

Generation of Short Laser Pulses

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Abstract

Progress in the technology of ultrashort pulse generation during the last years is outlined. After a short reminder of the basic active/passive mode locking processes and the combined pulse forming action of passive mode locking and gain saturation in the Colliding-Pulse Mode Locking arrangement (CPM) the recently developed Coupled Cavity/Additive Pulse Mode Locking (CCM/APM) configurations are reviewed.

The Kerr Lens Mode Locking (KLM) process constitutes an important advance towards simplicity and reliability. Its lack of a self-starting property has been of concern but can finally be overcome by custom-built semiconductor nonlinear absorbers.

Reduction of the thermal load of the active materials, higher output efficiencies and much enhanced beam quality result from the use of laser diodes to pump solid state lasers.

Synchronisation of the process of picosecond laser pulse generation with an external signal with subpicosecond phase jitter is an important subject. As illustration the CERN Synchro Laser System in use at the CLIC Test Facility for the generation of short electron bunches is presented. Possibilities for future improvements in this system as a consequence of recent technological advances are indicated.

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Introduction

Several comprehensive review articles dealing with every aspect of the technology of ultrashort laser pulse generation have been published during the last years with extensive reference lists up to the most recent developments [1-13]. The purpose of this article is thus not to add another paper on a well documented subject but to survey in general terms some of the major recent achievements in the field. For obvious reasons this overview can only be selective. It will be limited to those fields of laser technology where progress towards simplicity, stability and ease of handling directly concerns the typical pulsed laser systems which are built and operated for the purpose of electron bunch generation at accelerator laboratories like BNL, KEK, SLAC, LANL, CERN, to name only a few [14-19].

Developments of such laser systems have been reported at various conferences and workshops. At the workshop on 'RF guns' held in March 1993 at Fermi National Laboratory, Batavia/Ill. which was run concurrently with the TESLA collaboration meeting, various laboratories and institutions presented the state of development of their respective laser-driven photocathode equipped RF guns.

It was common opinion that for a reliable electron gun front end system for the TESLA project, the need is for a laser/photocathode system which works for 24 hours per day, 7 days per week. High stability and sufficient laser energy should enable the system to meet the stringent demands with respect to repetition rate, pulse intensity and laser photon energy for the production of long trains of ultrashort dense electron bunches.

For the simple reason that this high reliability laser system, combining the best of all worlds, is despite undisputed progress still not yet in sight, a classical front end system remains favoured as the working configuration.

In high quality laser-driven photocathode RF guns the two constituents laser and cathode are strongly interlinked. If one looks for excellent performance on one side, one will be faced with difficult operating conditions on the other. Cathode materials for instance with very high quantum efficiencies in the visible spectral range like Cs₃Sb or CsK₂Sb suffer from limited lifetimes in the range of some hours only. Yet they allow the construction of relatively straightforward Nd:YLF laser systems capable of delivering high stability long pulse trains at the second harmonic over long periods of accelerator operation [17]. In this very advanced and well engineered system, the photocathode side needed extreme design and construction efforts to enable the preparation, placing and removal of the CsK₂Sb photocathodes under 10⁻¹⁰ Torr vacuum.

The other extreme may be seen in the laser system in use at the CLIC Test Facility at CERN. The photocathode material used is CsI, whose work function is 6,2 eV, which is simply evaporated as a 350 nm thick layer on a polished stainless steel plug. It is easy to use and to install, insensitive to air, exhibiting high quantum efficiencies when illuminated with 209 nm laser light and still working strongly after several hundred hours of operation at 10 Hz under nC charge extraction [20].

The ease of handling and operation offered by the CsI photocathode material goes together with the burden of technological difficulties in providing the 5th harmonic of the modelocked Nd:YLF laser with acceptable energy stability and beam shape. After passage through three nonlinear crystals the beam shape of the 209 nm light is anything but smooth. At 209 nm, besides Fresnel reflection losses on uncoated surfaces, scattering losses on mirrors and AR coatings are already appreciable so that on the long beam path to the cathode a considerable fraction of the energy is already lost [21].

The remarkable progress during the last decade towards simple and reliable mode-locked lasers resulted in the 'milestone' of the self-starting self-mode-locked Ti:sapphire femtosecond oscillator. For a full assessment we will not omit the different intermediate results (which all have been 'last results' at their time) along the way towards the actual state of development.

The notion of *passive mode locking* is crucial as all techniques of mode-locked pulse generators are based on this effect, be it by dye cells or dye jets, nonlinear optical fibers in external cavities or semiconductor absorbers.

Active/Passive Mode Locking

The majority of devices used to generate very short optical pulses requires a laser to operate in a particular regime called mode locking. A typical laser consists of an optical resonator, made up of plane or curved mirrors, separated by a distance L and enclosing the active medium, fig. 1. The electromagnetic field inside can be described in terms of cavity modes, characterized by particular field distributions and regularly spaced resonance frequencies. The active medium provides gain for a large number (10^4 -- 10^5) of modes. To obtain light pulses of duration t_p , the active medium has to have a gain bandwidth of at least the inverse of the pulse duration

$$\Delta\nu \cong 1/t_p,$$

This fundamental relationship is basic to all approaches for generating short light pulses and defines the shortest pulse duration ultimately attainable with an active laser medium of a given fluorescent bandwidth $\Delta\nu$. All modes sustained by the gain medium circulate independently in the cavity and their phases and amplitudes are randomly distributed, so that the output power fluctuates in an irregular manner, see fig. 2(a).

Locking together the independent cavity modes such that they maintain a constant phase relation, fig. 2(b), can be achieved by inserting into the resonator a device for periodic modulation of the cavity losses [22]. The modulation may be achieved actively by an acousto-optic modulator, where the loss is created by Bragg diffraction in a quartz prism driven by an externally applied signal.

In an actual laser the light travels back and forth between the cavity mirrors many times. The light stays in phase with the loss modulation if the modulation frequency is an integral multiple of the inverse cavity round-trip time. Under these conditions the modulation results in locking together the phases of the oscillating modes generating a train of discrete laser pulses, separated by the cavity round trip time. The modulator response speed is limited by the driving electronics and is independent of the pulse duration. As the pulse gets shorter the shortening effect of the modulation decreases. The final number of oscillating modes is determined by the spectral range over which sufficient gain is available. Usually with active modulators the number of oscillating modes is small compared with the number of modes contained in the gain bandwidth.

Passive mode locking is a widely used technique and based on an entirely different process. No external signal source for driving the modulator is required, since it is the laser light itself, which provides the modulator control signal. The modulator element within the laser cavity is a saturable absorber, which is characterized by a typical nonlinear transmission response to increasing laser light intensities.

At low incident power density the absorber transmission is constant. At sufficiently high incident power density the transmission begins to increase because the light intensity partially depletes the ground state of the absorber. Consequently the effect of the absorber on transmitted pulses is that stronger pulses see less absorption than weaker pulses. Hence they can draw more gain when passing through the active medium than the weaker pulses.

Another effect to be stated is that a transmitted pulse is somewhat shortened. Light intensity in the leading wing of the pulse is used to bleach partially the absorber, such that the following pulse peak suffers less losses as a result of the nonlinear absorption characteristic. The trailing pulse wing will again see enhanced absorption only when the recovery time of the absorber is short compared to the pulse duration. If this condition is not satisfied the trailing part of the pulse passes through a still transparent absorber and will hence not suffer absorption loss. As a result the pulse will assume an asymmetric shape with a steep pulse front and a longer tail.

With this particular operation of the absorber in mind it is easy to follow the pulse evolution in a laser cavity containing a saturable absorber. The phases of the cavity modes are randomly distributed initially when stimulated emission begins. The radiation field consists of many irregular fluctuations at low power, see fig. 3(b). As power builds up the peak intensity of the biggest fluctuation will become comparable with the saturation intensity of the absorber. This peak will start bleaching the absorber. The biggest peak always experiences a higher gain than all the rest of the fluctuations and this peak will grow at the fastest rate, fig. 3(c). Finally one big pulse will have collected most of the available energy before the smaller fluctuations have grown to a comparable level. The energy carried by the rest of the fluctuations remains very small compared with the energy of the main pulse. The initially chaotic energy distribution is thus transformed by the saturable absorber into a single, well defined pulse, fig. 3(d).

Most saturable absorbers to date have been organic dyes in a solvent which use resonant excitation and an excited state population to produce absorption saturation. Since the laser photons themselves modify the absorber transmission, passive mode locking is a powerful technique for ultrashort pulse generation in both dye lasers and solid state lasers. It produces much shorter pulses than active mode locking, because both peak light intensity and saturable absorber action increase as the pulse is shortened [22].

Pulse Compression

Optical pulse compression is a very powerful technique for reducing the pulse width of cw mode-locked lasers, often by more than an order of magnitude. Efficient pulse compression increases the peak power of the optical pulse, an interesting feature for efficient generation of higher harmonics. Furthermore pulse compression can occur outside the laser cavity which permits independent optimization of the laser system and the compressor.

A pulse of a given temporal duration has a corresponding limit to its bandwidth known as the 'transform limit'. If the temporal width of a pulse is to be shortened beyond this limit, its bandwidth must be increased and equally important, it must be dephased, or chirped in a manner that permits subsequent rephasing of the chirped spectral components.

Treacy was the first to recognize that a pair of diffraction gratings was a suitable means to achieve this rephasing [23]. While Treacy used this technique to compress the output pulses of a mode-locked Nd:glass laser, carrying already a considerable chirp from the dispersive glass rod, optical fibers came into widespread use later to provide the necessary frequency modulation of the optical pulse [24].

In a medium with a constant refractive index n_0 an optical pulse propagates with a velocity $v = c/n_0$ without changing the shape of its envelope. Taking into account the first order frequency dependence of the index, the 'dispersion', the pulse still maintains its shape but the propagation velocity is now the group velocity v_g

$$v_g = c / (n_0 + n_1) \quad n_1 = \omega_0 \cdot dn / d\omega$$

When an optical pulse of low intensity is focused into an optical fiber it will travel down the fiber with the group velocity v_g and experience the normal dispersion of the fiber material as given by $dn / d\omega > 0$, i.e. the red light travels faster than the blue light (positive group velocity dispersion, GVD). This broadens the temporal width of the pulse as the frequency components separate. The magnitude of this effect is directly proportional to the length of the fiber.

High power densities of the optical pulse will drive the fiber material into the regime of nonlinear interaction with the optical field and generate a change of the refractive index

$$\delta n \approx n_2 \cdot E^2(t)$$

n_2 is called the nonlinear index of refraction ($n_2 > 0$). Under these circumstances the optical pulse will now travel at a reduced velocity according to

$$v_g = c / (n_0 + n_1 + \delta n)$$

As the pulse propagates along the fiber it spreads and develops a rectangular temporal profile with steep leading and trailing edges. These steep-slope regions where δn varies from zero to maximum and back to zero generate additional frequencies, because the rapidly varying intensity results in rapidly varying phase shifts which is a frequency shift and thus results in a broadening of the spectral width of the pulse. In the case of positive GVD, the red-shifted light generated at the leading edge travels faster than the blue-shifted light generated at the trailing edge and this leads to pulse spreading and a rectangular pulse shape. Because the new frequencies are primarily generated at the leading and trailing edges, which gradually move apart in time, the pulse develops finally a linear frequency chirp over the entire pulse.

The combined action of self-induced spread of existing frequency components and the simultaneous generation of new frequencies is called 'self-phase modulation' (SPM). The contribution of SPM to the spectral width is approximately given [25] by

$$(\Delta\nu)_{\text{SPM}} = v_0 \cdot z \cdot \delta n / c \cdot t_p$$

where the dependence on z indicates the particular interest of using long fibers to integrate the frequency bandwidth broadening effect during $\delta n \neq 0$ along its length z .

The dependence on the reciprocal of the pulse duration t_p describes the importance of SPM-generated bandwidth especially for femtosecond pulse technology.

To rephase the spectrally broadened pulse a dispersive delay line is required in which the propagation times of the different spectral components are different. The Treacy compressor mentioned above is a pair of diffraction gratings arranged in tandem with their faces and grooves parallel. This device provides a negative group velocity dispersion, which means that the red spectral components are delayed with respect to the blue ones.

