A laser comprises a pump laser (202, 204, 206) for generating a pump laser beam, and a main laser (208, 210) for generating a main laser beam and arranged to be pumped by the pump laser beam. Various measures are adopted to enable the initiation and maintenance of self-mode-locking of the main laser beam even at low threshold pump laser powers. A device for initiating mode-locking of the main laser beam is also disclosed.
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A LASER AND A DEVICE FOR INITIATING
MODE-LOCKING OF A LASER BEAM

This invention relates in general terms to a laser and to a
device for initiating mode-locking of a laser beam. The
invention relates more particularly to a laser which is powered
by an arrangement of one or more semiconductor lasers (or "laser
diodes") and which is capable of producing a frequency-tunable
(vibronic) laser beam of short duration pulses by the technique
of self-mode-locking. Such pulses may have a duration in the
femto second (fs) regime (1fs = 10^{-15}s).

Lasers capable of producing pulses in the femto second regime
are of use in time-domain-laser spectroscopy (for example,
photophysics, photochemistry and photobiology). They are also of
use in radar, range-finding, communications and optical or
optoelectronic data processing applications, as well as in many
engineering and medical applications.

The present inventor is author or co-author of a number of
publications disclosing techniques for self-mode-locking lasers.

In a paper by Spence, D.E., Kean, P.N. and Sibbett, W. entitled
"60-fsec pulse generation from a self-mode-locked Ti:sapphire
self-mode-locked large frame Argon-ion laser pumped Ti:sapphire
laser was demonstrated which was capable of generating 60-fs
pulses at peak powers of 90kW. Self-mode-locking was initiated
by tapping one of the laser mirrors of the near-concentric
extended resonator. In a further paper by Spence, D.E., Evans,
J.M., Sleat, W.E. and Sibbett, W. entitled "Regeneratively
initiated self-mode-locked Ti:sapphire laser" (Optics Letters,
Vol. 16, No. 22, p.1762, published on 15th November 1992) various
more effective schemes for initiating the self-mode-locking were
disclosed, including the use of saturable absorber dyes, various
types of coupled-cavity schemes, active cavity length modulation
and acousto-optic modulation.

In a paper by the present inventor entitled "Femtosecond
Laser Sources For Near-Infrared Spectroscopy" (Institute of
Physics Conference Series 1992, No. 126, p.1, published in June 1992), a qualitative explanation of the self-mode-locking process was provided. In summary, the preliminary requirement is that an initial pulse be generated by suitable initiating means within the laser cavity, of sufficient intensity to access a $\chi^3$-type (or Optical Kerr-type) non-linearity in the laser gain medium or additional intracavity non-linear medium. When a sufficient intracavity initial pulse intensity has been established then a focussed beam in the gain medium (or additional non-linear medium) gives rise to self-phase-modulation and self-focussing (optical Kerr-lens) effects. The spectral expansion due to self-phase-modulation and the spatial beam changes due to self-focussing, together with controlled intracavity Group Velocity Dispersion (GVD) lead to substantial pulse shortening and pulse shaping processes.


The self-mode-locked lasers disclosed in the papers by the present inventor referred to above were Argon-ion laser pumped Ti:sapphire lasers. However, large frame Argon-ion lasers are expensive, bulky (some metres in length), cumbersome (they require water cooling) and inefficient (about 0.5% efficiency). Further, they can consume of the order of 40kW of electricity, and require a three-phase power supply. In addition, they suffer from beam intensity variability arising from electrical ripple in their power supplies and plasma instabilities in the ion-laser tubes. Such variability can give rise to long-term timing jitter.

A solution to these problems would be to pump the main laser with a semiconductor laser arrangement (for instance, a high power, broad stripe or multi-stripe laser diode array) rather than the Argon-ion pump. Semiconductor lasers are relatively cheap, comparatively small (a few millimetres in length), easily handled and efficient (about 50% efficiency). Further, they consume relatively small amounts of electricity (typically less
than 1 kW) and do not require a three-phase supply. In addition, they suffer less markedly from beam intensity variability. If such a semiconductor laser pump arrangement were combined with a Ti:sapphire or other similar solid-state vibronic laser medium, a cheap and compact all-solid-state laser could be produced.

The present inventor has already suggested such a combination in his paper entitled "Femtosecond Laser Sources For Near-Infrared Spectroscopy" (published in June 1992), referred to previously. However, no teachings enabling such a combination to be built and operated successfully were given.

A self-mode-locked, semiconductor laser pumped Nd:YLF laser has also been disclosed in a paper by Malcolm, G.P.A. et al. entitled "Self-mode locking of a diode-pumped Nd:YLF laser" (Optics Letters, Vol. 16, No. 24, p.1967, published on 15th December 1991). The pump power was provided by two high power laser diodes, producing a combined pump output power of about 5W. Self-mode-locking was initiated and maintained not in the gain medium but in a separate non-linear medium in the cavity. Pulse durations of 6ps were reported. This arrangement has the disadvantages firstly that the addition of a separate non-linear medium renders the cavity arrangement more complicated and cumbersome, and secondly that the duration of the pulses is insufficiently short for many purposes.

It has now been discovered, pursuant to the present invention, that self-mode-locking can be successfully initiated and maintained, even using a relatively low power semiconductor laser (for example, less than 2 to 3 W) as a pump laser, even without a separate non-linear medium and even at ultra-short pulse durations, provided various surprising measures are adopted. These measures are described in relation to the various aspects of the invention stated below. Such measures are particularly important when a semiconductor laser is used as the pump laser, but can more generally improve the self-mode-locking performance of lasers however they are pumped.

According to a first aspect of the present invention, there
is provided a laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the beam pointing of the pump laser beam being stable to within ± 30µ rad, preferably to within ± 10µ rad, more preferably to within ± 5µ rad.

This aspect of the invention arises from the discovery pursuant to the present invention that strict control of the beam pointing (or directionality) of the pump beam can be important. It has been discovered that if the beam pointing is controlled to within at least ± 30µ rad, then the gain mode volume in the laser medium in the main laser can be spatially defined with high precision. This in turn can assure that the laser beam generated by the main laser is accurately spatially confined so that the propagation path followed by the intensity pulses in traversing the main laser cavity is accurately reproduced and stable and thus so that the laser cavity frequency is precisely defined. If the cavity frequency is precisely defined, the longitudinal mode separation can be maintained constant. By applying suitable modulation (for example, amplitude modulation), there can thus be coherent communication between the longitudinal modes, so that the modes can be phase coupled over enlarged bandwidths. In this way the spectral broadening necessary for pulse shortening can be enhanced.

One additional advantage of the cavity frequency being precisely defined has been found to be that long-term timing jitter can be maintained at low levels.

