High Intensity MHz Mode-Locked Laser

9-15-2009

Martin Richardson  
University of Central Florida

Arnaud Zoubir  
University of Central Florida

Find similar works at: http://stars.library.ucf.edu/patents

University of Central Florida Libraries http://library.ucf.edu

Recommended Citation

http://stars.library.ucf.edu/patents/235

This Patent is brought to you for free and open access by the Technology Transfer at STARS. It has been accepted for inclusion in UCF Patents by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
Systems, configurations and methods of using an ultrafast, self-starting, mode-locked laser are provided. The systems, devices and methods of using stable, self-starting mode-locked lasers, can be compact, use fewer optical elements and have energies sufficient for most micro-processing and micro-structuring applications. The large spectral bandwidth of ultra-short (femtosecond) laser pulses can be used in laser sensing applications, micro-machining, time-resolved experiments, where short-lived transient species can be observed in biological or chemical reactions. Terahertz radiation can be generated using ultrashort pulses and used for imaging applications.
OTHER PUBLICATIONS
* cited by examiner
**Fig. 1**
(PRIOR ART)

**Fig. 2**
(PRIOR ART)

**Fig. 3**
(PRIOR ART)
Fig. 4

SM1, SM2: Spherical mirrors R= 10 cm
SM3: Spherical mirrors R= 50 cm
CM1, CM2: Chirped mirrors 60%/10% reflection
TM: Turning mirror
FL: Focusing lens f=12.5 cm

SAM, Saturable Absorber Mirror
MPC: Multipass cell with
MI, M2: 4" Diameter, 2mm.r.o.c, 6.5mm-holes
OC: Output coupler 12% transmission

Fig. 5
Fig. 6

SAM Mode Locking element
Multipass Mirror System
Lasing element
Dispersion compensating elements
Cavity Dumper

Fig. 7
Fig. 8

- Ti:Sapphire crystal
- AOC: Acousto-optic cell

`510` through `512`, `520` through `528`
Fig. 9
2 MHz laser oscillator

![Graph of 2 MHz laser oscillator showing amplitude and time in nanoseconds.]

Fig. 10

90 MHz laser oscillator

![Graph of 90 MHz laser oscillator showing amplitude and time in nanoseconds.]

Fig. 11

(PRIOR ART)
1

HIGH INTENSITY MHZ MODE-LOCKED LASER

This invention claims the benefit of priority based on the U.S. Provisional Application Ser. No. 60/571,907 filed May 17, 2004, the contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates to ultrafast mode-locked lasers generating pulses with picosecond or less in duration, and, more particularly to systems, devices and methods of using stable, self-starting mode-locked lasers, which are compact, use fewer optical elements and have energies sufficient for most micro-processing and micro-structuring applications.

BACKGROUND AND PRIOR ART

Extremely short duration optical pulses, which are also known as femtosecond pulses, are important for high speed signal processing, communications, imaging, sensing applications, time resolved experiments, where short-lived transient species can be observed in biological and chemical reactions.

The early development of laser technology involving the production of extremely short pulses is disclosed in U.S. Pat. No. 4,727,553 to Fork et al. The early version of a passively mode-locked laser is described as containing a saturable absorbing element optically coupled to a gain medium in an optical resonator. Additional variations of the saturable absorbing element positioned between reflective (mirror-like) elements are disclosed in U.S. Pat. No. 5,237,577 to Keller et al. and U.S. Pat. No. 5,278,855 to Jacobovitz-Veselka et al. The so-called Semiconductor Saturable Absorber Mirrors (SESAMs) are described in U.S. Pat. Nos. 6,538,298 B1 and 6,393,035 B1 to Weingarten et al. The saturable absorber element functions as a shutter.

Further development of passively mode-locked lasers includes use of astigmatic mirrors with spacing and a unique twist angle to correct the optical path in an absorption cell (U.S. Pat. No. 5,291,265 to Kebabian) and subsequently, the integration of the saturable absorber with the optical element as discussed below.