A prism compressor, equivalent in operation to the Treacy compressor is an alternative way to produce negative GVD [26,27]. Two prisms are arranged so that the exit plane of prism 1 is parallel to the entrance plane of prism 2. Optical losses when producing negative GVD are low for Brewster-angle shaped prisms. The disadvantage of the prism method is their small dispersion so that the prism separation has to be considerably larger (up to 2 orders of magnitude) than that of the grating pairs. Use of prism materials with larger dispersion like SF10 [27] or TeO₂ single crystals [28] permits a substantial reduction of the interprism distance. Concerning low dispersion fused quartz prisms, their application is more advantageous inside a laser cavity to compensate for the small intracavity GVD, for instance from the dye solvents of a CPM ring dye laser.

A schematic view of the prism pair compressor method is shown in fig. 4. Its principle is based on a theorem which Martinez *et al* worked out [28,29,30]. It says that negative GVD can be obtained using refraction in optical components that need not have negative material dispersion themselves, much the same way as negative GVD in the Treacy compressor is obtained by diffraction from gratings.

When an optical pulse of spectral bandwidth $\Delta\lambda$ enters prism 1 close to its tip, it is refracted at both the entry and exit face and leaves the prism with an angular dispersion $d\varepsilon/d\lambda$. After travelling the distance L to prism 2 the dispersed bundle has a lateral width d of approximately

$$d \approx L(d\varepsilon/d\lambda)\Delta\lambda$$

The action of prism 1 is to change the temporal delays of each spectral component to a spatial dispersion. When the angularly dispersed pulse traverses prism 2 the different spectral components traverse different lengths and thus experience different delays until they emerge as a bundle of transversally displaced parallel rays. The mirror reflects them backward and the pulse leaves prism 1 coincident with the input light beam. The second pass through the prisms is necessary to remove the lateral displacement of the different pulse components and maintain the integrity of the spatial mode. The temporal dispersion constant [30] turns out to be

$$dT/d\lambda = 2(L\lambda/c)(d\epsilon/d\lambda)$$

Accounting for the signs of the dispersion the red components are delayed with respect to the blue ones and the prism pair thus has negative group velocity dispersion and therefore can be used for compression of positively chirped pulses. In fact, this configuration adds both negative and positive GVD. The negative contribution is determined by the spacing L between the prisms while the prism glass material itself adds positive dispersion to the system. This allows one to adjust the net dispersion by adjusting the prism spacing, or more conveniently by adding or subtracting prism glass through translating the prism tip into or out of the beam.

Colliding Pulse Mode Locking (CPM)

Since real absorber elements have real, finite recovery times the pulse shortening effect is limited to the action on the leading edge of the pulse as indicated above. To adequately shorten the trailing edge a different mechanism is needed, which is provided by its counterpart, the gain medium, a material similar to the saturable absorber. When the pulse passes through the gain medium it provides a net gain for the central region. Due to gain saturation by the pulse peak the trailing edge experiences only reduced gain. Because these shaping elements largely recover before the pulse returns on each round-trip of the resonator and because they respond passively and with negligible delay they provide a rapid and correctly timed shaping. In short, pulse reshaping consists in cutting the tails and enhancing the peak amplitude progressively with each round trip.

A technical realisation of this pulse shortening principle, where gain and absorber medium act in different ways on different parts of the pulse, is the CPM colliding pulse mode-locked ring dye laser [31]. The gain and absorber medium are dyes in a viscous solvent, pumped through narrow nozzles, thus forming jets which are flat to interferometric precision.

The central idea of a CPM laser is to utilize the "collision" of two pulses in the optical cavity to enhance the effectiveness of the saturable absorber. Fig. 5 shows the ring cavity configuration where two oppositely directed pulses travel around the cavity and meet in the saturable absorber. Since both pulses are coherent and interact with the absorber at the same time, they interfere with each other, creating a standing wave. The maximum intensity occurs at the nodes which completely saturates the absorber and minimizes loss. At the antinodes of the field the absorber is unsaturated, but then the field is a minimum, again minimizing the loss.

To fully take advantage of the standing wave field to saturate the absorber, it is important to reduce the optical length of the absorber medium to the pulse width, which in practice means to less than $10 \mu\text{m}$.

Proper positioning of the absorber and gain jets enhances the stability of laser operation. Fig. 6 illustrates the positions of the absorber and gain media at approximately one-fourth of the round-trip around the ring. Since the two oppositely directed pulses meet in the absorber, they will draw power from the gain medium with the same time delay corresponding to a one-half cavity round-trip time. In this manner both pulses see the same gain since the gain dye has the same time to recover following each pulse.

The recovery time of the absorber is determined by the relaxation time of its excited state population. If this recovery time is longer than the pulse duration the absorber is called "slow". Femtosecond pulse generation has required the use of gain media that also saturated dynamically. Pulse formation in this way is called "slow" saturable absorber modelocking [32].

The CPM dye laser, in which pulses as short as 28 fs have been produced [33] is an example of how well it works.

Short pulse formation using slow saturable absorbers relies on a careful balance of saturable absorber and saturable gain action, which is only obtained at a certain wavelength. Stable short pulse operation requires that the absorption cross section be greater than the gain cross section, i.e. that the absorber saturates before the gain. Furthermore the absorber has to recover before the gain, in order to keep the cavity clean and avoid amplifying noise.

Finally mode locking is plausible only where absorber and gain are resonant: This is the reason why most CPM systems operated on Rhodamin 6G and DODCI at 625 nm. The CPM laser is essentially non-tunable, because the gain and absorber dyes have a limited bandwidth and a pulse of 30-50 fs basically fills the entire available bandwidth.

In solid state lasers like Ti:sapphire, Nd:YAG or Nd:YLF slow saturable absorber modelocking is difficult. These active media have extremely low gain cross sections in the range of $\sigma \sim 10^{-19} \text{ cm}^{-2}$ and long gain relaxation times of the order of 1-100 μs and longer.

Saturable absorber dyes have been used to mode lock some solid state systems, but their use has been limited by their high insertion loss and their relative slowness (relaxation time $\sim 1 \text{ ps}$). Pulse shaping in these systems still depends upon absorber recovery.

Despite such inconveniences as missing tunability and the limitation to the visible spectral range, the creation of femtosecond optical pulses is a striking achievement of laser technology. Femtosecond techniques based on the CPM laser have opened the way to the study of ultrafast processes in physics, chemistry and biology. They permit the direct measurement of processes that previously were inaccessible to study like transient phenomena in organic dyes and high speed electronic devices or time-resolved studies of phase transitions [34].

Coupled Cavity Mode Locking/Additive Pulse Mode Locking (CCM/APM)

An entire new line of development opened up when the "slow" absorber, limiting the available degree of pulse shortening by its finite recovery time was superseded by the introduction of a "fast" absorber (response time shorter than the pulse width). The effect of passive mode locking, equivalent to that of a 'fast saturable absorber' is accomplished by a new cavity arrangement where an external, auxiliary cavity, containing a nonlinear element like an optical fiber, is coupled to the main cavity. This configuration was a considerable progress since a saturable gain medium as needed in the CPM laser to shape the trailing edge of the pulse is no longer needed.

APM was originally proposed by Ouellette and Piché [35]. It proved its potential in mode locking various laser systems, often producing the shortest pulses ever obtained with the corresponding bulk active media. The APM scheme is particularly attractive in that it has been shown to be self-starting, i.e. no intracavity amplitude or phase modulator is required to initiate the self-starting process in a range of Nd-doped laser materials.

The concept of APM implies that a pulse would be shaped when added to a phase modulated version of itself. The light intensity in the coupled cavity forces the fiber to react in a nonlinear way by self-phase modulation (SPM) such that the high intensity peak of the light pulse is phase retarded with respect to the low intensity pulse wings. The pulses from the master cavity and from the coupled cavity add coherently at the output coupler of this composite optical resonator. When the nonlinear phase shift is adjusted to give constructive interference at the center and destructive interference in the wings of the pulses from both cavities, a strong pulse width reduction results [36], see fig. 7. The nonlinear external cavity can be regarded as a nonlinear termination equivalent to a mirror with an intensity-dependent reflectivity [37,38].

A direct evaluation of the two possible cavity arrangements of the APM scheme, the Fabry-Perot type and the Michelson type is given in [39]. It turned out that the compactness of the Michelson cavity, compared to the Fabry-Perot arrangement, makes it less vulnerable to vibrations and that it tolerates larger fluctuations in pump power.

Recently the Michelson interferometer arrangement has been employed to generate pulses of 260 femtoseconds duration from a Nd³⁺-doped garnet laser [40].

In contrast to mode locking using saturable absorber dyes, APM does not rely on population excitation and thus can simulate instantaneously an effective saturable absorption action that is extremely fast. Furthermore, since the Kerr effect is broadband, operation is possible over a wide range of wavelengths. Thus APM permits the generation of wavelength tunable pulses and it has been applied to mode-lock a wide range of solid-state lasers like Ti:sapphire [41,42], Nd:YAG [43], Nd:YLF [44] and Nd:glass [45].

Table 1:

The shortest pulses resulting from various techniques used to mode lock laser diode-pumped Nd³⁺-doped YAG, YLF and glass. From Hughes and Barr, Ref. [9].

	Nd:YAG	Nd:YLF	Nd:glass
Fluorescence linewidth	120 GHz	360 GHz	5300 GHz
AM mode locking	55 ps	7 ps	5 ps
FM mode locking	12 ps	9 ps	9 ps
APM mode locking	1.7 ps	1.5 ps	0.6 ps

Table 1 shows the best performance (i.e. the shortest pulse duration) obtained for three types of mode locking of laser diode-pumped Nd-doped laser media, using active amplitude (AM), frequency (FM) and APM mode locking. It indicates clearly the superiority of the APM scheme in exploiting the available fluorescence bandwidth provided by the Nd-ion in the various host materials.

The principal disadvantage of APM is that the laser behaviour is interferometrically periodic in cavity length. In order to compensate actively the relative length variations of the two interferometer arms the high reflectivity mirror of the cavity is mounted on a piezoelectric transducer [40]. The error signal for active stabilisation was derived from the laser output [46]. This unwelcome complexity in its operation makes the APM configuration finally an impractical pulse source despite its obvious merits of producing ultrashort pulses. An experimental account on construction, operation and performance of an APM laser is given by Mitschke *et al* [36].

Kerr Lens Mode Locking (KLM)

The need for active piezoelectric stabilisation was overcome by a significant advance in the technique of passive mode locking by nonlinear pulse shaping, the Kerr lens mode locking (KLM). The key feature of this mode locking scheme is that the nonlinear process needed to achieve fast saturable absorber action is displaced from the coupled cavity directly into the amplifying medium of the main cavity. Unlike APM where nonlinear phase shifts can be integrated over the fiber length to achieve mode locking at *low* powers, KLM uses bulk nonlinearities which makes it well suited for mode locking bulk solid-state lasers which have *high* intracavity intensities.

It has been known for a long time that intense laser beams are subject to self-focusing when they propagate through optical media that have a nonlinear, intensity-dependent index of refraction. This Kerr self-focusing effect leads to slight changes in the spatial profile of the resonator mode in the laser oscillator.

The basic principle used to obtain intensity-dependent transmission through an intracavity aperture is shown in fig. 8. To a first order approximation self-focusing of a gaussian beam

incident on a nonlinear medium can be described as a self-induced quadratic index gradient [47]. The medium acts like a GRIN lens with a focal length which changes with the intracavity intensity. Given these circumstances the size of the beam at any point in the cavity is then intensity-dependent. Introducing a variable aperture at a position in the cavity where the mode size decreases for increasing intensity will introduce losses which are intensity-dependent. Transmission through the aperture will thus be higher for a high power beam than for a low power beam. This phenomenon will then push the laser to run in the regime which gives the highest peak power, that is in the short pulse regime. It was observed that for the same cavity adjustment the mode-locked operation had a four times higher average power than when it was running non-mode-locked [48].

Due to the instantaneous response of the Kerr nonlinearities the amplitude modulation induced by self-focusing is able to simulate ultrafast equivalent saturable absorber action and support pulse formation down to the femtosecond regime. By changing the aperture size the intensity-dependent loss is adjusted, and thus the effective cross section of this equivalent saturable absorber. This new control parameter provides a powerful means for optimizing performance.

The first demonstration of this technique termed self-mode locking or Kerr lens mode locking (KLM) [49] was reported at CLEO 90 for a Ti:Sapphire (Ti:S) laser [50]. Ti:S is an attractive gain medium which presents some unique features like large gain bandwidth (680 - 1100 nm) and high emission cross section, making it especially well suited to ultrashort pulse generation and amplification.