It has also been discovered that control of the pump beam pointing to the degree stated above can further enhance the self-mode-locking process via what is referred to hereinafter as "self-amplitude modulation". If the pump beam is directionally highly stable, the main laser beam is subjected to the self-focussing effects referred to previously. These, it has now been discovered, can lead to "gain guiding" in which areas of higher gain are accessed by the self-focussed beam, and hence to an increase in intensity (self-amplitude modulation).
In other words, gain guiding (or spatial dependence of gain) arises because a self-focussed beam will have access to an amplification that is different from that of a beam which has not experienced any significant self-focussing effect. The pumping on axis (and therefore the gain) is higher than that away from the axis in the laser medium.

Hence, if the beam pointing of the pump laser beam is stable to within the prescribed limit, self-mode-locking may be successfully initiated and maintained, even at relatively low intracavity power levels.

According to a second aspect of the present invention, there is provided a laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the pump laser beam being within 30%, preferably within 20%, more preferably within 10%, even more preferably within 5% of the diffraction limit.

This aspect of the invention arises from the discovery pursuant to the present invention that a near-diffraction limited pump beam can be an important measure in ensuring the successful initiation and maintenance of self-mode-locking of the main laser beam. It has been discovered that, unless the pump laser beam performs to within 30% (or less) of the diffraction limit, the pump laser beam may not be confined to a sufficiently small volume in the main laser medium or provide sufficiently good spatial overlap with the main laser beam to permit intensity-induced non-linearities to be accessed by that main beam. However, if the beam is near-diffraction limited, then the power levels in the laser medium can become sufficiently high to access these non-linearities.

A closely related aspect of the invention provides a laser comprising a pump laser for generating a pump laser beam and a main laser including a laser medium arranged to be pumped by the pump laser beam, the minimum cross-sectional area of the pump laser beam in the laser medium being less than 3000μm², preferably less than 1000μm², more preferably less than 300μm²,
even more preferably less than 100μm², the pump laser beam confocal parameter being at least 50%, preferably at least 75%, and more preferably being roughly 100% of the operational length of the laser medium.

5 The areas of 3000, 1000 and 300μm² correspond to beam waists (diameters) of roughly 60, 35 and 20μm. Since the cross-sectional area of the beam may vary with time, the values given above would usually be considered as time-averaged values. The confocal parameter is defined as twice the distance from the beam location of minimum cross-sectional area to the beam location of twice that minimum area.

10 The article by Malcolm, G.P.A. et al. entitled "Self-mode locking of a diode-pumped Nd:YLF laser" (published 15th December 1991), and referred to earlier, discloses a pump beam waist in the gain medium of 270μm. A relatively low confocal parameter would obtain due to the type of optics used for focussing. The beam waist for the main laser beam (not the pump beam) is disclosed as being 30μm in the additional intra-cavity non-linear medium. It is to be noted that the pump beam does not impinge on this non-linear medium.

15 This aspect of the invention arises from the discovery, alluded to in relation to the preceding aspect of the invention, of the importance of a near-diffraction limited pump beam, especially at relatively low pump output powers. The particular values for the cross-sectional area and confocal parameter limits have been derived from a series of experiments. As regards the confocal parameter specifically, it has been found to be important that the pump beam remains focussed for a significant proportion of the operating length of the laser medium.

20 Whether or not an additional intra-cavity non-linear medium is provided, the minimum cross-sectional area of the pump laser beam in the gain medium itself is preferably less than 3000μm², more preferably less than 1000μm², even more preferably less than 300μm², and more preferably still less than 100μm². This can ensure that self-mode-locking occurs in the gain medium rather
than (or as well as) in the non-linear medium. The advantage of self-mode-locking occurring in the gain medium is that beneficial self-amplitude and gain guiding effects can occur there.

According to a further aspect of the present invention, there is provided a laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the pump laser being arranged to operate in a single longitudinal mode.

This aspect of the invention arises from the discovery pursuant to the present invention that operation of the pump laser in a single longitudinal mode can be an important measure in ensuring the initiation and maintenance of self-mode-locking. By arranging that the pump laser lases at a single longitudinal mode frequency, mode beating (or gain competition) effects can be avoided and thus a pump beam of very constant intensity can be produced, free from significant phase variations. Thus the self-mode-locking process, which relies on intensity-induced non-linear effects, can be stable so that ultrashort (high coherence) intensity pulses can be reliably and regularly produced.

According to another aspect of the present invention, there is provided a laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the intensity of the pump laser beam being stable to within 1%, preferably to within 0.1% of its root mean square value.

The paper entitled "Femtosecond Laser Sources For Near-Infrared Spectroscopy" (published in June 1992), and written by the present inventor, discloses the requirement that the pump laser beam should be free from any intensity variability in order to minimize timing jitter.

This aspect of the invention is closely related to the previous, near-diffraction limited pump beam aspect in that it has been found pursuant to the present invention that a pump beam having the intensity stability qualities as aforesaid can reliably produce ultrashort (high coherence) intensity pulses in
the main laser. Such intensity stability qualities can also serve to minimize long-term timing jitter.

According to another aspect of the present invention, there is provided a laser comprising a pump laser, including a radiation source comprising a semiconductor laser arrangement, for generating a pump laser beam, a main laser including a laser medium arranged to be pumped by the pump laser beam to generate a main laser beam, and means for matching the cross-sectional shape, and preferably also the size, of the pump and main laser beams in the laser medium.

This aspect of the invention arises from the discovery pursuant to the invention that the cross-sectional shapes of the pump and main laser beams must be closely matched in the laser medium if self-mode-locking is to be successfully initiated and maintained at low intra-cavity power thresholds. It has been found that unless close matching occurs there, sufficiently efficient lasing cannot occur. With a semiconductor laser arrangement as the radiation source, the two beams will not usually have matching shapes; the output beam from a semiconductor diode is usually highly elliptical, whereas the main laser beam is usually circular or near-circular.

Hence in practice it is often preferable that the matching means comprises means (such as an anamorphic optical device, for example a cylindrical lens) for circularising the beam output by the semiconductor laser arrangement.

It has been found pursuant to the present invention that one way by which a pump beam may be produced from a semiconductor laser arrangement, of sufficiently high quality to initiate and maintain self-mode-locking, is to injection lock the semiconductor laser or lasers. Injection locking may, for instance, be achieved by a master laser or external cavity arrangement.

disclosure of the use of this laser as a pump laser.

In a further aspect of the present invention, there is
provided a laser comprising a pump laser for generating a pump
laser beam in a pump laser cavity and a main laser arranged to be
pumped by the pump laser beam, the pump laser including means for
converting the frequency of the pump laser beam, the converting
means being mounted within the pump laser cavity.

This aspect of the invention arises from the discovery
pursuant to the present invention that the quality of the pump
beam, and especially its intensity stability, may be insufficient
to initiate and maintain self-mode-locking if the frequency
conversion means is mounted external to the pump laser cavity,
and that an intracavity location is a convenient solution to this
problem. Mounting the frequency conversion means intra-cavity
has the advantage that the efficiency of the harmonic generation
process is enhanced through the higher level of power available
inside the cavity rather than outside it.