Current conventional, commercial, ultrafast mode-locked lasers have basic constituents, which include an active laser medium, resonator mirrors, and optical components, usually prisms that compensate for dispersion in the resonator. The mode-locking element in simpler devices is a nonlinear optical effect occurring in the laser medium itself. A typical mode-locked laser design is shown in FIG. 1; the laser of this design has drawbacks in that it is not “self-starting” and is sensitive to effects of alignment, optical pumping, and the like.

More recently, other components have been added to the general structure shown in FIG. 1. Instead of using prisms as the dispersive elements, special mirrors, known as, Chirped Mirrors have been developed. Chirped Mirrors or Negative Group Velocity Dispersion (NGVD) as discussed in U.S. Pat. No. 6,055,261 to Reed et al. have been used to provide an ultrafast laser device with a significantly shortened resonant cavity. Additional prism replacements include a fold mirror (U.S. Pat. No. 5,812,308 to Katka et al.); a dispersive dielectric mirror (U.S. Pat. No. 5,734,503 to Szipoes et al.); a self-tuning saturable reflector comprising two Bragg reflectors (U.S. Pat. No. 6,141,359 to Cunningham et al.); and heated mirrors (U.S. Pat. No. 6,188,475 to Imman et al.) in semiconductor processing.

SUMMARY OF THE INVENTION

It is a primary objective of the present invention to provide a family of low cost, compact, high peak power ultra-short pulse lasers.

A second objective of the present invention is to provide an ultrafast megahertz (MHz) mode-locked laser of increased ruggedness that is self-starting.

A third objective of the present invention is to provide high intensity MHz mode-locked lasers that are low cost and easy to manufacture.

A fourth objective of the present invention is to provide a mode-locked ultrafast laser with a cavity-dumping feature.

A preferred compact, high intensity megahertz (MHz) mode-locked laser is provided wherein the laser system includes, a laser source coupled to a resonator cavity having a gain medium, a saturable absorber mirror in the resonator cavity for self-starting and stable mode-locking operation, a multi-pass mirror in combination with the saturable absorber mirror in the resonator cavity for lowering repetition rate of the laser system to below approximately 50 megahertz (MHz), dispersion compensating element in the resonator cavity for dispersion compensation, and an output coupler to the laser for releasing pulses with energies sufficient for micro-machining and micro-structuring applications.

The preferred laser source includes a diode laser. The preferred multi-pass mirror slows down the repetition rate of laser pulses to between approximately 1 MHz to approximately 50 MHz.
The preferred gain medium includes, but is not limited to, Yb:KYW, a KY[WO₄]₂ (KYW) crystal doped with Ytterbium ions, Yb:YAG, a Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Titanium ions.

A cavity dumping component is used to extracting energy trapped inside of the resonant cavity. Thus, a more preferred laser system of the present invention includes a cavity dumping component having an optical gate located between the output coupler and the saturable absorber mirror. The preferred cavity dumping component is either an acousto-optically driven gate or an electro-optically driven gate.

A preferred method of improving the pulse energy of a compact, high intensity megahertz mode-locked laser includes, providing a resonant laser cavity having a saturable absorber mirror and a laser gain medium, positioning a cavity dumping component within the laser cavity between an output coupler and the saturable absorber, pumping the laser gain medium, and extracting energy trapped inside the cavity by dumping excess energy through an optical gate, which can be acousto-optically driven or electro-optically driven. The saturable absorber mirror is a broadband saturable absorber.

Another preferred method of providing low cost, simple, compact, ultrafast laser with high pulse energies for micromachining applications includes, providing a laser configuration having a laser gain medium, a resonator cavity, a saturable absorber mirror, a multipass mirror and an output coupler, pumping the laser gain medium, generating femtosecond pulses with intensities in the megawatt range from the laser source, and simultaneously lowering the repetition rate of each pulse, thereby minimizing damage associated with the thermal load accumulated pulse after pulse. The femtosecond pulses have an energy of approximately 10 nano Joules (nJ) and approximately 150 nano Joules (nJ). The repetition rate of the femtosecond pulses is in a range between approximately 1 MegaHertz (MHz) and approximately 50 MegaHertz (MHz).