Fig. 9 represents the cavity schematic. The main laser cavity, consisting of mirrors M_0 to M_3 is z-folded to compensate the astigmatism introduced by the Brewster-angled Ti:S crystal rod. The spherical mirrors M_1 and M_2 ($r=10$ cm) were highly reflecting over the 850 - 1000 nm spectral region and highly transmitting for the 488 - 514 nm pump wavelength of the argon laser. The pump beam was focused into the Ti:S rod by the spherical mirror M_4 .

The pump power threshold for cw operation was 1 W. For 6 W pump power the laser could be made to self-mode-lock by a slight misalignment of the cavity, such that lasing occurred simultaneously on two transverse modes TEM_{00} and TEM_{05} and pulses of 2 ps duration have been produced. Their pulse spectrum indicated that they had a very large pulse length-bandwidth product ($\Delta\nu \Delta t_p=2.7$). This implies that the pulses were strongly frequency chirped, which was due primarily to the presence of self-phase modulation (SPM) within the Ti:S rod. With the two-prism sequence shown in the inset in fig 9 the pulse broadening effect can be overcome. With an optimum prism separation of 35 cm pulses having durations as short as 60 fs were generated. The spectral data associated with these pulses indicated a duration-bandwidth product of $\Delta\nu \Delta t_p=0.33$, very close to the Fourier transform limit of 0.32. This is clear evidence that the pulses are essentially free from excess frequency chirp.

Since KLM produces fast equivalent saturable absorber mode locking by using intracavity Kerr effect nonlinearities, the pulse shaping process will be affected by the presence of self-phase modulation. The role of SPM and GVD was first recognized in the CPM dye laser [33,51]. With the recent advent of mode-locked solid state lasers it is especially important to consider the role of intracavity SPM, since these systems have high intracavity peak intensities. Most of these lasers are designed with a beam focus in the medium (see mirror M_1 and M_2 action in fig 9) and a pulse can experience appreciable SPM from the nonlinear refractive index of the solid state crystal. The compensation of the SPM (positive frequency sweep) by the negative GVD from the intracavity prism pair is evidently of great importance for the pulse shortening process.

This report by D.E. Spence *et al* [50] on the simplest kind of femtosecond laser ever invented initiated many rapid developments. Soon it became apparent that the critical "misalignment" of the cavity was not necessary for pulsed operation [52] and that the many different mode locking schemes operate with the same basic self-focusing effect in the gain medium.

The KLM self-focusing effect need not be restricted to the Ti:S gain medium alone, where it works particularly well. Recently a scheme has been reported [53], where Kerr lens mode locking of a diode-pumped Nd:YAG laser has been achieved using the gain medium as the Kerr

medium and no intracavity slit. Its role has been accomplished by the pump-beam-induced thermal lensing, which plays a significant aperturing role in this laser. 8.5 ps pulses at a repetition rate of 100 MHz with an average power of 1 W were generated.

Another example of novel passive techniques of mode-locking based on nonlinear pulse shaping is presented by G.P.A. Malcolm and A.I. Ferguson [54] who investigated the possibility of self-mode-locking a diode-pumped Nd:YLF laser.

Diode-pumped all-solid-state lasers have achieved unprecedented efficiency and compactness. Use of the highly stable laser diode also offers great advantages over the traditional flashlamp as pump source for mode-locked solid state lasers, including shorter pulses and superior stability.

Active mode locking have produced pulses of 7-10 ps [55,56]. More recently the coupled cavity mode locking technique has been shown to produce pulses as short as 1.5 ps in diode-pumped Nd:YLF lasers, see Table 1. However these systems require that a significant portion of the diode-pumped laser output be directed into the optical fiber inside the coupled cavity to achieve pulse shaping, thus significantly reducing the available output. Moreover coupled cavity systems require interferometric stabilisation.

The novel feature of the system in Ref. [54] is the demonstration of self-mode locking of a diode-pumped Nd:YLF laser using the technique of Kerr lens mode locking to produce in a completely passive manner, without intracavity modulator and associated rf generator, pulses of 6 ps duration. Because all-optical modulation and pulse shaping are used, the laser is also self-stabilizing, therefore no interferometric matching of cavity lengths is required as in the case of coupled cavity mode locking.

Longitudinal end pumping schemes for diode-pumped solid state lasers are efficient. The minimum focused spot from a high power diode laser array requires that the laser mode size in the gain medium be fairly large, in excess of 100 μm , to ensure high efficiency. The nonlinearity produced in the gain medium is therefore too small to achieve self-mode locking of the diode-pumped laser. Instead a 1 cm rod of Brewster-angled SF 57 glass placed at an intracavity focus of about 30 μm provided the necessary nonlinearity. A variable aperture slit near the output coupler completes the scheme for self-mode locking.

Bandwidth limited pulses of 6 ps have been produced with excellent stability and an amplitude noise of less than 1 % rms from dc to 10 kHz.

G. Gabetta *et al* [57] demonstrated another interesting procedure to mode lock a Ti:S laser by using a nonlinear Kerr lens modulator as an end mirror of a standard z-folded, dispersion compensated argon laser-pumped cavity. The modulator consists of a focusing lens and a "microdot" mirror as shown in fig. 10. The mirror is made from BK7 glass with an AR coating on the front side and an array of high reflectivity spots with varying diameters on the rear surface.

The laser beam can be aligned onto an arbitrary spot by transverse translation of the mirror. A fast saturable absorber effect is produced by nonlinear self-focusing. When the laser beam propagates through the BK7 glass, self focusing produces smaller beam sizes at the microdot reflector for higher intensities. The reflection characteristics can be set by changing the reflecting spot diameter. The microdot mirror thus provides mode locking by fast saturable absorber action (decreasing loss for increasing intensity) due to its intensity-dependent mirror characteristics.

In contrast to other KLM techniques that use the nonlinearity of the solid state gain medium, which requires careful cavity design to determine the exact positions of the intracavity components, this microdot mirror is highly modular and can be used in an arbitrary cavity as end reflector.

Starting and Self-Starting Mechanisms

The mechanism for self-mode locking of a Ti:sapphire laser is based on the Kerr-lens self-focusing inside the Ti:S rod. Because the Kerr-lens effect scales with peak intensity, cw intensity fluctuations alone are too weak to self-start and sustain KLM operation. For self-start the absorber must efficiently enhance a long initial fluctuation before competing processes can disperse it. Therefore a sufficiently intense external perturbation must be applied to the free running laser, strong enough to provide an amplitude variation to be distinguished from noise and to be amplified.

Several different methods have been in use to start the KLM laser. The fluctuations can be initiated either by higher order spatial mode-beating noise from a slightly misaligned laser as already mentioned above [50] or by using the traditional mode locking elements as intracavity saturable absorber dye jets [13,52,58], active acousto-optic mode lockers [54,59,60,61] or by perturbing the cavity. This is mostly done by knocking on the table, tapping a mirror [54], moving an external cavity mirror [62], moving periodically one of the cavity mirrors using a shaker [63] or finally by varying the cavity length by a pair of rotating Brewster plates inside the cavity [49].

Since the Kerr effect is directly proportional to the peak intensity, which is very weak for noise spikes in cw lasers, self-starting is a fundamental problem. Owing to this non-starting one drawback of self-mode-locked systems is their sensitivity to mechanical vibrations and shock and hence their tendency to fall back periodically into cw operation. The need for a single, reliable, all-solid-state and passive starting mechanism was obvious and extensive research was directed toward this problem.

One of the proposed solutions was to use resonant passive mode locking (RPM) as a continuous starting mechanism for a femtosecond KLM Ti:sapphire laser [13,64]. RPM is a new coupled-cavity mode locking technique, see fig. 11, where an amplitude nonlinearity such as absorption bleaching in a semiconductor quantum well reflector introduces an intensity-dependent reflectivity which strongly mode locks the laser. Semiconductor saturable absorbers allow an all-solid-state technology, are compact and cover bandgaps from the visible to the infrared.

The nonlinearity is based on absorption bleaching, where the absorption is first decreased by the carriers generated within one laser pulse and then increased by recombination of these carriers. The recombination time and therefore the recovery time of the saturable absorber is significantly reduced by using a special low-temperature Molecular Beam Epitaxy (MBE) growth technology during the fabrication process. In using this saturable absorber in a low-Q coupled cavity one obtains a resonant passive coupled-cavity mode-locked laser, demonstrated first with Nd:YLF by Keller *et al* [65].

A comprehensive review article, covering the theory of RPM lasers and presenting experimental results on improved RPM Nd:YLF lasers, producing stable pulses of 3.7 ps at a repetition rate of 250 MHz has been published by Keller and Chiu [5].

RPM operation without any active length control is self-stabilized only at the expense of small optical frequency fluctuations [66]. An *intracavity* passive mode locking technique would remove the requirement for active stabilization and, equally desirable, the overall cavity design would become more compact.

This has been accomplished [67] by using an intracavity antiresonant Fabry-Perot saturable absorber (A-FPSA) that has a relatively fast InGaAs/GaAs semiconductor saturable absorber monolithically integrated between two reflecting mirrors, fig. 12. The top reflector is a TiO₂/SiO₂ dielectric mirror with 98% reflectivity. At antiresonance the intensity inside the Fabry-Perot cavity is always smaller than the incident intensity which increases the effective saturation intensity and the damage threshold of the semiconductor absorber. The top mirror significantly reduces the net reflectivity change (only 2% enter the Fabry-Perot), but the

nonlinear reflectivity due to absorption bleaching is still large enough to strongly mode lock the Nd:YLF laser.

In terms of coupled-cavity mode locking, the A-FPSA forms a monolithic coupled-cavity configuration for which the A-FPSA determines the end mirrors for the two coupled cavities that spatially overlap. The top mirror of the A-FPSA forms the end mirror of the main cavity, and the dielectric mirror underneath the saturable absorber layer forms the end mirror of the nonlinear coupled cavity. Because of monolithic integration of these two end mirrors within the same element, no relative cavity-length fluctuations exist. Thus there is no need for active cavity length stabilization.

The demonstrated limited tuning range of 30 nm only was a major drawback of the RPM starting mechanism [13]. By engineering the absorption edge of the saturable absorber it was possible to extend the tunability range of a RPM Ti:sapphire laser to more than 100 nm [68] using the low temperature MBE process already mentioned. A nonlinear bi-temporal reflector was produced with a slow and a fast time component in its absorption bleaching response. The fast component (sub-100 fs) is due to intraband thermalization while the slower component (few ps) is due to carrier recombination [67].

Further development work on the bi-temporal A-FPSA [69] applied to Nd:YLF and Nd:YAG lasers evaluated the dominant pulse forming mechanism of the fast component under steady state conditions in passively mode locked lasers. Variation of the carrier lifetime showed the importance of the slow time constant for starting and sustaining stable mode locking. Self-starting performance could thus be optimized by carrier lifetime engineering and adjustment of the top reflector.

Diode Pumping

Recent advancements in the development of high power semiconductor laser diodes as pump sources for all-solid-state lasers have led to a veritable revolution in this field of laser technology. Laser diode pumping has been used since to develop highly efficient, compact, reliable and intrinsically stable all-solid-state laser devices.

Three decades of development since the first pulse from a ruby laser have resulted in considerable advances in the techniques to produce, for instance, ultrashort pulses or extremely high power. Yet these evident accomplishments have not found until recently an equivalent wide range of applications, mainly due to the inefficiency, cooling requirements, large size and complexity of the technology.

The new class of diode-pumped solid-state lasers now allows the design and construction of miniaturized laser sources of very high efficiency. The consequences of this revolution in laser technology may be as profound as the revolution in electronics caused by the invention of the transistor.

It is impossible in the context of this paper to present more than just a few examples of the most important aspects of diode pumping. Three comprehensive survey articles on this rapidly advancing branch of modern laser technology have recently been published by Malcolm and Ferguson [10], and Hughes and Barr [9] citing as much as 193 references, while the paper by Fan and Byer [11] presents a more historical overview of the performance of various solid state lasers.

The diode laser was demonstrated as early as 1962. First generations exhibited only very limited output power capabilities and thus flashlamp pumping was the preferred technology for high power applications in spite of its low efficiency. The enormous progress in the fabrication of high power laser diode bars and arrays during the past five years now offers highly efficient pump sources yielding in all-solid-state laser systems unprecedented overall efficiencies.

The laser diode itself cannot be used for high power applications. The short recombination lifetime of the electron-hole pairs (~ 1 ns) prohibits energy storage, compared to the upper level

lifetimes of the Nd:YAG or glass laser (200 μ s) or YLF laser (480 μ s) indicating their potential for high power Q-switching.

