing broad band nonresonant optical nonlinearities have developed and used for femtosecond pulse generation in a number of different solid state laser oscillators. From a physical point of view the unique feature of this new ultrafast technology is that the behavior and performance of solid state femtosecond sources are predictable using a small number of well defined parameters in this paper. What makes these solid state devices stand out, from a technical point of view is their reliability, compactness, and the high degree of reproducibility of their performance. These characteristics have given rise to a progress in ultrashort pulse laser science of incredible pace see the corresponding plot in Figure 1, and to the commercial availability of lasers delivering light pulses shorter than 10^{-13} sn. Advances in ultrafast all optical modulation techniques, new solid state laser materials and laser pumped solid state lasers suggest that a whole family of compact and solid state femtosecond sources can be developed. Experimental results on different laser systems that are of general importance for the development of femtosecond solid state sources and relate them to the theoretical considerations presented. These developments are expected to result in a rapid proliferation of femtosecond lasers in laboratories throughout the world and to generate a wealth of activities in ultrafast research in physical sciences.

Perhaps the most elegant scheme for starting passively mode locked lasers is regenerative feedback mode locking. Modulation frequency and pulse repetition rate are thus interdependent and cannot drift apart. Amplitude modulation regenerative feedback mode locking has recently been used to start and stabilize picosecond and femtosecond Ti:sapphire lasers. Since regenerative mode locking is the only efficient passive starting mechanism that does not rely on a wavelength dependent optical device. It can be expected to become widely used in future femtosecond solid state systems.

They have demonstrated a first generation all solid state tunable laser system by employing high peak powers to allow efficient frequency conversion and laser pumping. Future systems based on pumping of tunable solid state gain media by multi watt output frequency doubled diode pumped Nd lasers, including continuous wave operation of Ti:sapphire, promise a new range of high efficiency, widely tunable laser systems [12].

We have described a practical approach to generating nearly transform limited ultrashort pulses tunable through the infrared, visible and ultraviolet ranges. Frequency resolved optical gating is shown to be a helpful tool for characterizing and optimally compressing these pulses. Laser power, wavelength, linewidth, pulse length, and beam profile must all be optimized for a particular application. Of course, there is no one laser that can fulfill all needs, so many different laser technologies have been developed over the years. With a long history of laser research and development, coherent offers an extensive range of laser systems that are suitable for applications in all major research areas. Our record of innovation and ongoing commitment to laser development in a variety of technologies, such as ultrafast, continuous wave tunable, Q-switched, ion, diode pumped solid state, diodes lasers, pulsed and CO_2, ensures that coherent lasers will remain at the forefront of scientific research.

The work presented outlines the recent progress made in the development of femtosecond lasers that offer a range of sources that can be both compact and efficient. Many of the laser designs are diode pumped yielding femtosecond sources that offer a level of practicality above that from comparable Ti:sapphire lasers. The Cr:YAG source has been designed to rigorous user requirements and offers levels of performance that have enabled major advances in optical systems technology. Yb doped sources offer enormous potential giving femtosecond sources with unprecedented levels of electrical to optical efficiency along with output powers of 100's mW. Semiconductor technology also offers great promise both in terms of passive components for vibronic crystal based lasers and as electrically pumped gain materials for the direct generation of femtosecond pulses. A further area of excitement is the use of optically pumped external cavity semiconductor lasers where sub 500 femtosecond pulses have been generated by Hoogland et al [38].

It should be remembered however that the user requirements will ultimately define the particular choice of gain material. For example; in optical communications, high peak powers are not favoured due to the non linear interactions between pulses in optical fibre. In the case of biophotonics by contrast higher peak powers may be of interest to enable multiphoton processes. New passive devices are showing the potential for simple control of laser output parameters. Ultimately femtosecond lasers must progress to the stage where they are thought of as a module within particular application architecture. In order to achieve this goal, simple control over a wide range of laser parameters including output power, wavelength, pulse duration and coding sequence should be achieved.

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