Another preferred high intensity megahertz (MHz) mode-locked laser system has a laser that includes, a laser source and a gain medium, a saturable absorber mirror in the system for self-starting and stable mode-locking operation, a multipass mirror in the laser system for lowering repetition rate of the laser system to below approximately 50 megahertz (MHz), a dispersion compensating element in the laser system for dispersion compensation, and an output coupler to the laser system for releasing pulses with energies sufficient for micromachining and micro-structuring applications. The preferred gain medium is a Ti:Sapphire crystal, or a thin disk-shaped gain medium.

A preferred basic laser system includes a lasing element, dispersion compensating elements coupled to the lasing element, a SAM mode-locking element coupled to the dispersion compensating element, a multipass mirror system coupled to the SAM mode-locking element, and an output coupler coupled to the multipass mirror system for providing an output from the laser system.

A more preferred laser system includes a lasing element, dispersion compensating elements coupled to the lasing element, a SAM mode-locking element coupled to the dispersion compensating element, a multipass mirror system coupled to the SAM mode-locking element, a cavity damper coupled to the multipass mirror system, and an output coupler coupled to the cavity damper for providing an output from the laser system.

Preferred embodiments of the invention include a cavity-dumping feature to extract all the energy trapped inside the cavity by dumping the beam, using an optical gate that can be either acousto-optically or electro-optically driven. The preferred embodiments provide a several-fold improvement in the usable pulse energy; approximately one order of magnitude higher pulse energies than current mode-locked lasers.

Further objects and advantages of this invention will be apparent from the following detailed description of the presently preferred embodiments, which are illustrated schematically in the accompanying drawings.

**BRIEF DESCRIPTION OF THE FIGURES**

FIG. 1 is a conventional mode-locked laser configuration with Kerr-lens mode locking and a prism pair as the dispersion compensating element. (Prior Art)

FIG. 2 is a mode-locked laser with the addition of Chirped mirrors, as the dispersion compensating element, and Saturable Absorber (SAM) mode-locking element. (Prior Art)

FIG. 3 is a mode-locked laser with Kerr-lens mode locking and a prism pair as the dispersion compensating element and the addition of Multipass mirrors. (Prior Art)

FIG. 4 is a mode-locked laser of the present invention with a special Saturable Absorber Mirror as the mode-locking element, Chirped mirrors as the dispersion compensating element, and Multipass mirrors.

FIG. 5 is a first embodiment of the present invention with a Ti:Sapphire oscillator.

FIG. 6 is a second embodiment of the present invention with a face-pumped Yb:YAG or Yb:KYW thin disk laser configuration.

FIG. 7 is a third embodiment of the present invention incorporating a cavity dumper.

FIG. 8 is a fourth embodiment of the present invention with a Ti:Sapphire crystal and an acousto-optic cell cavity dumping scheme.

FIG. 9 is a surface profile of laser micro-machined trenches in Arsenic trisulfide (As₂S₃) using the mode-locked laser of the present invention.

FIG. 10 is an oscilloscope trace of a 2-MHz laser pulse train, having a pulse separation of approximately 500 nanoseconds (ns).

FIG. 11 is an oscilloscope trace of a standard 90-MHz laser pulse train, having a pulse separation of approximately 10 nanoseconds (ns).

**DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Before explaining the disclosed embodiments of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of the particular arrangements shown since the invention is capable of further embodiments. Also, the terminology used herein is for the purpose of description and not of limitation.

Acronyms and terminology used throughout this description are defined as follows:

CM—Chirped mirrors that are able to provide second- and third-order dispersion compensation using a scheme where each frequency component is reflected at different depths through the dielectric coating, which consists of multiple stacks of varying thickness. Chirped mirrors provide very robust and compact arrangements for the design of ultrafast lasers.
According to the present invention, the above objectives are met by incorporation of special Saturable Absorber (SAM) mirrors with mode-locking elements in combination with a Multipass Mirror system to slow down the repetition rate, and create a system that is more stable, self-starting and commercially viable for micro-machining applications.