Basic to the efficient pumping of Nd³⁺-doped host materials like YAG or YLF is the overlap between the spectral emission region of semiconductor GaAs/GaAlAs laser diodes at around 800 nm and the strong absorption peak at 807 nm of the Nd³⁺ ions which are excited into pump bands just above the upper laser level. This situation is already one of the major advantages of the diode pumping scheme: The amount of waste heat generated is a fraction only of that produced by flashlamps. Typically in excess of 90% of the laser diode pump is absorbed by a Nd:YAG rod so that optical conversion from the diode light at 810 nm to the 1064 nm high gain line of Nd:YAG can be as high as 50%. The most recent laser diode devices exhibit 50% conversion efficiency from electrical input to optical power so that overall (or "wallplug") efficiencies from electrical input to output radiation at 1064 nm of about 30% have been realized.

A comparison with flashlamp pumping will give evidence of the superior characteristics of diode pumping. Typical arc lamps will emit on several strong lines around 800 nm with a background of blackbody radiation. Useful emission in the region of Nd:YAG absorption is about 5% of the energy supplied to the lamp. Poor overlap of the flashlamp pumped volume and the cavity mode volume reduces the efficiency and causes excess heat within the gain material, inducing thermal lensing and birefringence. Overall efficiency of a flashlamp pumped Nd:YAG laser is therefore limited to about 0.5%.

One of the greatest advantages of diode pumping, the achievable degree of noise reduction, is actually being exploited in an extremely ambitious experiment on gravitational wave detection by a Michelson interferometer [70]. Cooling of flashlamp pumped systems and poor overlap between pump volume and lasing volume results in thermal fluctuations which cause frequency instabilities in the laser output. The reduced densities of waste heat in the diode pumping process, combined with intrinsically more stable solid-state diode pumps, results in improvements in performance of several orders of magnitude. Diode-pumped lasers have been demonstrated to yield 1 Hz linewidth compared with around 100 kHz for flashlamp pumped lasers.

The output from a laser diode is highly divergent and astigmatic due to the dimensions of the emitting region. To obtain good laser mode quality without suffering a large loss in efficiency this radiation has to be matched into the resonator mode volume in the gain medium. The most common schemes are longitudinal end pumping and transverse side pumping of the gain medium.

Both pumping geometries which may loosely be related to the two categories of 'high quality' and 'high power' have found extensive use. For longitudinal pumping the output from the laser diode is collimated and beam shaped by a set of cylindrical and spherical lenses to achieve a circular profile before being focused down to form a pump spot which is assumed constant from the end face throughout a certain length of the laser rod. This technique is a very efficient method for generating diffraction limited power due to the good spatial overlap between pump light and the TEM₀₀ lasing mode (mode matching) [71,72,73,74].

The most popular cavity configuration for longitudinal diode pumping is the z-folded cavity [54,56,63,75,76], compare figs. 9, 13, 24. One end of the rod is plane cut and has a multilayer dielectric coating, being highly transparent at 800 nm for the pump light and highly reflecting at 1060 nm for the laser light. The other end is cut at the Brewster angle for low loss within the cavity. The angle of the cavity fold at the spherical mirror can be adjusted to compensate for the astigmatism produced by the beam refraction at the Brewster surface. The laser mode size in the crystal is defined by the curvature of the folding mirror and the length of the cavity arm. An additional benefit of this cavity design is the near collimated arm which enables insertion of mode lockers or Q-switches as illustrated in figure 13. In this advanced z-folded cavity the diode-pumped Nd:YLF rod is used to amplify seed pulses from a z-folded diode-pumped mode-locked Nd:YLF oscillator from 4 pJ at 8 ps up to 92 μ J at 11 ps pulse width and 1kHz repetition rate.

The recently accomplished enhanced performance of laser diode arrays by increasing the length of the active area allowed multiwatt power levels with end-pumped lasers. One of these designs is reported by Shannon and Wallace [77]. In order to make efficient use of the new long-aperture-length diodes (10mmx1 μ m) in an end-pumped configuration they developed a resonator that operates with an elliptically cross-sectioned TEM₀₀ mode, which relaxes the stringent focusing requirements of long-aperture-length diodes. The light collection scheme for the 10 W diode is illustrated in fig. 14. Two cylindrical lenses and an aspheric condenser produce a focused spot of 1.1 mm x 150 μ m containing 84% of the diode light. At all pumping levels this laser operated in the TEM₀₀ mode and produced 1.9 W of output power. Q-switched operation resulted in 160 μ J pulses and frequency doubling in KTP in 75 μ J pulses at 10 kHz repetition rate.

The high efficiency of the end-pumping scheme has motivated as well a further design by Tidwell *et al* [78]. To achieve high power, good beam quality and high efficiency simultaneously the pump power of eight 15-W laser diode bars are combined in an angularly multiplexed pump geometry, and an output power of 60 W in a near-diffraction-limited beam has been generated, fig. 15.

The ultimate limit of such power scaling is determined by the thermal fracture strength of the laser material. In spite of its negligible thermal distortion and stress-induced birefringence, Nd:YLF had to be excluded here owing to its low fracture strength [79]. Nd:YAG was the preferred material but for good beam quality corrections of the strong thermal distortions were needed.

Above certain power levels it becomes more advantageous to use a side-pumping geometry, but this makes it more difficult to obtain the desired mode overlap for efficient TEM₀₀ operation.

The simple multipass pumping geometry reported by Ajer *et al* [80] may serve as introduction to the presentation of side-pumping schemes, fig. 16. The circumference of a 2 mm diameter Nd:YAG rod is coated with a highly reflective coating for the pump light with two narrow entry slits left open for the close-coupled diode bars. A large fraction of the pump light is absorbed since the light makes several bounces inside the rod. The high absorption efficiency in the small diameter rod enables a good spatial overlap between the gain distribution and the TEM₀₀ mode, resulting in an optical conversion efficiency of 27%, claimed to be the highest efficiency into a TEM₀₀ mode so far for a true side-pumped Nd:YAG laser.

An even higher conversion efficiency in the TEM₀₀ mode operation, exceeding 40% has been obtained by Baer *et al* [81,82] in the tightly folded resonator laser, fig. 17. It may be considered a special case of an end-pumped laser since the folding angle in this design is $\sim 5^\circ$ and kept as small as possible. The pump module consists of a laser diode bar of ten 1-W diode arrays located at 1 mm centers, collimated by a fiber lens onto the active medium of 5x5x20 mm dimensions. Two opposing parallel sides are coated highly reflective for the laser light and highly transparent for the pump light. The folding angle is adjusted by setting the cavity mirrors such that the intracavity TEM₀₀ mode bounces back and forth between the opposing sides with vertices located at each diode location. This geometry provides an excellent overlap between the pump volume excited by the diode bar and the TEM₀₀ laser mode. Fig. 18 illustrates the side view of this design.

The high peak power of a later Q-switched Nd:YLF version of this design [82,83] allowed generation of frequency-doubled output pulses using the nonlinear crystal LBO of 125 μ J at 4 kHz and still 40 μ J at 10 kHz repetition rate. Its diffraction limited output power at the fundamental was as high as 3.9 W at 10 W pump level.

The advantages of single-axial-mode lasers for coherent lidar, coherent optical communications, spectroscopy etc. have motivated the development of different techniques to obtain single frequency (i.e. TEM₀₀ mode *plus* single-axial-mode) operation of solid-state lasers by using ring resonators [84] as those shown in fig. 19 or microchip lasers [85,86,87].

A laser cavity defines longitudinal modes with frequency spacing $\delta\nu = c/2L$ as shown in fig. 1(b). The simplest approach to single-frequency operation of a solid-state laser is thus to reduce the cavity length L so that only one longitudinal cavity mode lies within the gain bandwidth.

Taira *et al* [88] reported the generation of a single axial mode using a longitudinally laser diode-pumped microchip in an attempt to construct a stable single-frequency master oscillator for injection locking of Nd-laser systems. Instead of using a Nd:YAG microchip as proposed by Zayhowski [86], Taira and coworkers have chosen Nd³⁺-doped yttrium vanadate Nd:YVO₄ as the active medium. This material exhibits much higher efficiency of absorption than Nd:YAG, being strongest for the pump polarization oriented parallel (π) to the c-axis of the Nd:YVO₄ crystal.

The cavity length of this miniature laser was defined by the 0.5 mm thickness of the microchip with the dielectric mirrors directly deposited onto the opposing crystal surfaces, see fig. 20. 103 mW single-mode output power could be obtained and frequency tuning within a certain range was possible without mode hopping by shifting the laser crystal temperature.

Further amplification of the single-frequency oscillation generated by a miniature microchip laser as described above or by a unidirectional ring laser [84] is mandatory for instance for the next generation of gravitational wave detectors using a Michelson interferometer. The interferometers need extremely sophisticated lasers as light sources, needing to be rapidly tunable yet to have a high frequency stability in cw operation. Diode-pumped Nd:YAG lasers are supposed to replace the usual single-frequency argon lasers because they are scalable to high power levels, introduce much less technical noise, have very high operational lifetimes and two orders of magnitude higher overall efficiencies.

Injection locking techniques have to be used in order to achieve high power levels. Golla *et al* [70] report on the realization of an injection-locked Nd:YAG laser, operating at up to 15 W of single-frequency output, conserving the spectral properties of the master oscillator. Since the power scaling possibilities of end-pumped configurations are limited due to geometrical constraints around the laser rod end faces, Golla *et al* decided to apply side-pumping for projected cw output powers up to 100 W. 28 water-cooled linear diode arrays with a nominal output power of 10 W each are symmetrically arranged around the 4 mm diameter, 90 mm long water-cooled rod as illustrated in fig. 21. Future efforts will be concentrated on raising the output power up to 30 W and on further enhancement of the spectral purity.

Synchronisation

High resolution measurement systems such as electro-optic sampling require the laser pulses to be compared with signals originating from an external electronic source [89]. For these and other experiments involving synchronisation of two lasers or of different pulses in the pulse train it is essential to have a low pulse-to-pulse timing jitter. The absolute timing jitter of a free running laser is too large for subpicosecond resolution. Increased phase noise leads necessarily to significantly increased sample periods if one wants to maintain the desired signal-to-noise ratio. It is thus imperative that all contributions to noise be reduced to a minimum.

The pulse timing jitter characteristics of cw mode-locked lasers have received increased attention after analysing techniques have been developed for the accurate measurement of amplitude, pulse duration and timing fluctuations in laser outputs [90]. These techniques enable direct measurement of phase noise in mode-locked lasers by inspection of relevant harmonics of the laser output using microwave frequency spectrum analysis methods.

Based on phase locking the optical oscillator to an ultrastable electronic reference oscillator, a significant noise reduction of an actively mode-locked Nd:YAG laser has been achieved by Rodwell *et al* [91]. Active phase locking consisted in mixing the output of a monitor photodiode with a reference signal to derive a phase-error signal. Amplification, integration and level comparison of this signal allowed a suitable error signal to be supplied to a piezo-electric

transducer (PZT) controlled cavity mirror to maintain the output of the laser in phase quadrature with the reference signal.

Recently two research groups reported simultaneously the extension of this successful phase noise reduction scheme from acousto-optic mode locking to the passive colliding-pulse mode-locked (CPM) laser arrangement [92,93]. The translation of one of the cavity mirrors of a 7-mirror CPM ring dye laser system, similar to the system reported by Valdmanis *et al* [94] was PZT controlled and enabled the active control of the oscillators repetition frequency by varying the optical cavity length. Darack *et al* employed within the phase-locked loop a chopper stabilized phase detector, described by Rodwell [91] to reduce the many problems associated with double-balanced mixers, including the conversion of amplitude noise to phase noise (AM-to-PM conversion) at the mixing stage. For various reasons Walker *et al* [92] have chosen the double-balanced mixer scheme paying special attention to the rejection of AM-to-PM conversion by using high level mixers.

Timing jitter is most easily measured by observing the phase noise of the laser in the frequency domain using spectrum analysis techniques to measure the power spectrum. Most of the significant jitter in the CPM laser is at frequencies less than 1 kHz, with jitter at higher frequencies well under 1 ps.

Employing both an independent photodiode and the phase-locking reference photodiode indicated for the free running laser the presence of significant timing fluctuations of the order of about 10 ps rms in the 50 to 500 Hz frequency range [92]. The majority of this low frequency timing jitter is determined by external influences including pump laser amplitude instabilities, environmental acoustic perturbations, dye jet noise, table and mirror mount vibrations.