According to a further aspect of the present invention, there
is provided a laser comprising means for generating a laser beam
having at least two distinct frequency components, and means for
initiating mode-locking of the beam. The laser would usually
generate the two or more distinct frequency components
simultaneously and preferably in time synchronisation. The
distinct frequency components may also be spatially distinct at
various locations.

This invention is based on the surprising discovery that a
laser can be arranged to produce two or more distinct frequency
components whilst in a mode-locked (for example,
self-mode-locked) configuration. Hitherto, it had only been
believed possible to produce distinct frequency components whilst
in a continuous wave configuration.

Operation at two or more distinct frequencies in a
mode-locked configuration has several advantages. For example, in
many types of photophysical, photochemical or photobiological
investigations it may be useful to have pulses at different
frequencies. One particularly important advantage, provided that the two distinct frequency components are temporally synchronised, is that these components (with one or both of the frequencies possibly being frequency converted) can be mixed in a non-linear device to provide a difference frequency which can (and usually will) be quite different from the fundamental frequencies.

Hence new, previously unavailable frequency ranges can be provided. The short duration, high peak power pulses produced by the mode-locking process can ensure that the difference frequency beam can be generated relatively efficiently by the non-linear device.

In any of the aspects of the invention, the main laser medium may include a gain medium and a separate non-linear medium, and, indeed, where the gain medium is not extended (for example, a colour-centre crystal or dye jet) a separate non-linear medium may be essential. However, it is generally preferred that the laser medium consists only of gain medium. This can improve the functioning of the self-mode-locking process since self-amplitude-modulation and gain guiding effects (which can only occur in the gain medium) would be exploited to the full. Additionally, removal of the non-linear medium can render the whole laser more compact, especially since this would remove the need for the cavity optics required with the non-linear medium.

The invention extends to the laser as aforesaid including means for initiating mode-locking of the main laser beam. However, such means may in some rather limited circumstances not be necessary; mode-locking may, for instance, in certain circumstances be initiated simply by tapping one of the mirrors of the laser cavity.

According to a further aspect of the present invention, there is provided a laser comprising means for generating a laser beam and means for initiating mode-locking of the laser beam, the initiating means being arranged to initiate an intensity pulse of duration less than 50ps, preferably less than 20ps, more preferably less than 10ps, even more preferably less than 5ps.
In the article entitled "Regeneratively initiated self-mode-locked Ti:sapphire laser" (published on 15th November 1991) referred to above, the acousto-optic modulator employed as the initiating means in the Argon-ion pumped laser yielded a relatively slow amplitude (intensity) modulation with a period of approximately 12 ns. In these circumstances it has been found that the initial pulse is relatively long (of the order of some hundreds of picoseconds to one nanosecond). It has been discovered pursuant to the present invention that, especially in the circumstances of low to moderate pump power (as opposed to the relatively high power of the Argon-ion pump laser), non-linearities in the gain medium (or additional intracavity non-linear medium) may not be adequately accessible by initial pulses of such duration due to their insufficient peak powers.

Thus this aspect of the invention arises from the discovery pursuant to the invention that the duration of the initial (or enabling) pulses produced by the initiating means needs to be sufficiently short before self-mode-locking can be successfully initiated and maintained, and that, all other circumstances being equal, the lower the pump laser power, the shorter the duration needs to be. The duration may need to be especially short if the radiation source for the pump laser is a semiconductor laser arrangement of relatively low power (for example, 1 to 3W).

In one preferred embodiment of means for initiating mode-locking of a laser beam, the initiating means includes a saturable absorbing medium having an operating thickness less than 100µm, preferably less than 75µm. It has been discovered pursuant to the present invention that such an absorbing medium is capable of ultrafast (less than 50ps, of the order of 20 to 40 ps) recovery. Such a recovery time leads to the production of an initial pulse having a duration in the 10 to 15ps region.

In another preferred embodiment, the initiating means comprises a support element having cavities (usually a large number of preferably volumetric micro-cavities or inclusions), and a saturable absorbing medium contained in the cavities. Such
an arrangement can provide a chemically stable saturable absorber capable of ultrafast operation.

Preferably, the support element consists of a sol-gel material. By "sol-gel material" is meant a material made by a sol-gel process. A sol-gel material is advantageous because it can be manufactured at temperatures sufficiently low to avoid decomposition of the saturable absorbing medium. High temperatures, by contrast, are incompatible with molecular or microcrystallite stability requirements. A further advantage stemming from the low temperature processing and consequent absence of surface annealing is that the existence of a higher surface density of states can lead to pronounced fast-response non-linear characteristics.

In a further preferred embodiment, the initiating means includes means, preferably an acousto-optic modulator, for modulating a property of the beam, the modulation being effected at a frequency higher than 150MHz, preferably higher than 200MHz and more preferably higher than 250MHz. Such a modulator can afford a suitably fast response. Preferably, the depth of modulation is at least 20%, so that a strong discrimination can exist between the continuous and mode-locked operational status.

In a further preferred embodiment, the pump laser beam is itself mode-locked. This can afford a satisfactory alternative means of initiating mode-locking of the main laser beam. It will of course be understood that any of the above described aspects of the invention may be provided in any appropriate combination one with another.

Preferred features of the present invention are now described, by way only of example, with reference to the accompanying drawings, in which:-

Figure 1 illustrates the far-field intensity distribution from a typical semiconductor laser diode;

Figure 2 is a schematic representation of a first variant of a first embodiment of laser according to the present invention;
Figure 3 is a schematic representation of a pump laser for use in the first variant;

Figures 4a and 4b are respectively schematic plan and side view representations of a pump laser for use in a second such variant;

Figure 5 is a block diagram of a second embodiment of laser according to the present invention;

Figure 6 is a more detailed schematic representation of the second embodiment;

Figure 7 shows two plots illustrating the beam pointing stability of a pump laser for use in the second embodiment;

Figure 8 demonstrates the characteristics of a saturable absorber suitable for use in the present invention;

Figure 9 is an embodiment of laser according to the present invention for generating a laser beam having two distinct frequency components; and

Figure 10 illustrates the tuning range of this laser.

FIRST EMBODIMENT OF LASER

Reference is made first to Figures 1 to 4, which illustrate a first embodiment of laser according to the present invention. The first embodiment illustrates two different schemes (the "first" and "second" variants) for pumping a vibronic laser medium directly using a semiconductor laser diode source.

Figure 1 illustrates the far-field intensity distribution from a typical broad stripe high-power laser diode 100. The laser beam 102 emitted by the diode is nowhere near its diffraction limit and, as explained previously, is hence unsuitable for creating and sustaining self-mode-locked conditions in a laser medium. Indeed most such diodes yield multiple lobe problems in the far-field. A dual lobe pattern (lobes 102a and 102b) is illustrated in Figure 1. It will be appreciated that more lobes may appear for higher power devices. One of the objects of the first embodiment is to improve the quality of the beam produced by such a laser diode.