FIG. 4 is a mode-locked laser of the present invention with special Saturable Absorber mode-locking element 100 and Multipass mirrors 102. Referring now to FIG. 4, this is a general layout of the components in the high intensity MHz mode-locked laser of the present invention. A saturable absorber mirror 100 is positioned in close proximity to the multi-pass mirror system 102 and plays the role of both the high reflector and the mode-locking element. The new laser can include a laser element 104, dispersion compensating elements 106 coupled to the lasering element, and an output coupler 108 to provide output from the laser system.

The order of the elements can vary; for example, a SAM mode-locking element 100 can be coupled to the dispersion compensating element 106, a multipass mirror system 102 can be coupled to the SAM mode-locking element 100 and an output coupler 108 can be coupled to the multipass mirror system 102 for providing an output from the laser system.

FIG. 5 is a first embodiment of the present invention with a Ti:Sapphire oscillator. In FIG. 5, a pump beam 200 from a diode pumped solid state laser is focused, with focusing lens 12, on a Ti:Sapphire crystal 202 positioned between two spherical mirrors 204 and 222. The spherical mirrors 204, 222 have a radius of approximately 10 centimeters (cm). The light beam passes through the multi-pass cell formed by mirrors 210 and 214. The multi-pass cell is approximately 4 inches in diameter, approximately 2 meters (m) in length with r.o.c., 6.5 mm holes. Light passes through the multi-pass cell and reflects on the chirped mirrors 218 and 220 each having ~60 fs/2 reflection, and to the SAM 212. A curved mirror 208, with a radius of approximately 50 cm, is used to focus light onto the SAM 212 in order to reach the saturation intensity. A turning mirror 206 is used to steer the beam in order to reduce the laser footprint. The order in which light passes through these elements does not matter.

If the same architecture were utilized with a directly-diode pumped Yb:YAG or Yb:KYW laser, for instance the configuration, and footprint would be much smaller. FIG. 6 shows a laser schematic in a face-pumped Yb:YAG or Yb:KYW thin disk laser configuration. The thin disk laser head 300 acts as the gain medium and as a mirror at the same time. In FIG. 6, the beam path is very similar to that illustrated in FIG. 5, except that it is folded one more time on the thin disk 302, allowing a more compact system.

The light beam resonates inside the cavity formed by the output coupler 304 and a Broadband Saturable Absorber Mirror 318. Each path, the light beam goes through the multi-pass cell formed by mirror 312 and 314. The multi-pass cell is approximately 4 inches in diameter, with a length of approximately 3 feet (ft.) with r.o.c., 6.5 mm holes. Light passes through the multi-pass cell and reflects on dispersion compensated mirrors 306, 308, is reflected by the thin disk 302 through Brewster plate 320, before exiting the output coupler.
through the gain medium, to the multipass cell formed by two spherical mirrors and the output coupler mirrors with high pulse energies will enable a wider range of ultrafast operation schemes. These systems are complex, cost-ineffective because the order in which light passes through these elements does not matter. The difference between the laser footprint. The turning mirror recollimates the beam outside the cavity. The beam 25 inches in diameter, approximately 2 meters (m) in length with r.o.c., 6.5 mm holes. Light passes through the multipass cell and reflects on the chirped mirrors 522 and 524 each having ~60 fs^2/reflection, and to the SAM 516. A curved mirror 514, with a radius of approximately 50 cm, is used to focus light onto the SAM 516 in order to reach the saturation intensity. A turning mirror 512 is used to steer the beam in order to reduce the laser footprint. The order in which light passes through these elements does not matter. The difference between the light path in FIG. 8 is that every time the acousto-optic cell 528 is triggered, a transient Bragg grating is created in the cell, which deflects the beam outside the cavity. The beam then bypasses the output coupler 526, is picked up by a mirror 530 delivering pulses of higher energy. The curved mirrors 508, 510 are used to focus the beam onto the grating and recollimate it.