The phase-stabilized noise spectra obtained by analyzing the fundamental and the twentieth harmonics of the frequency-referenced laser output revealed a reduction of temporal jitter by almost two orders of magnitude to 0.25 ps rms in the 50 to 500 Hz bandwidth.

S.B.Darack *et al* report similar results [93]. The timing jitter of their free running laser, 24 ps rms, was in the band from 50 to 100 Hz and was attributed to vibrations of the laser optics, mounted at 18 cm height above table. Active stabilization of the cavity length reduced the absolute jitter to 1.7 ps over the 0.15 to 1 kHz band.

It is interesting to consider the relationship between timing jitter δt and cavity length change δL . It depends on the rate of change in the cavity [95]

$$\delta t = \delta L / 2\pi f_m L$$

where L is the cavity length and f_m is the frequency of the cavity length change. If a CPM ring laser of 3 m cavity length (100 MHz repetition rate) is oscillating at 100 Hz, a cavity length change of the order of 0.01 μm results in 5 ps timing jitter. The fact that such small changes in cavity length can introduce large timing errors underlines the importance of eliminating internal mechanical resonances and damping out external sources of vibration and acoustic coupling to reduce low-frequency jitter.

Walker *et al* [92] applied the same spectral analysis techniques as well to a coupled-cavity mode-locked (CCM) KCl:Tl color-center laser system [96,97]. The color-center laser cavity, synchronously pumped by a cw mode-locked Nd:YAG laser, had to be organized into the Michelson type arrangement [98,35] such that one of the mirrors which were common to both cavities could be piezo-electrically translated to control the laser repetition rate without compromising the interferometric matching condition. The end mirror of the coupled cavity was also piezo-electrically translated to maintain enhanced mode locking. The two operations were independent and could be separately adjusted.

It turned out that the nonlinear Michelson cavity exhibited great tolerances to deviations from the synchronization between pump laser repetition rate and the cavity frequency of the CCM

laser. It was thus possible to phase lock the RF drive signal for the acousto-optic modulator of the pump laser to the reference oscillator and operate pump and color-center laser resonators at zero cavity detuning.

Operating the CCM laser in this stabilized arrangement yielded rms timing jitter values of 0.17 ps at 50 to 500 Hz and 0.1 ps at 0.5 to 5 kHz, calculated from the single side band phase noise spectral densities.

The cavity frequency locking technique has once more been demonstrated by D.E.Spence *et al* [61] to be a powerful stabilisation scheme by applying it to a self-mode-locked Ti:sapphire laser. The mode locking process in Ti:S is self-sustaining but normally not self-starting. In order to initialize and stabilize the mode-locked output from the laser an acousto-optic modulator has been incorporated into the cavity. The modulator drive signal was derived from a frequency component of the laser output, so that the drive frequency to the acousto-optic device was automatically matched to the cavity frequency. This type of scheme [99] is called regenerative mode locking.

A pulse timing jitter characterisation was carried out in the usual way as described above for both the free running and the cavity frequency-locked laser [91,92]. The timing jitter values for the respective frequency bands are shown in Table 2.

Table 2:
Reduction of pulse timing jitter of a passively mode-locked CPM laser through active cavity length stabilization. From Walker et al, Ref. [92].

	50 - 500 Hz	500 Hz - 5 kHz	5 - 50 kHz
free running	10.6 ps	0.85 ps	0.47 ps
frequency locked	0.64 ps	0.46 ps	0.17 ps

The authors point out that further improvements in timing jitter would require better isolation from the surrounding environment and, more importantly, a quieter pump source such as a frequency-doubled diode-pumped Nd:YAG system to avoid the 'technical' noise sources associated with the argon laser's power supply unit.

The CTF Synchro Laser at CERN

The CERN Linear Collider (CLIC) study [100,101,102] is a two beam acceleration scheme where the 30 GHz RF power pulses for electron acceleration in the main linac are extracted by a Transfer Structure from the drive beam carrying bunched high currents at lower energy. A study actively addressed at the CLIC Test Facility CTF is the generation of these short (some ps), intense bunches by a laser-driven photocathode inside a 3 GHz RF gun with 100 MV/m accelerating field. Efficient generation of electron bunches synchronous with the 3 GHz pulse from a klystron demands laser pulses of 7 - 10 ps duration only and a sub-picosecond timing stability. The laser wavelength required is determined by the quantum efficiency of the cathode material used. Actually the CTF operates with CsI and the photon energy has to be adequate to the 6.2 eV work function of this material [20,21].

A relatively high pulse energy is needed, since in the particular case of 30 GHz RF power generation the high bunch charge will have to be generated by using a string of up to 24 identical sub-pulses with 3 GHz repetition rate, generated from one single pulse by a Train Generator [103], an arrangement of precisely made beamsplitters. From a first, preliminary 8-pulse version a train of eight electron bunches has been obtained as shown in Fig. 22.

The laser system in use to produce the picosecond pulses is shown in fig. 23. The oscillator is a Lightwave model 130 laser diode-pumped Nd:YLF laser, mode-locked at a frequency of 249.879 MHz, the twelfth subharmonic of the 2.99855 GHz klystron frequency. The advantages of longitudinal laser diode pumping for high beam quality have been outlined above and need not be repeated here.

The particularly interesting feature of the model 130 laser is its built-in timing stabilizer, which enables a timing jitter specification of <1 ps. It incorporates a phase-lock loop and can use either external or internal reference signals to reduce phase jitter. To match the cavity length to the fixed frequency of the mode locker, a piezo element translates the folding mirror in the cavity, see fig. 24.

In November 1991 a series of acceptance tests were carried out on the model 130 laser. Its optical output pulses were picked up by an ultrafast InGaAs photodiode, model 1011 from New Focus, with an inherent 9 ps rise time (3dB bandwidth of 45GHz). The pulse width in fig. 25 was measured with a Hewlett-Packard 50 GHz Sampling Oscilloscope HP 54 124 T. The manufacturer determined the true pulse width by autocorrelation and a sech² fit as 6.6 ps, see fig. 26. Amplitude jitter of the output pulses has been measured from a set of 1008 samples to be 1.72 %rms.

The time jitter between the optical output of the model 130 and the external 250 MHz reference oscillator (HP 8665 B Signal Generator) was measured to be about 0,8 ps, see fig. 27. To trigger the sampling scope another step recovery diode (impulse train generator HP 33003 A) was used.

Another measurement concerned the jitter between the 250 MHz from the internal reference generator and the 3 GHz signal which is generated via the 12-fold multiplication using a step recovery diode module and a 3 GHz bandpass filter, explained in fig. 28. The measured result is 1.1 - 1.3 ps displayed on the sampling scope with an intrinsic jitter of 0.8 ps of the scope itself, fig. 29.

The output of the model 130 phase detector (input frequency 125 MHz) has been made externally accessible in order to monitor the working point of the mode lock circuits.

The power amplification part of the synchro-laser system in fig. 23, comprising the regenerative amplifier, the two single-pass amplifiers and the harmonic generators, has been designed and built by Quanta System (Milano, Italy). A chain of three nonlinear crystals (KD*P, BBO) permits the generation of the second, fourth and fifth harmonic of the fundamental 1047 nm wavelength laser light. The fused silica Pellin-Broca prism at the end separates the four collinear beams.

Timing and synchronisation electronics are controlled by the internal 250 MHz generator of the model 130 laser. The block diagram in fig. 23 shows the general structure:

- The 250 MHz signal is divided by 5. This yields a 50 MHz square wave signal which was filtered, amplified and used at an earlier stage of development as input signal to the driver of an acousto-optic mode locker in the regenerative amplifier.
- The 50 MHz signal is further divided by 4 to generate a 12.5 MHz clock for the CAMAC based timing system.
- On the other hand the 250 MHz signal feeds a step recovery diode module. By extracting the 12th harmonic with a 3 GHz bandpass the reference frequency is generated for the klystron amplifier.

The system is in operation at the CTF for months-long test runs. In beam-free times it is worked on almost continuously in an attempt to provide optimum operation. In this respect fig. 23 shows rather a momentary situation. This concerns for instance the electro-optic modulator which had been intended to cut every other pulse out of the 250 MHz pulse train from the oscillator to get rid of residual satellite pulses leaking sometimes through the Pockels cells. Now the situation has changed in that the full 250 MHz repetition rate is needed. One of the latest ideas under test consists in capturing in the regenerative amplifier (8.7 ns round trip time) by appropriate timing of the two Pockels cells two successive input pulses (4 ns separation) from the oscillator. Amplification in the regenerative amplifier and the linear amplifiers yielded two pulses of almost equal energy [104] (several mJ at 9 ps), most welcome as input to the Train Generator.

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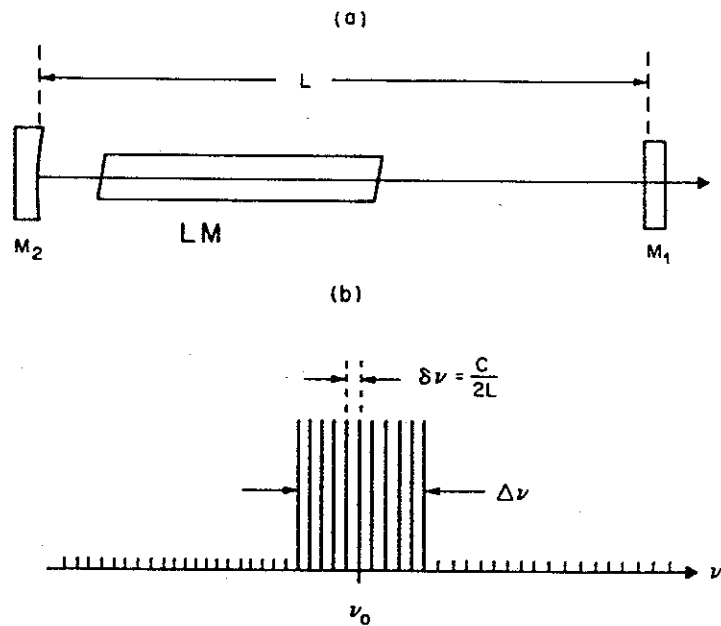


Figure 1: (a) Schematic of a laser cavity (M_1 and M_2 : mirrors, LM: laser medium). (b) Spectrum of the longitudinal cavity modes of a cavity of length L . The mode spacing is $\delta\nu$, while the gain bandwidth is $\Delta\nu$. From v.d.Linde, Ref. [1]

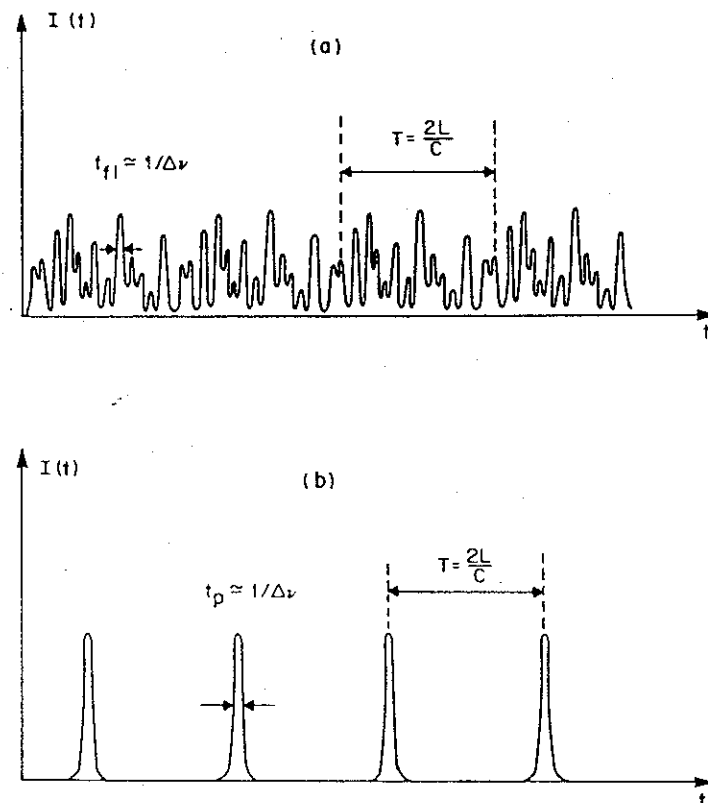


Figure 2: Multimode laser output (a) for random phases, and (b) for constant phases. From v.d.Linde, Ref. [1]