The first variant of the first embodiment is illustrated with reference to Figures 2 and 3. The laser shown in Figure 2
includes a main laser cavity 110 comprising a relatively extended Cr:LiSAF (Chromium:Lithium-Strontium-Aluminium-Fluoride) laser medium 112 (which absorbs light at 450-670 nm and emits at 750-1000 nm), optical elements 114 which are, where appropriate, reflecting and transmitting at the appropriate wavelengths of light to allow lasing to occur, an optional aperture 116 for tuning purposes (and to assist gain guiding at higher-power levels), a prism pair 118 to compensate for second and higher order group velocity dispersion effects, and an acousto-optic modulator 120 or other means for initiating the self-mode-locking process. Such means are described in more detail later in the section entitled "Means for Initiating self-mode-locking".

The main laser cavity 110 is pumped in this embodiment by four MOPA's (Master Oscillator, Power-Amplified diode laser), MOPA 1 to MOPA 4, producing high quality laser beams around 670 nm wavelength, via two PBC's (Polarisation Beam Combiners), PBC 1 and PBC 2 and via focussing elements of the optical elements 114. The MOPA's will be described later in more detail in relation to Figure 3.

This embodiment of laser functions as follows. Horizontally polarised light is injected into the laser cavity 110 from MOPA 1 and MOPA 3 whilst vertically polarised light is injected from MOPA 2 and MOPA 4. The Cr:LiSAF laser medium 112 has an absorption coefficient which varies significantly in dependence on the polarisation of light, so that the PBC's provide a convenient way of combining light from the sources. Because of the high beam quality of the pump beams entering the main laser cavity the non-linearities in the laser medium can be accessed even though the MOPA's are of relatively low power (0.25 to 0.5W). Self-mode-locking of the laser beam is initiated by means of the acousto-optic modulator 120 and is sustained by means of the high beam quality of the pump beams. Picosecond or even femtosecond duration pulses can be produced which are output via optical element 114c (or 114d if preferred).

In a modification of the first embodiment suitable for OEM
(Original Equipment Manufacture) purposes, instead of the MOPA outputs being combined using polarisation beam splitters, they could be combined using an optical fibre coupler such as that disclosed in European Patent Application No. 90908297.6 (in the name of the British Technology Group).

It will be appreciated that other laser media than Cr:LiSAF could be employed, provided that the wavelength of light available from the MOPA's is compatible with the absorption spectrum of the laser medium in question. Possible alternative media are Cr:LiCAF (Chromium:Lithium-Calcium-Aluminium-Fluoride) and Cr:LiSCAF (Chromium:Lithium-Strontium-Calcium-Aluminium-Fluoride).

A typical MOPA is shown in Figure 3. The MOPA comprises an AlGaInP (Aluminium-Gallium-Indium-Phospohide) dual-mode slave laser diode 130 (which emits at 670nm), a comparatively low power (5mW), high beam quality, short cavity length semiconductor master laser 132 operating in a single longitudinal mode at 670nm, times 20 magnification microscope objective lenses 134 and 136, which are anti-reflective at 670nm, interposed between the slave and master lasers, a cylindrical lens 138 of 25mm focal length and a uni-directional device 140 interposed between the lenses 134 and 136.

The master laser 132 is of high beam quality due largely to its short cavity length and low power. It acts to "injection seed" (or injection lock) the dual-mode slave laser diode 130 in such a way that the slave laser produces a single longitudinal mode, high quality output beam which is matched to and controlled by the wavelength of the master laser. In other words, the output beam is both spatially and spectrally enhanced so that it is near-diffraction limited. If the power of the slave laser is 250mW (as is often the case), the output power will typically be on the order of 200mW or higher.

The cylindrical lens 138 functions to circularise the output beam, since otherwise the output beam would be highly non-circular (see Figure 1), and hence unsuitable for producing an optimal spatial distribution of gain within the main laser.
medium. The optimal spatial distribution is provided when the pump beam in the laser medium is matched to the transverse mode of the main laser beam.

The laser diode is powered from an electrical power supply via an electrical smoothing unit (not shown) to assist the MOPA in producing a constant intensity output.

As of 1992, the maximum power available from a commercial laser diode operating at roughly 670nm is 15W. It will be appreciated that fewer MOPA's would be required if higher power laser diodes became available, since the MOPA's need only be provided in sufficient numbers to achieve in combination the power necessary to access the non-linearities in the laser medium.

A second variant of the first embodiment of laser according to the present invention is now described with particular reference to Figures 4. The basic configuration is the same as that with the first variant (see Figure 2) but, instead of the four MOPA's, four corresponding external-cavity injection locked laser diode pump arrangements are provided.

Plan and side views of one of these pump arrangements are shown in Figures 4a and 4b. The arrangement includes an AlGaInP laser diode 142. A portion of the laser diode output is "injected" back into the diode by means of an external cavity 144 comprising a times 20 magnification microscope objective lens 146 which is anti-reflective at 670nm and serves to focus the laser diode output, a 25mm focal length cylindrical lens 148, and a mirror 150 which is highly reflective at 670nm.

By injecting some of the light back into the laser diode 142, the spatial beam quality of the pump output beam (which is output via the mirror 150) can be significantly enhanced. In fact, output beams of only 1.2 times the diffraction limit have been produced pursuant to the present invention. However, unlike the first variant (using a master laser), no control of the wavelength of the beam is effected, so that there is no spectral enhancement.

In a modification of the first embodiment of the invention, the pump laser is itself either actively, passively or
self-mode-locked. This is explained later in the section entitled "Means for initiating self-mode-locking" in relation to the third embodiment of initiating means. If the high beam quality injection-locked external cavity arrangement described in relation to Figures 4 is adopted, one way of self-mode-locking the pump laser is to use an intracavity ultrafast saturable absorber. Such an absorber is described in more detail in relation to the first embodiment of initiating means.

It will be appreciated that in the first embodiment of laser stable beam pointing is assured by use of the injection locking technique (whether a master oscillator or a coupled cavity is utilised). Also, laser diodes in general have higher beam pointing stability than Argon-ion lasers; this of itself can make a significant contribution to the beam pointing stability of the laser. Further, the fact that the laser medium is end-pumped ensures that the advantages of the high beam pointing stability are exploited.

Also, it will be appreciated from the foregoing that the injection locking technique in either of its variants produces a near-diffraction limited pump beam of sufficiently small cross-sectional area and high confocal parameter to permit the initiation and maintenance of self-mode-locking.