Cavity dumping relies on bypassing the output coupler (OC) that has a low transmission coefficient, by dumping inside the Fabry-Perot cavity where most of the energy is located. This is achieved by inserting an acousto-optic cell, in which an acoustic wave creates a Bragg grating that diffracts light. Generation of femtosecond pulses with intensities in the MW range is essential for a number of applications including optical harmonic generation, investigation of ultrashort non-linear optical phenomena and laser micromachining. The development of low cost, simple and compact laser sources with high pulse energies will enable a wider range of ultrafast laser applications, making this technology more available to both the research and the development communities.

In laser micromachining applications, minimum pulse energy of several 100 s of nano Joulies (nJ) is generally required. Consequently, most research studies utilize laser systems typically composed of a laser oscillator followed by an amplification stage, employing chirped pulse amplification schemes. These systems are complex, cost-ineffective and require high pump power levels. We propose, as an alternative, to use the laser system described above for such applications and demonstrate its ability to produce ultrashort light pulses, with sufficient energy for micromachining applications.

FIG. 9 is a surface profile of laser micro-machined trenches in Arsenic trisulfide (As_2S_3) using the mode-locked laser of the present invention. The femtosecond regime minimizes heat disposition and allows the fabrication of fine features measuring less than approximately 10 microns.

FIG. 9 shows the surface profile of laser micromachined trenches in Arsenic trisulfide using pulse energies of approximately 20 nJ (image taken with an interferometric microscope Zygo New View 5000).

FIG. 10 is an oscilloscope trace of a 2-MHz laser pulse train, having a pulse separation of approximately 500 nanoseconds (ns).

In addition to an increase of the pulse energy, lowering the repetition rate minimizes damage problems associated with the thermal load accumulated after the pulse. The insertion of the multipass cell increases with time separation between each pulse, leaving more time to the material to recover from the previous pulse. Recovery time artifacts are thus avoided. This is illustrated by FIG. 10 showing the oscilloscope trace of a 2-MHz laser pulse train having a pulse separation of approximately 500 ns. In comparison, a standard 90-MHz laser, shown in FIG. 11, has a pulse separation of approximately 10 ns. FIG. 11 is an oscilloscope trace of a standard 90-MHz laser pulse train, having a pulse separation of approximately 10 nanoseconds (ns).

The advantages of the invention are less cost, more versatile laser equipment, greatly increased ruggedness, ease of manufacture and compatibility with both disk laser and diode pumped solid-state laser.

While the invention has been described, disclosed, illustrated and shown in various terms of certain embodiments or modifications which it has presumed in practice, the scope of the invention is not intended to be, nor should it be deemed to be, limited thereby and such other modifications or embodiments as may be suggested by the teachings herein are particularly reserved especially as they fall within the breadth and scope of the claims here appended.

We claim:

1. A compact, high intensity megahertz (MHz) mode-locked laser, the laser consisting of:

- a laser source for producing a light beam coupled to a resonator cavity having a gain medium, the gain medium selected from the group consisting of Yb:KYW, a KY[WO_4]_2 (KYW) crystal doped with Ytterbium ions, Yb:YAG, a Y_3Al_5O_12 (YAG) crystal doped with Ytterbium ions, and Ti:Sapphire, a sapphire (Al_2O_3) crystal doped with Titanium ions, the resonator cavity consisting essentially of:

- a saturable absorber mirror in the resonator cavity for self-starting and stable mode-locking operation;

- a multipass mirror system having only a first mirror and second mirror, each of the first and second mirror having only one hole, in combination with the saturable absorber mirror in the resonator cavity for lowering repetition rate of the laser system to below approximately 50 megahertz (MHz), the first mirror and the second mirror aligned to allow the light beam to enter through the one hole in the first mirror to reflect plural times within the multipass mirror system and exit through the one hole in the second mirror;

- dispersion compensating element in the resonator cavity for dispersion compensation; and

- an output coupler to the laser for releasing pulses with intensities in a range between approximately 1 Mega-
Hertz (MHz) and approximately 50 Megahertz (MHz), and having an energy of between approximately 10 nano Joules (nJ) and approximately 150 nano Joules (nJ) for micro-machining and micro-structuring applications, the light beam resonating inside the resonator cavity formed by the output coupler and the saturable absorber mirror.