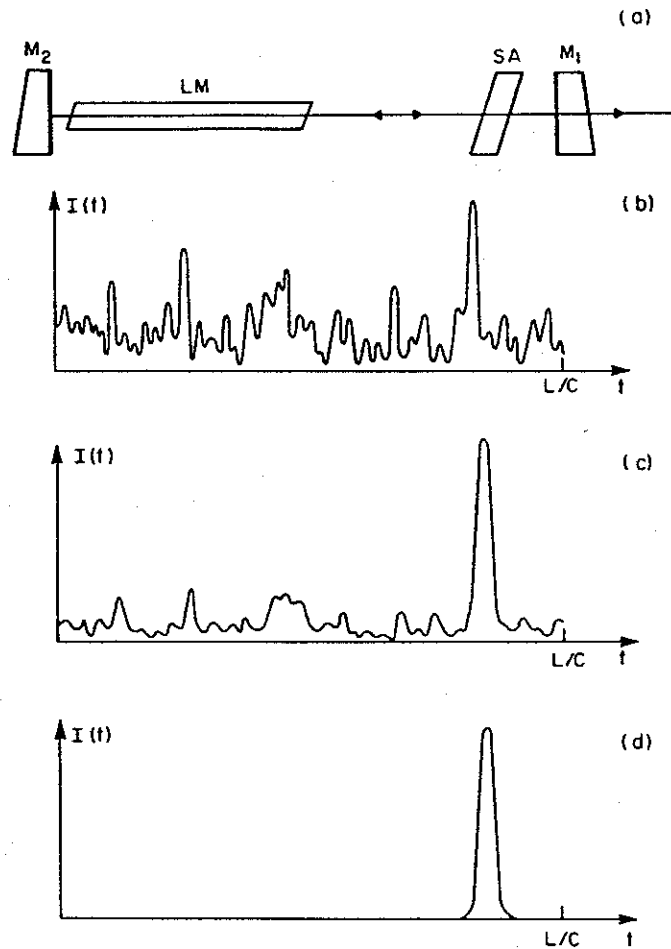


Figure 3: Evolution of short pulses in a laser with saturable absorber. (a) Schematic of a typical cavity configuration; (b) low intensity regime with random fluctuations; (c) onset of discrimination of weak peaks; (d) final energy distribution. From v.d.Linde, Ref. [1].

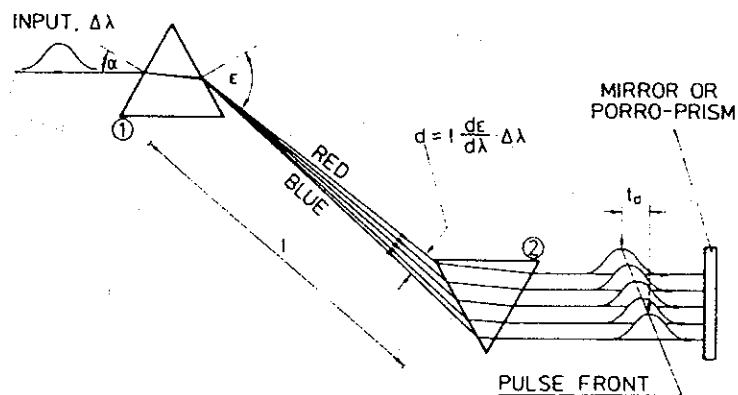


Figure 4: Prism pair pulse compressor. The red spectral components have longer paths in the glass. Thus due to the difference between phase and group velocities they are delayed with respect to the blue components. From Bor and Racz, Ref. [30]

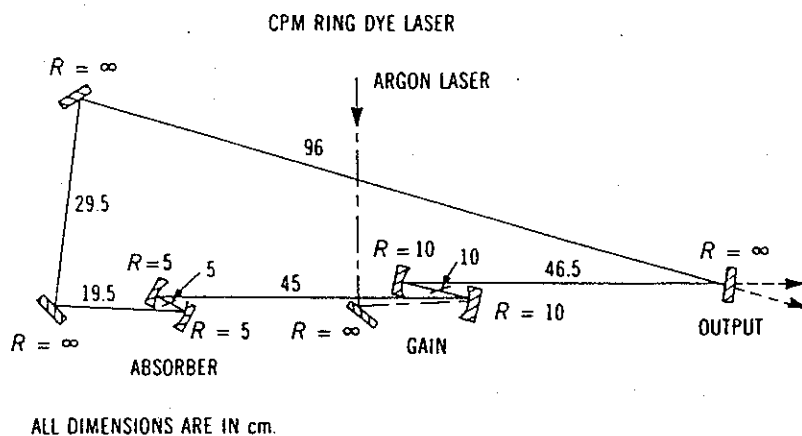


Figure 5: Cavity configuration for the colliding pulse mode-locked laser pumped by an argon laser. From Shank *et al*, Ref. [31].

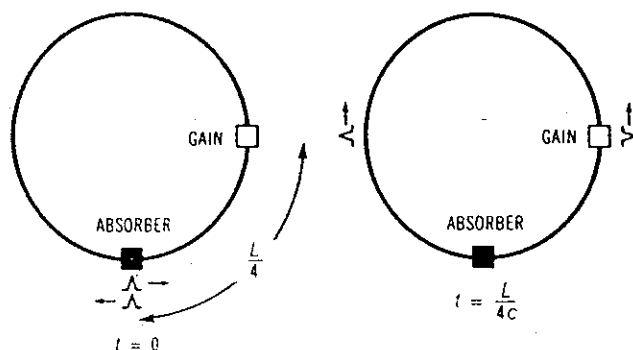


Figure 6: Illustration of the proper $L/4$ spacing between the gain and absorber media. From Shank *et al*, Ref. [31].

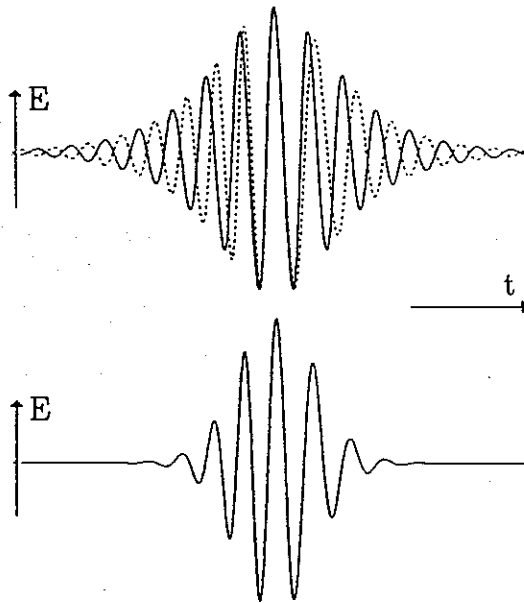


Figure 7: Simplified sketch of how from interference of two pulses with different chirp a shorter pulse can be generated: An unchirped (solid line) and a chirped (dashed line) replica of the same sech^2 -shaped pulse interfere (top); due to destructive interference in the wings the result is a shorter pulse (bottom). From Mitschke *et al*, Ref. [36].

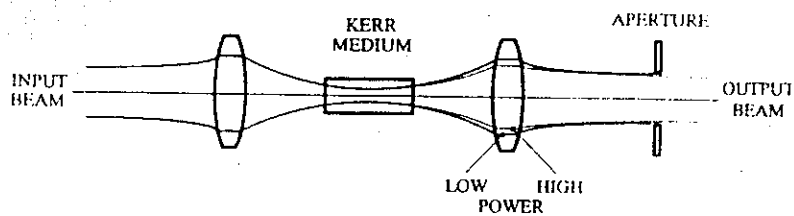


Figure 8: Intensity-dependent transmission through an aperture using self-focusing. Low power beam (dotted line), high power beam (solid line). From Krausz *et al*, Ref. [6].

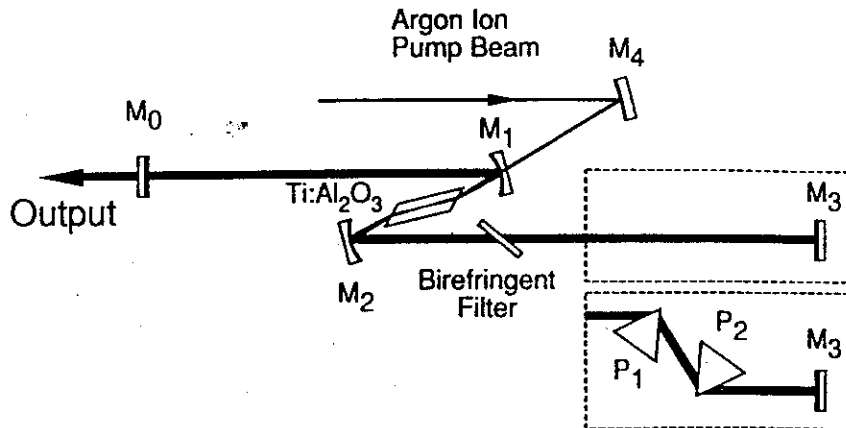


Figure 9: Schematic of cavity arrangement of self-mode-locked Ti:sapphire laser. The inset shows the intracavity prism pair used for group velocity dispersion compensation. From Sibbett, Ref. [98].

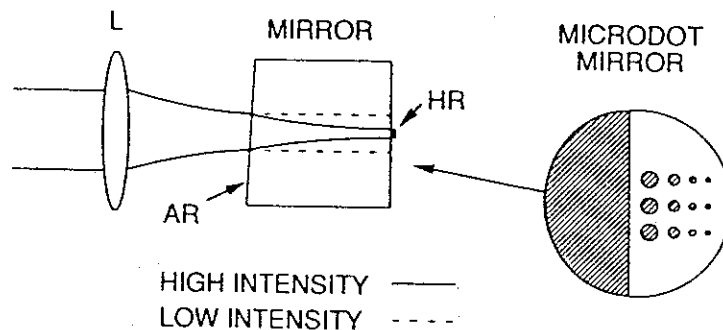


Figure 10: Schematic of the microdot mirror modulator. The beam is focused by the input lens L into an antireflection-coated BK7 substrate that has high reflectivity microdots on the rear surface. The nonlinear self-focusing in the glass produces a smaller focal spot and an increasing reflectivity for higher intensities. From Gabetta *et al*, Ref. [57].

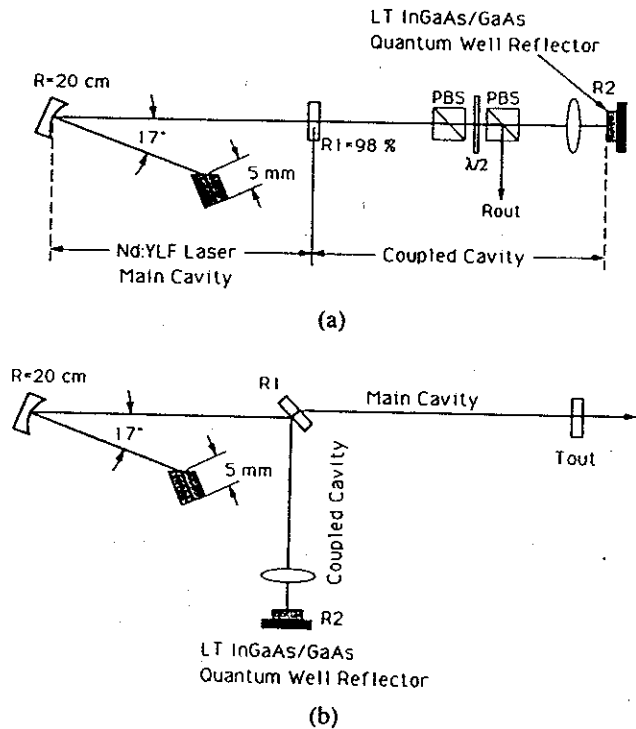


Figure 11: RPM cavity design. (a) Fabry-Perot type and (b) Michelson type. From Keller and Chiu, Ref. [5].

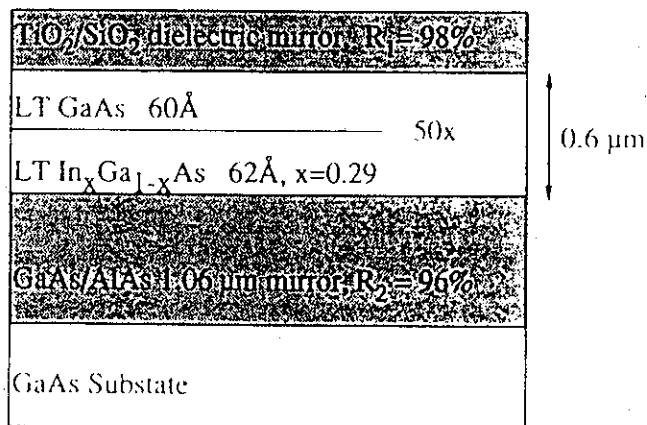


Figure 12: Intracavity saturable absorber: an antiresonant semiconductor Fabry-Perot saturable absorber. From Keller and Chiu, Ref. [5].