SECOND EMBODIMENT OF LASER

The second embodiment of laser according to the present invention is now described with reference to Figures 5 to 7. As of 1992, semiconductor laser diodes of higher power than those discussed in relation to the first embodiment are commercially available, but these only emit at higher wavelengths, for example 810nm (for an AlGaAs laser diode) as compared with 670nm (for an AlGaInP laser diode). The second embodiment utilises such higher power diodes. Pump beam quality is assured by arranging that the diodes pump an intermediate pump laser medium. Compatibility with the absorption spectrum of the pumped, possibly vibronic, main laser medium can be achieved by the use of intracavity frequency doubling in the pump optical cavity.
The second embodiment of laser is illustrated in broad terms with reference to Figure 5. A laser diode 200 pumps a pump laser comprising a pump micro laser cavity 202, a micro laser medium 204 and an optional intracavity frequency doubling crystal 206. The pump laser in turn pumps a main laser comprising a main laser cavity 208 and a vibronic laser medium 210. The diode 200 may be AlGaAs at 810nm for pumping a Nd:YAG (Neodymium:Yttrium-Aluminum-Garnet) micro laser medium 204 or AlGaAs at 795nm for pumping a Nd:YLF (Neodymium:Yttrium-Lithium-Fluoride) micro laser medium. The frequency doubling crystal may be a KTP (Potassium-Titanyl-Phosphate) or LBO (Lithium-Triborate) non-linear crystal, and is employed if required to render compatible the emission wavelength of the laser diode 200 and the absorption spectrum of the vibronic medium 210.

Thus the frequency doubling crystal is required if, for instance, the vibronic medium 210 is Ti:Al$_2$O$_3$ (Titanium:Sapphire), pumped around 530nm (frequency doubled 1064nm Nd:YAG, or 1053, 1047nm Nd:YLF), or if it is Cr:LiSAF, Cr:LiCAF, or Cr:LiSCAF, pumped around 660nm (frequency doubled 1320nm Nd:YAG or Nd:YLF).

The frequency doubling crystal is not required if vibronic media such as Cr$^{4+}$:Forsterite, Cr$^{4+}$:YAG, KCl:Tl (Potassium Chloride:Thallium) or NaCl:OH$^-$ colour-centre crystals are employed, since these media have absorption bands which are directly compatible with the output of a Nd:YAG (or Nd:YLF) micro laser.

Use of the frequency doubling crystal can also be avoided by the technique of co-doping the micro laser medium. Co-doped ions (for example Cr ions in a Nd:YAG medium) can transfer energy at one wavelength to another species at another wavelength.

To ensure self-mode-locking in the vibronic medium, the micro laser is either arranged to operate in a single longitudinal mode or is itself mode-locked.

One specific embodiment is illustrated with reference to Figure 6. A pair of high power AlGaAs laser diodes 200 pumps a micro laser medium 204 consisting of a Brewster-angled Nd:YAG
slab. In addition to the microlaser medium, the pump cavity 202 comprises plane mirrors 212a and 212b which are highly reflecting at 1064nm, optical elements 214a and 214b which are highly reflecting at 1064nm and highly transmitting at 532nm and which have a radius of curvature of -100mm and a separation of 100mm, an LBO frequency doubling crystal 206, and a unidirectional device 216. The output of the pump cavity 202 is passed to the main laser cavity 208 via optical element 214a. The main optical cavity 208 includes a Ti:sapphire vibronic laser medium 210 and some means, such as an acousto-optic modulator 218, for initiating self-mode-locking of the output laser beam.

The laser diode pair 202 is arranged for balanced optical pumping of the Nd:YAG slab by being located on opposite sides of the slab. This permits control of thermal lensing effects in the slab so that the beam pointing stability (beam directionality) from the pump cavity 202 can be ultrastable.

The pump cavity 202 is configured as a ring cavity and is rendered unidirectional by the unidirectional device 216. This arrangement ensures that the pump laser beam operates in a single longitudinal mode, by avoiding standing wave effects. As mentioned previously, it is important for the initiation and maintenance of self-mode-locking that the pump laser beam operates in a single longitudinal mode (unless it provides a mode-locked output). This ensures that a good and stable fundamental spectral intensity is available at the output of the pump cavity. Operation in a single longitudinal mode is particularly important if a frequency doubling crystal is used, since the quadratic intensity dependence of the frequency-doubling process has the effect of exacerbating any unwanted variations in the intensity of the fundamental-frequency radiation.

It will be appreciated that operation in a single longitudinal mode can alternatively be achieved in a standing wave cavity with the gain (laser) medium located near one end of the cavity.

Whilst the frequency doubling crystal 206 could alternatively
be mounted outside the pump cavity 202, it is preferably mounted inside the cavity because beam intensity there is generally higher.

Figure 7 shows the beam pointing stability achieved in practice with the microlaser described in relation to Figure 6. \( \alpha_1 \) and \( \alpha_2 \) are the pointing angles in the two orthogonal beam output directions. It can be seen that the beam pointing is stable to within roughly \( \pm 10 \mu \text{rad} \).

In a variant of the second embodiment of the invention, the microlaser is itself either actively, passively, or self-mode-locked. This is explained later in more detail in the section entitled "Means for initiating self-mode-locking" in relation to the third embodiment of the initiating means.

It will be understood that in the second embodiment of laser stable pointing of the pump laser beam is assured by the use of a uni-directional ring cavity for the pump laser and by the use of the balanced laser diode array. As stated above, operation of the pump laser beam in a single longitudinal mode is achieved using the uni-directional ring cavity. It will also be understood in the second embodiment that the uni-directional ring cavity can produce a near-diffraction limited pump beam due to the extended length of the cavity and the operation of the cavity in a fundamental transverse mode (that is, a Gaussian beam). Such a near-diffraction limited pump beam can be of sufficiently small cross-sectional focussed area and high confocal parameter to permit the initiation and maintenance of self-mode-locking.

In certain circumstances it may be desired to use the laser for the synchronous pumping of an external cavity containing non-linear crystals for the purposes of frequency conversion (for example, frequency doubling) or parametric oscillation. Such circumstances might be the provision of doubly or triply resonant cavities for pump, signal and idler waves. In such circumstances high beam pointing stability of the pump laser and operation by the pump laser in a single longitudinal mode may be vital to ensure the reproducibility of beam paths and thus avoid intra-crystal intensity variations.
In both of the embodiments, an asymmetrical main laser cavity may be used to reduce the beam waist and mode volume still further. It has been found pursuant to the present invention that such reductions can reduce the pulse durations still further because the exploitable non-linear effects of self-phase modulation and self-focussing can be further enhanced in the higher focal intensity regions resulting from the reduced mode volume.

MEANS FOR INITIATING SELF-MODE-LOCKING

Various means for initiating the self-mode-locking of a laser beam are disclosed in the paper entitled "Regeneratively initiated self-mode-locked Ti:sapphire laser", published on 15th November 1991. Such initiating means include saturable absorbers, coupled-cavity schemes, active cavity length modulation and acousto-optic beam modulation. Any such means may be appropriate in the embodiments of laser described above, provided it is used appropriately. The manner in which such means may be used appropriately is now described.