2. The laser of claim 1 wherein the laser source includes a diode laser source.

3. The laser of claim 1 wherein the multi-pass mirror slows down the repetition rate of laser pulses to between approximately 1 MHz to approximately 50 MHz.

4. A compact, high intensity megahertz (MHz) mode-locked laser, the laser consisting essentially of:
   - a laser source for producing a light beam coupled to a resonator cavity having a gain medium, the gain medium selected from the group consisting of Yb:KYW, a KY[WO₄]₂ (KYW) crystal doped with Ytterbium ions, Yb:YAG, a Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Titanium ions, the resonator cavity consisting essentially of:
     - a saturable absorber mirror in the resonator cavity for self-starting and stable mode-locking operation;
     - a multi-pass mirror system having a first mirror and second mirror in combination with the saturable absorber mirror in the resonator cavity for lowering repetition rate of the laser system to below approximately 50 megahertz (MHz), the first mirror and the second mirror aligned to allow the light beam to reflect plural times within the multi-pass mirror system;
     - a dispersion compensating element in the resonator cavity for dispersion compensation;
     - an output coupler to the laser for releasing pulses with intensities in a range between approximately 1 Megahertz (MHz) and approximately 50 Megahertz (MHz), and having an energy of between approximately 10 nano Joules (nJ) and approximately 150 nano Joules (nJ), sufficient for micro-machining and micro-structuring applications, the light beam resonating inside the resonator cavity formed by the output coupler and the saturable absorber mirror; and
     - a cavity dumping component for extracting energy trapped inside of the resonant cavity.

5. The laser of claim 4 wherein the cavity dumping component is an optical gate located between the output coupler and the saturable absorber mirror.

6. The laser of claim 5 wherein the cavity dumping component is an electro-optically driven gate.

7. The laser of claim 5 wherein the cavity dumping component is an electro-optically driven gate.

8. A method of improving the pulse energy of a compact, high intensity megahertz mode-locked laser consisting of the steps of:
   - providing a resonant laser cavity having a saturable absorber mirror and a multipass cell formed by only one first and only one second mirror, each of the first and the second mirror having only one hole to allow a light beam from a laser source to enter and exit, and a laser gain medium, the gain medium selected from the group consisting of Yb:KYW, a KY[WO₄]₂ (KYW) crystal doped with Ytterbium ions, Yb:YAG, a Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Titanium ions;
   - passing a light beam through the gain medium and the multipass cell during each pass of the light beam inside the resonator laser cavity formed by the output coupler and the saturable absorber mirror, the light beam entering the multipass cell though the one hole in the first mirror, reflecting plural times within the multipass cell and exiting the multipass cell through the only one hole in the second mirror;
   - positioning a cavity dumping component within the laser cavity between an output coupler and the saturable absorber;
   - pumping the laser gain medium;
   - extracting energy trapped inside the cavity by dumping excess energy through an optical gate; and
   - outputting femtosecond pulses with intensities in a range between approximately 1 Megahertz (MHz) and approximately 50 Megahertz (MHz), and having an energy of between approximately 10 nano Joules (nJ) and approximately 150 nano Joules (nJ).