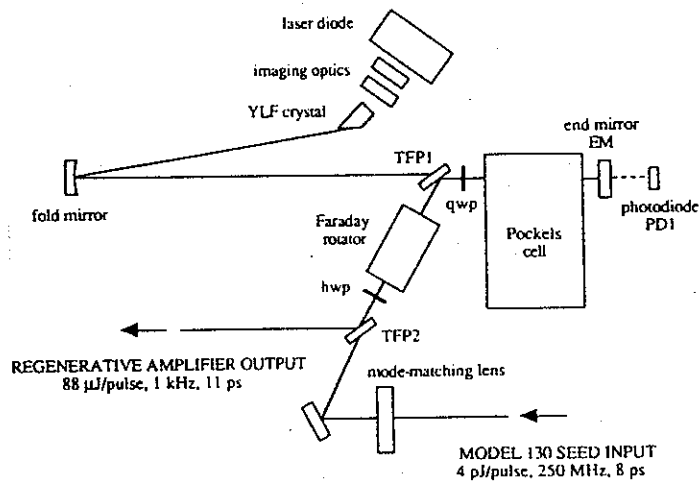


Figure 13: Schematic of the half-wave switching arrangement. TFP's, thin-film polarizers; qwp, quarter-wave plate. A seed pulse is trapped in the cavity when the Pockels cell quarter-wave voltage is applied, then cavity dumped with the half-wave voltage. The pulse buildup is monitored by PD1, whereas the output pulse is monitored by a second photodiode, not shown. From Gifford and Weingarten, Ref. [76].

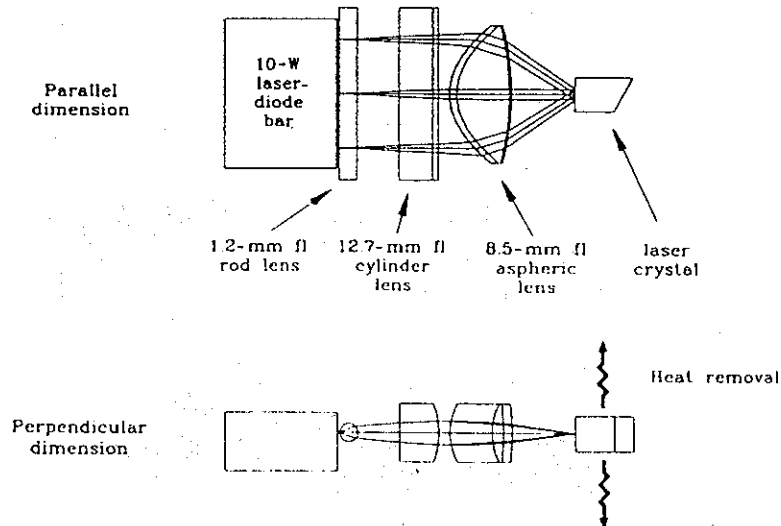


Figure 14: Optical arrangement used to focus light from a 10-W laser-diode bar. The distance between rod and cylinder lenses is 1 mm, between the cylinder and the aspheric lenses it is 1 mm, and between the aspheric lens and the Nd:YAG crystal it is 4.5 mm. The optical traces represent the extreme rays from three of the individual emitters within the laser-diode bar. fl, focal length. From Shannon and Wallace, Ref. [77].

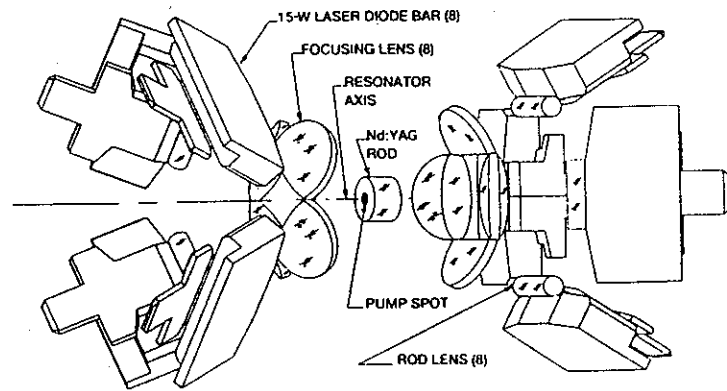


Figure 15: Angularly multiplexed pump geometry used to focus the power of eight 15-W laser diode bars into each laser rod. From Tidwell *et al*, Ref. [78].

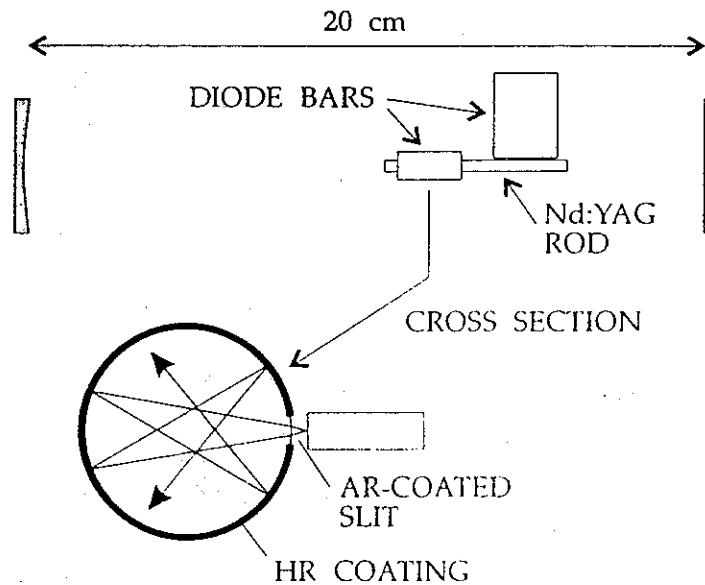


Figure 16: Schematic view of the laser diode side-pumped Nd:YAG laser showing the multipass pumping geometry. From Ajer *et al*, Ref. [80].

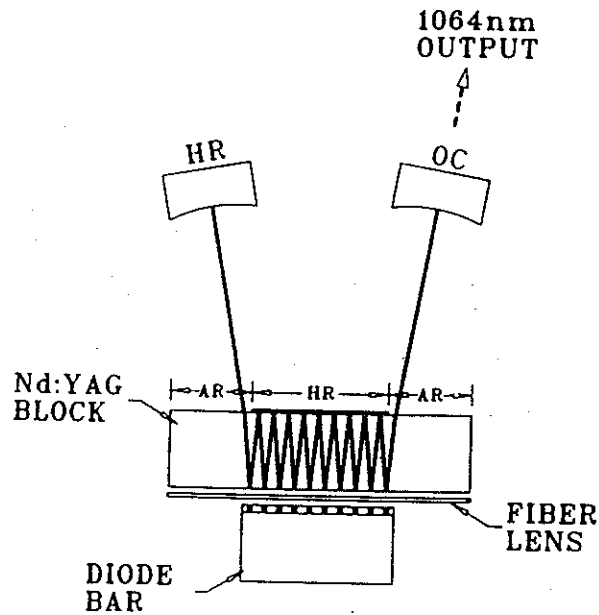


Figure 17: Top view of the TFR laser design. Each vertex in the Nd:YAG block is aligned with a diode laser array on the diode bar. From Baer *et al*, Ref. [81].

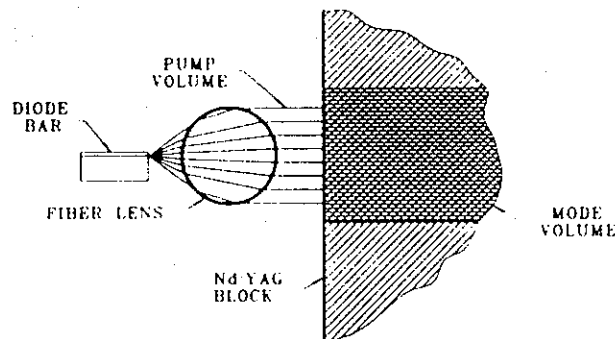


Figure 18: Side view of the TFR laser design illustrating the collimating fiber and the overlap of the pump and lasing regions in the active medium. The pump region has a height of $\sim 200 \mu\text{m}$. From Baer *et al*, Ref. [81].

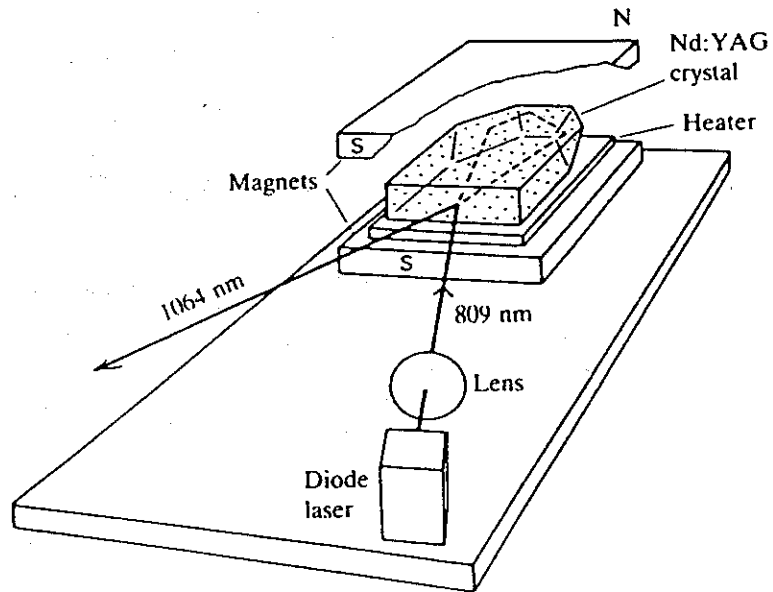


Figure 19: The single-frequency diode-pumped non-planar ring oscillator. From Kane and Byer, Ref. [84].

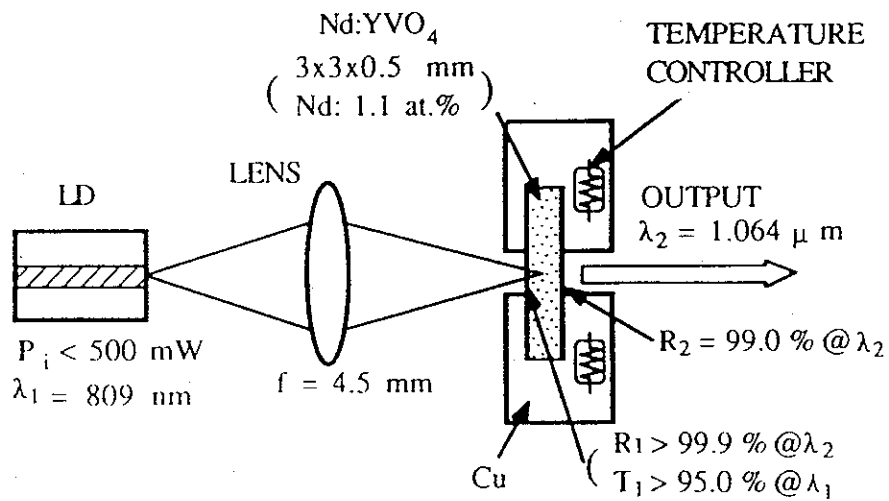


Figure 20: Schematic of the laser diode-pumped Nd:YVO₄ microchip laser with single-longitudinal-mode oscillation. LD, laser diode. From Taira *et al*, Ref. [88].

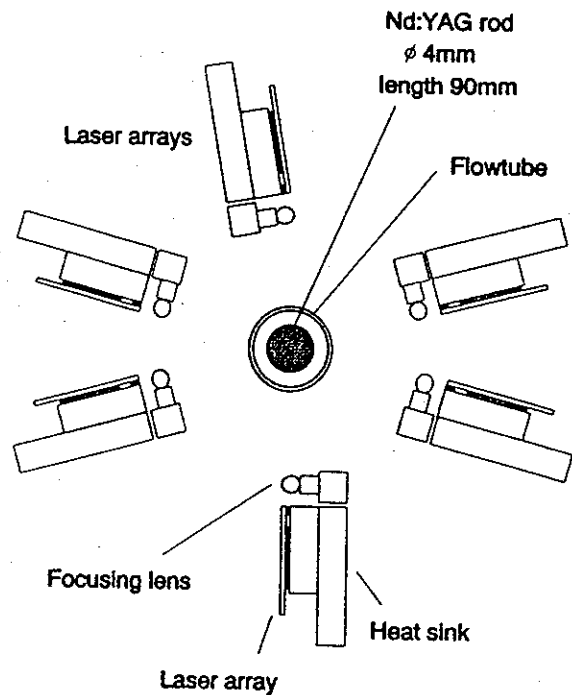


Figure 21: Schematic diagram of the laser head, side-pumped by 28 diode lasers (6 pump modules with 4 or 5 diode lasers each). From Golla *et al*, Ref. [70].