In broad terms, the theory underlying the initiation of self-mode-locking is that a suitably intense initial (or "enabling") pulse must be established so that the non-linear effects of such self-mode-locking phenomena as self-phase-modulation, self-amplitude-modulation and self-focussing (preferably in combination with controlled Group Velocity Dispersion compensation) can lead to substantial pulse shortening (typically into the femto second regime). Most of the practically feasible initiating means generate the initial pulse by applying a modulation to the laser beam at the cavity frequency (or a multiple or sub-multiple thereof). Such a modulation generates sidebands which can be precisely matched to the longitudinal modes of the cavity. If a good phase coupling of the longitudinal modes can be achieved, a short duration initial pulse may be generated. Once established, the initial pulse can access the non-linearities in the laser medium if it is suitably intense so that self-mode-locking occurs. It will be
understood that the initiation means serves only to generate the initial pulse, and generally not to maintain the self-mode-locking process.

With semiconductor laser devices which typically have relatively low power (unless, for example, a large number of laser diodes are combined), relatively short initial pulses are required in order that the non-linearities in the laser medium can be accessed. This requires in turn that the amplitude (or intensity) modulation provided by the initiating means is relatively fast. Various embodiments of initiating means according to the present invention are now described which fulfil this requirement.

A first embodiment of initiating means is a passive, loss modulation scheme consisting of a saturable absorbing medium having an ultrafast (less than 50ps) recovery time so that short pulses can be produced. In addition, in order that the absorbing medium can function under low intra-cavity power levels, the absorber has a low optical density, is relatively weak and is thus readily saturated.

One particular medium having these characteristics is a thin slice (~50μm thickness) of semiconductor-doped glass (for example, Schott (trade mark) glass colour edge-filter, RGB30 containing a CdSₓSe₁₋ₓ microcrystallite dopant). The characteristics of this glass are shown in Figure 8 for various thicknesses of glass (<90μm, 400μm and 3mm). It can be seen from Figure 8 that a thin (<90μm) absorber can permit a substantial frequency tuning range in the laser.

A preliminary test of the effectiveness of this saturable absorber has been carried out pursuant to the present invention. An Argon-ion pump laser was used to pump a Ti:sapphire main laser with the saturable absorbing medium located intra-cavity. The arrangement was operated to give a low output average power of just 10mW through a 3.5% transmission output coupler. This average output power corresponded to an intra-cavity average power level of only 285mW. Despite these low power levels, pulse
durations as short as 80fs were achieved over a tuning range of 780–830nm. The average output power level of 10mW could be readily achieved using a laser diode pump laser. Thus this test demonstrates the feasibility of this particular initiating means at low power thresholds such as might be encountered when using a laser diode pump laser.

Another suitable saturable absorber consists of a high optical quality sol-gel material, doped either with semiconductor microcrystallites, silver particles or a fast recovery dye or cocktail of dyes. A sol-gel material is one made by the "sol-gel" process. Suitable materials for such processing are glass or other polymers. A sol-gel material is amorphous and sponge-like, and has a large number of volumetric, pervasive micro-cavities in which the saturable absorbing medium is contained. If a dye dopant is employed, the dye species can be very stable because it is protected in the micro-cavities within the sol-gel glass. Such an absorbing medium permits a wide range of absorber spectral ranges and absorption characteristics to be made available.

A further suitable saturable absorbing medium is a low-temperature-grown epitaxial polycrystalline semiconductor structure such as AlGaAs (which is suitable for part of the wavelength range of Ti:Sapphire lasers).

A second embodiment of initiating means is an active amplitude modulation scheme involving acousto-optic modulation (see the Spence et al. "Regeneratively initiated self-mode-locked Ti:sapphire laser" paper). In order to produce sufficiently short initial pulses, the acousto-optic modulator is operated at a significantly higher frequency than that disclosed in the Spence et al. paper. A typical frequency is 250MHz.

A third embodiment of initiating means is a "synchronous", gain modulation scheme in which the pump laser itself is mode-locked. Mode-locking of the pump laser can be achieved by any suitable mode-locking scheme (including self-mode-locking). Because of the high peak powers of the pulses from the pump
laser, the mode-locked pump beam may be easily frequency doubled if appropriate.

In this third embodiment of initiating means, the mode-locked pump beam is applied to the main, vibronic laser medium to provide a synchronous amplitude modulation in this medium. With the pump cavity and main cavity periods appropriately matched, and suitably stable, then a sufficiently short (<10ps) initial pulse can evolve even at modest average pump power levels (<2W).

USES OF THE LASER OF THE PRESENT INVENTION

It will be appreciated that both of the embodiments of laser described above have high quality output beams capable of producing femtosecond duration pulses at the frequency of the main laser cavity. As suggested earlier, such beams may be used in many technical areas, such as spectroscopy and communications. Because of the high quality of such beams, they are particularly suited to the synchronous pumping of non-linear media such as frequency doublers and parametric oscillators.

One particularly important use of the laser of the present invention is in the generation of a beam having two (or more) distinct frequency components. A variant of the laser described in relation to Figure 2 and suitable for this purpose is now described with reference to Figure 9. In Figure 9, like parts to those in Figure 2 are denoted by like reference symbols. The laser medium 112 in this case is a Ti:sapphire medium and is pumped by a focussed beam from a semiconductor laser diode arrangement 300 at a suitable pump frequency. The prism pair 118 of Figure 2 is replaced by a prism triplet 302 which serves both to provide Group Velocity Dispersion compensation and also to split the beam into two components ("1" and "2") according to their frequency. Pairs of apertures 1161 and 1162, for frequency tuning purposes, and optical elements 114d1 and 114d2 are provided, one each for the respective beam components. Output1 and Output2 are the respective output beam components at the two distinct frequencies.

In this embodiment, self-mode-locking of both beam components is effected with an acousto-optic modulator 120. However, it
will be understood that a variety of means for initiating mode-locking of the beam components may be utilised, such as those described in the preceding section. Further, both components may be self-mode-locked, or, for example, one component may operate in a self-mode-locked femto second regime whilst the other may operate in a purely regeneratively mode-locked pico second regime.

Successful operation of the laser in this two-frequency mode requires that an appropriate gain distribution is available for the two components of the laser beam. Furthermore, the cavity periods for the two frequencies should be arranged to be equal so that the two pulse sequences can be precisely synchronised.

The laser shown in Figure 9, with the modification that it is Argon-ion laser rather than laser diode pumped, has been demonstrated as being capable of generating a self-mode-locked laser beam operating simultaneously in two different wavelength regimes, \( \lambda_1 \) and \( \lambda_2 \). The tuning range of this laser over these wavelength regimes has been determined experimentally and is shown in Figure 10. A relatively short tuning range is available for the \( \lambda_1 \) regime, around 850nm, whereas a relatively long range is available for the \( \lambda_2 \) regime, between approximately 700 and 800nm.

Cross-correlation and auto-correlation experiments with the laser (in its Argon-ion laser pumped version) have confirmed that the pulse sequences at the different wavelengths are precisely synchronised. The jitter between the two pulse sequences was found to be 70fs for the 150fs pulse durations produced in these experiments.