9. The method of claim 8 wherein the optical gate is acousto-optically driven.

10. The method of claim 8 wherein the optical gate is electro-optically driven.

11. The method of claim 8 wherein the saturable absorber is a broadband saturable absorber.

12. A method of providing low cost, simple, compact, ultrashort laser with high pulse energies for micromachining applications, consisting of the steps of:
   - providing a laser configuration having a laser gain medium, a resonator cavity, a saturable absorber mirror, a multipass mirror cell having only one first and only one second mirror, each mirror having only one hole therethrough and an output coupler, the gain medium selected from the group consisting of Yb:KYW, a KY[WO₄]₂ (KYW) crystal doped with Ytterbium ions, Yb:YAG, a Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Titanium ions;
   - resonating a light beam inside the cavity formed by the saturable absorber mirror and the output coupler;
   - passing the light beam into the multipass mirror cell through the only one hole in the first mirror, reflecting the light beam plural times within the multipass mirror cell for lowering a repetition rate of the laser system, the light beam exiting the multipass mirror cell through the only one hole in the second mirror;
   - pumping the laser gain medium;
   - generating femtosecond pulses with intensities in a range between approximately 1 Megahertz (MHz) and approximately 50 Megahertz (MHz), and having an energy of between approximately 10 nano Joules (nJ) and approximately 150 nano Joules (nJ); and
   - simultaneously lowering the repetition rate of each pulse, thereby minimizing damage associated with the thermal load accumulated pulse after pulse.

13. A high intensity megahertz (MHz) mode-locked laser system, the laser system consisting essentially of:
   - a laser source and a gain medium, the gain medium selected from a group consisting of a Ti:Sapphire crystal and a thin disk-shaped gain medium;
   - a saturable absorber mirror in the system for self-starting and stable mode-locking operation;
   - a multipass mirror cell having a first mirror and a second mirror aligned with the first mirror in the laser system, each of the first and the second mirrors having only one hole to allow a light beam from the laser source to enter and exit, respectively, the light beam reflecting plural times within the multipass mirror cell for lowering a repetition rate of the laser system to below approximately 50 megahertz (MHz),
US 7,590,156 B1

11. A laser system, comprising:

a dispersion compensating element in the laser system for
dispersion compensation; and

an output coupler to the laser system for releasing pulses
with intensities in a range between approximately 1
MegaHertz (MHz) and approximately 50 MegaHertz
(MHz), and having an energy of between approximately
10 nano Joules (nJ) and approximately 150 nano Joules
(nJ) for micro-machining and micro-structuring applica­
tions.

14. A laser system, consisting essentially of:

a lasing element, the lasing element including a resonator
cavity having a gain medium, the gain medium selected
from the group consisting of Yb:KYW, a KY[WO₄]₂
(KYW) crystal doped with Ytterbium ions, Yb:YAG, a
Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and
Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Tita­
nium ions;

dispersion compensating elements coupled to the lasing
element;

a SAM mode-locking element coupled to the dispersion
compensating element; and

a multipass mirror system consisting of a first mirror and a
second mirror aligned with the first mirror and separated
by a distance, each of the first and second mirror having
one single hole therethrough coupled to the SAM mode­
locking element; and

an output coupler coupled to the multipass mirror system
for providing an output from the laser system with inten­
sities in a range between approximately 1 MegaHertz
(MHz) and approximately 50 MegaHertz (MHz), and hav­
ing an energy of between approximately 10 nano Joules
(nJ) and approximately 150 nano Joules (nJ).

12. A laser system, comprising:

a lasing element, the lasing element including a resonator
cavity having a gain medium, the gain medium selected
from the group consisting of Yb:KYW, a KY[WO₄]₂
(KYW) crystal doped with Ytterbium ions, Yb:YAG, a
Y₃Al₅O₁₂ (YAG) crystal doped with Ytterbium ions, and
Ti:Sapphire, a sapphire (Al₂O₃) crystal doped with Tita­
nium ions;

dispersion compensating elements coupled to the lasing

element;

a SAM mode-locking element coupled to the dispersion
compensating element; and

a multipass mirror system coupled to the SAM mode­
locking element, the multipass mirror system consisting
of a first mirror and a second mirror aligned with the first
mirror, each of the first and second mirror having one
single hole therethrough to allow a light beam from the
lasing element to enter the multipass mirror system
through the one hole, the light beam reflecting plural
times within the multipass mirror system before exiting
through an opposite hole;

cavity dumper coupled to the multipass mirror system;

and

an output coupler coupled to the cavity dumper for provid­
ing an output from the laser system, with intensities in a
range between approximately 1 MegaHertz (MHz) and
approximately 50 MegaHertz (MHz), and having an
energy of between approximately 10 nano Joules (nJ)
and approximately 150 nano Joules (nJ), the laser cavity
formed by the SAM mode-locking element and the out­
put coupler.

* * * * *