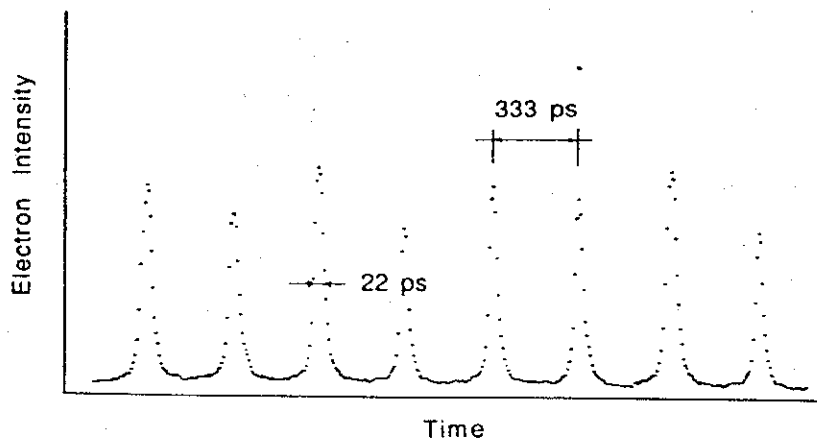


Figure 22: The train of eight 22 ps long electron drive bunches as measured by the streak camera.

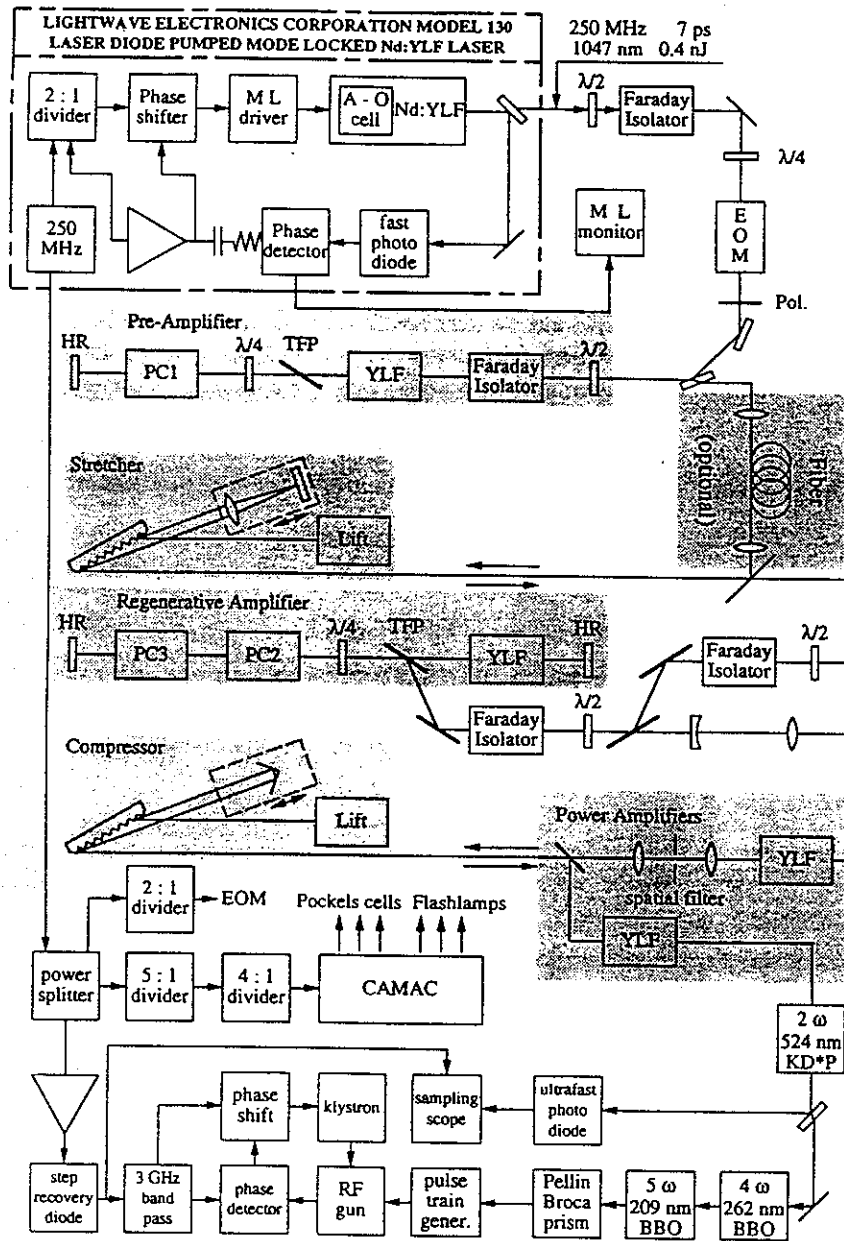


Figure 23: Synchro laser system for the CTF Rf gun at CERN.

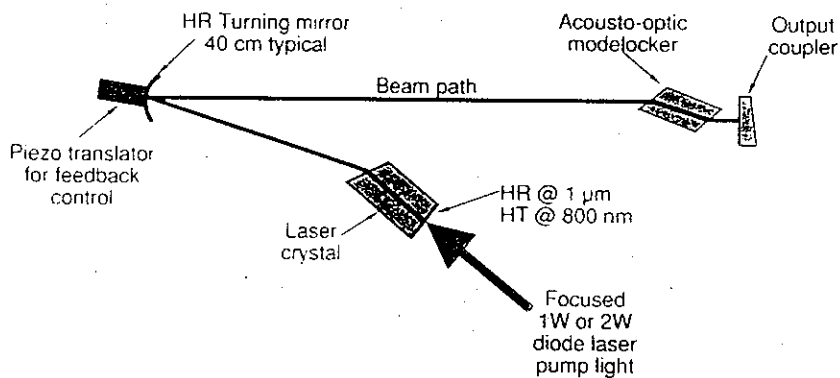
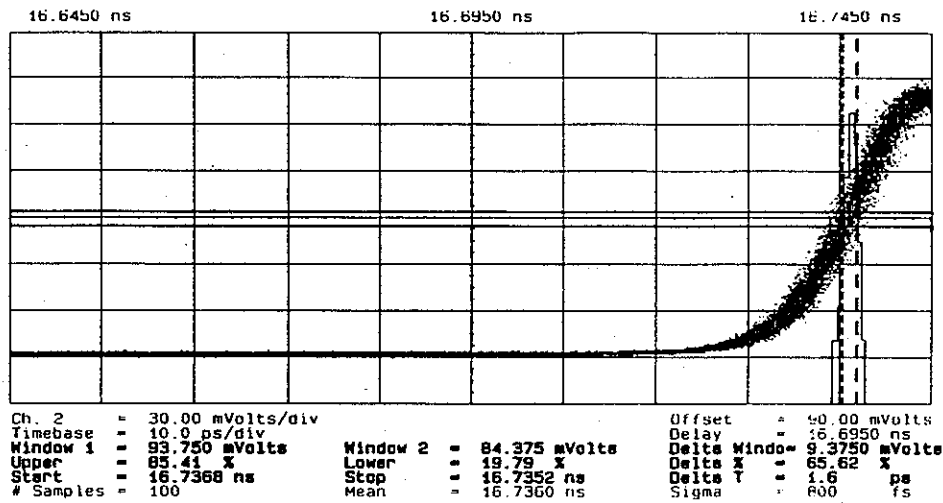


Figure 24: Model 130 folded cavity layout, showing the principle of longitudinal diode pumping and Brewster surfaces on intracavity components. From Weingarten et al, CLEO 91, paper CThR15.



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Figure 27: Time jitter measurement of 0.8 ps between optical output of the mode-locked laser and the external signal generator.

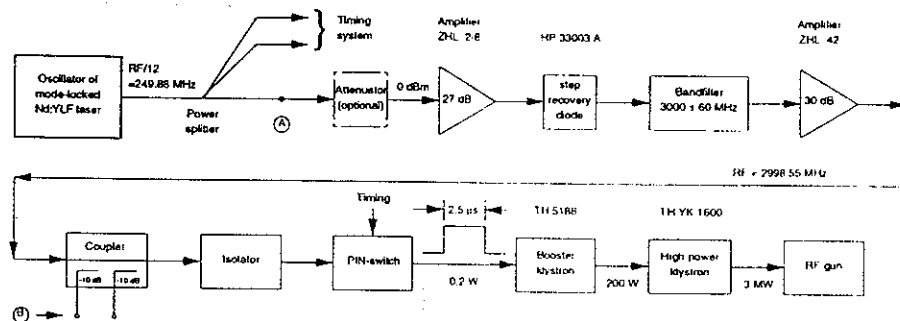


Figure 28: Synchronization between laser and RF gun. Time jitter of zero-crossing signal between A (249.88 MHz) and B (2998.55 MHz) is $\sigma_{\tau} = 1.3$ ps

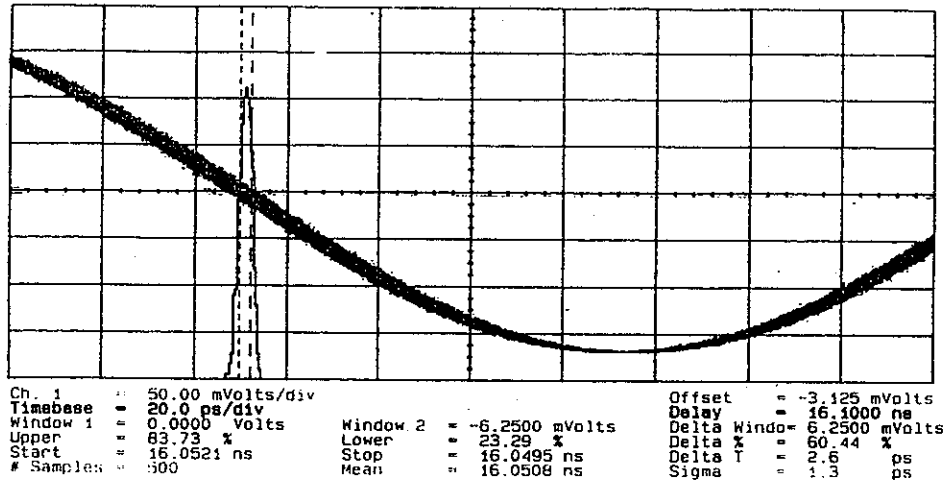


Figure 29: Time jitter of the RF signal at measuring point B: $\sigma_{\tau} \leq 1.3$ ps. Sampling scope HP 54124T triggered by the signal from output A.

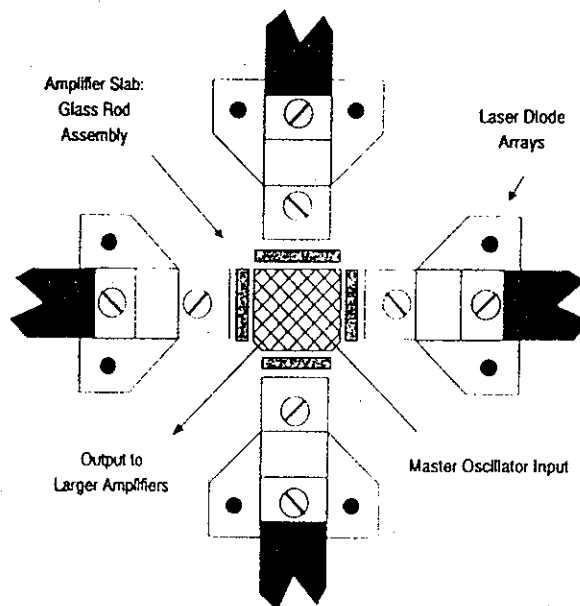


Figure 30: Top view of the APS amplifier with four two-bar stack diode arrays used as pumps from four sides. The dimensions are 8×8 cm² and the crystal is heat sunk from the top and underneath. The total path length inside the slab is 32 cm.