Although the above experiments have been carried out using an Argon-ion pump laser, it is to be expected that a semiconductor diode pump laser having the beam refinements described in the preceding sections will provide enhanced performance.

Some uses of the two-frequency laser described above are now described. One important use is in "excite and probe" measurements, where a material is excited at one wavelength and
probed with appropriate time delays at the second wavelength. By this technique the kinetics in photophysical, photochemical and photobiological systems can be time resolved. It should be noted that one of the beam components can be frequency upconverted (doubled, tripled, etc.) to further extend the wavelength ranges available from the two-frequency laser.

Moreover, the availability of two synchronised ultrashort pulse sequences at two distinct wavelengths opens up tuning ranges quite distinct from the fundamental wavelengths of the two components if difference-frequency mixing is employed. For instance, difference-frequency mixing in a non-linear crystal (for example, silver-gallium-selenide: AgGaSe₂) leads to the production of tunable mid-infrared radiation. Given that the femtosecond pulses from a self-mode-locked vibronic laser (for example Ti:Al₂O₃) can have peak optical powers in excess of 100 kW then such non-linear frequency-conversion processes can be relatively efficient.

As a specific example, a self-mode-locked vibronic laser (for example, Ti:Al₂O₃ or Cr:LiSAF) operating simultaneously at 750 nm and 850 nm is considered. The corresponding difference-frequency is then 6375 nm (or 6.375 μm) in the mid-infrared. From the tuning data shown in Figure 10, if λ₁ is taken to be 850 nm then as λ₂ is varied from 800 nm to 700 nm the corresponding mid-infrared tuning range will be 3967-13600 nm (that is, 3.967-13.6 μm).

By appropriately selecting the reflectivity characteristics of the mirrors in the laser cavity other tuning ranges could be accessed. For instance, λ₁ = 700 nm and λ₂ = 950 nm gives a mid-infrared wavelength of 2600 nm (that is, 2.6 μm). With regard to molecular spectroscopy, relating to carbon-hydrogen bonds for example, a wavelength around 3.3 μm might be especially advantageous. This could be readily obtained by difference-frequency mixing of λ₁ = 720 nm and λ₂ = 921 nm.

Another attribute of the two-frequency operation of the self-mode-locked vibronic laser is that one of the beam
components can be frequency upconverted (for example, doubled) before being difference-frequency mixed in a non-linear crystal. By this means some supplementary frequency tunability in the visible and near-infrared regions can be conveniently accessed. As examples, $\lambda_1 = 950\text{nm}$ and $\lambda_2$ frequency-doubled from 750nm to 375nm gives a difference-frequency output at 619nm which is shorter than the short wavelength directly available from either Ti:Al$_2$O$_3$ or Cr:LiSAF gain media. When $\lambda_1$ is frequency-doubled from 960nm to 480nm and $\lambda_2$ is 720nm then the difference-frequency output is at 1396nm which exceeds considerably the long wavelength limit from such media.

Hence the two-frequency operation of self-mode-locked lasers adds substantially to their spectral versatility. With direct laser diode pumping of gain media such as Cr-doped fluoride crystals (for example, Cr:LiSAF, Cr:LiSCAF, Cr:LiCAF), or Nd:YAG(YLF)-based microlaser pumping of media such as Cr$^{4+}$:YAG or Cr$^{4+}$:Forsterite (or frequency-doubled pumping for Ti:Al$_2$O$_3$, Cr:LiSAF, etc.), these enhanced systems can be seen to be highly advantageous.

It will of course be understood that the present invention has been described above purely by way of example, and that modifications of detail can be made within the scope of the invention.
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CLAIMS

1. A laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the beam pointing of the pump laser beam being stable to within ± 30 μrad, preferably to within ± 10 μrad, more preferably to within ± 5 μrad.

2. A laser according to Claim 1 wherein the pump laser beam is within 30%, preferably within 20%, more preferably within 10%, even more preferably within 5% of the diffraction limit.

3. A laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the pump laser beam being within 30%, preferably within 20%, more preferably within 10%, even more preferably within 5% of the diffraction limit.

4. A laser according to Claim 1, 2 or 3 wherein the main laser includes a laser medium in which the minimum cross-sectional area of the pump laser beam is less than 3000 μm², preferably less than 1000 μm², more preferably less than 300 μm², even more preferably less than 100 μm², and wherein the pump laser beam confocal parameter is at least 50%, preferably at least 75%, and is more preferably roughly 100% of the operational length of the laser medium.

5. A laser comprising a pump laser for generating a pump laser beam and a main laser including a laser medium arranged to be pumped by the pump laser beam, the minimum cross-sectional area of the pump laser beam in the laser medium being less than 3000 μm², preferably less than 1000 μm², more preferably less than 300 μm², even more preferably less than 100 μm², the pump laser beam confocal parameter being at least 50%, preferably at least 75%, and more preferably being roughly 100% of the operational length of the laser medium.

6. A laser according to Claim 4 or 5 wherein the laser medium comprises a gain medium in which the minimum cross-sectional area of the pump laser beam is less than 3000 μm², preferably less than 1000 μm², more preferably less than 300 μm², even more preferably less than 100 μm².
7. A laser according to any of the preceding claims wherein the pump laser is arranged to operate in a single longitudinal mode.
8. A laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the pump laser being arranged to operate in a single longitudinal mode.
9. A laser according to any of the preceding claims wherein the intensity of the pump laser beam is stable to within 1%, preferably to within 0.1% of its root mean square value.
10. A laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser beam, the intensity of the pump laser beam being stable to within 1%, preferably to within 0.1% of its root mean square value.
11. A laser according to any of the preceding claims wherein the pump laser includes a radiation source comprising a semiconductor laser arrangement.
12. A laser according to Claim 11 wherein the main laser is adapted to generate a main laser beam and includes a laser medium, and means is provided for matching the cross-sectional shape, and preferably also the size, of the pump and main laser beams in the laser medium.
13. A laser comprising a pump laser, including a radiation source comprising a semiconductor laser arrangement, for generating a pump laser beam, a main laser including a laser medium arranged to be pumped by the pump laser beam to generate a main laser beam, and means for matching the cross-sectional shape, and preferably also the size, of the pump and main laser beams in the laser medium.
14. A laser according to Claim 12 or 13 wherein the matching means comprises means for circularising the beam output by the semiconductor laser arrangement.
15. A laser according to any of Claims 11 to 14 wherein the semiconductor laser arrangement is injection locked.
16. A laser comprising a pump laser for generating a pump laser beam and a main laser arranged to be pumped by the pump laser
beam, the pump laser including a radiation source comprising an injection locked semiconductor laser arrangement.

17. A laser according to Claim 15 or 16 wherein the semiconductor laser arrangement is arranged to be injection locked by a master laser.

18. A laser according to Claim 15, 16 or 17 wherein the semiconductor laser arrangement is arranged to be self-injection locked by an external cavity.

19. A laser according to any of the preceding claims wherein the cavity of the pump and/or main laser is a ring cavity.

20. A laser according to any of the preceding claims wherein the cavity of the pump and/or main laser is uni-directional.

21. A laser according to any of the preceding claims wherein the laser medium in the main laser is arranged to be pumped by a pair of pump lasers, and/or the laser medium in the pump laser is arranged to be pumped by a pair of radiation sources, said pair being disposed about the laser medium for balanced pumping of the medium.

22. A laser according to any of the preceding claims further comprising means for converting the frequency of the pump laser beam, the pump laser including a pump laser cavity within which the converting means is mounted.

23. A laser comprising a pump laser for generating a pump laser beam in a pump laser cavity and a main laser arranged to be pumped by the pump laser beam, the pump laser including means for converting the frequency of the pump laser beam, the converting means being mounted within the pump laser cavity.

24. A laser according to any of the preceding claims wherein the main laser includes means for generating a laser beam having at least two distinct frequency components, and further including means for initiating mode-locking of the beam.

25. A laser comprising means for generating a laser beam having at least two distinct frequency components, and means for initiating mode-locking of the beam.
26. A laser according to any of the preceding claims wherein the laser medium includes a gain medium and a separate non-linear medium.

27. A laser according to any of Claims 1 to 25 wherein the laser medium consists only of gain medium.

28. A laser according to any of the preceding claims including means for initiating mode-locking of the main laser beam.

29. A laser according to Claim 28 wherein the initiating means is arranged to initiate an intensity pulse of duration less than 50ps, preferably less than 20ps, more preferably less than 10ps, even more preferably less than 5ps.

30. A laser comprising means for generating a laser beam and means for initiating mode-locking of the laser beam, the initiating means being arranged to initiate an intensity pulse of duration less than 50ps, preferably less than 20ps, more preferably less than 10ps, even more preferably less than 5ps.

31. A laser according to Claim 29 or 30 wherein the initiating means includes a saturable absorbing medium having an operating thickness less than 100μm, preferably less than 75μm.

32. A laser according to Claim 29, 30 or 31 wherein the initiating means includes a support element having cavities and a saturable absorbing medium contained in the cavities.

33. A device suitable for initiating mode-locking of a laser beam, comprising a support element having cavities, and a saturable absorbing medium contained in the cavities.

34. Apparatus according to Claim 32 or 33 wherein the support element consists of a sol-gel material.

35. A laser according to Claim 29 or 30 wherein the initiating means includes a semiconductor material.

36. A laser according to Claim 29 or 30 wherein the initiating means includes means, preferably an acousto-optic modulator, for modulating a property of the beam, the modulation being effected at a frequency higher than 150MHz, preferably higher than 200MHz and more preferably higher than 250MHz.
37. A laser according to Claim 36 wherein the depth of modulation is at least 20%.

38. A laser according to Claim 30 wherein the beam generation means includes a main laser for generating said laser beam and a pump laser for generating a pump laser beam to pump the main laser.

39. A laser according to Claim 38, or Claim 29 when dependent on any of Claims 1 to 24, wherein the initiating means includes means for mode-locking the pump laser beam.

40. A laser substantially as herein described with reference to Figures 1 to 3, or 1, 2 and 4, or 5 to 7, or 9 and 10 of the accompanying drawings.

41. A device for initiating mode-locking of a laser beam substantially as herein described with reference to Figure 8 of the accompanying drawings.
Fig. 5

Fig. 6
Fig. 7
Fig. 8
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<td>APPLIED PHYSICS.B.PHOTOPHYSICS AND LASER CHEMISTRY vol. B32, no. 1, September 1983, HEIDELBERG, DE pages 7 - 8 I.S.RUDDOCK ET AL. 'Bistable operation of a dual-wavelength synchronously mode-locked laser' see the whole document</td>
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<td>OPTICS LETTERS. vol. 16, no. 21, 1 November 1991, NEW YORK US pages 1609 - 1691 , XP000232622 S.CHEN ET AL. 'Self-starting issues of passive self-focussing mode locking' see abstract</td>
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<td>DIGEST OF TECHNICAL PAPERS XVIII INTERNATIONAL CONFERENCE ON QUANTUM ELECTRONIC, 21-25 MAY 1990 ANAHEIM, CA, US, PAPER JWAG pages 176 - 178 , XP000124660 G.B.ALTHSULER ET AL 'New laser media based on dye solution impregnated microporous glasses' see the whole document</td>
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Form PCT/ISA/210 (extra sheet) (January 1985)
### I. CLASSIFICATION OF SUBJECT MATTER

According to International Patent Classification (IPC) or to both National Classification and IPC

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<td>H01S</td>
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched:

### III. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of Document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to Claim No.</th>
</tr>
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<tbody>
<tr>
<td>X</td>
<td>PROCEEDINGS LEOS '88, 2-4 NOVEMBER, 1988 SANTA CLARA, CA, US pages 494 - 495, XP000075744 I.N.DULING III ET AL. 'High power mode-locked Nd:fiber laser pumped by an injection-locked diode array' see the whole document</td>
<td>8, 15-17, 19, 20</td>
</tr>
<tr>
<td>Y</td>
<td>----</td>
<td>18, 22, 23</td>
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- **X** Special categories of cited documents: 10
  - "A" document defining the general state of the art which is not considered to be of particular relevance
  - "E" earlier document but published on or after the international filing date
  - "L" document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  - "O" document referring to an oral disclosure, use, exhibition or other means
  - "P" document published prior to the international filing date but later than the priority date claimed

- **Y** later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

- **X** document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

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- **&** document member of the same patent family

### IV. CERTIFICATION

Date of the Actual Completion of the International Search: 22 JULY 1993

Date of Mailing of this International Search Report: 30.07.93

International Searching Authority: EUROPEAN PATENT OFFICE

Signature of Authorized Officer: GALANTI M.
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<td>X</td>
<td>OPTICS LETTERS. vol. 16, no. 15, 15 August 1991, NEW YORK US pages 1180 - 1182, XP000217663 CH.SPIELMANN ET AL. 'Femtosecond pulse generation from a synchronously pumped Ti:sapphire laser' see figure 1</td>
<td>30,38,39</td>
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<tr>
<td>X</td>
<td>OPTICS LETTERS. vol. 16, no. 21, 1 November 1991, NEW YORK US pages 1674 - 1676, XP000232618 F.SALIN ET AL. 'Mode locking of Ti:Al2O3 lasers and self-focusing: a Gaussian approximation' see the whole document</td>
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<td>X</td>
<td>OPTICS LETTERS. vol. 17, no. 19, 1 October 1992, NEW YORK US pages 1367 - 1369, XP000296101 B.E.LEMOFF ET AL. 'Generation of high-peak-power 20 fs pulses from a regeneratively initiated, self-mode-locked Ti:sapphire laser' see abstract; figure 1</td>
<td>30,36,37</td>
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