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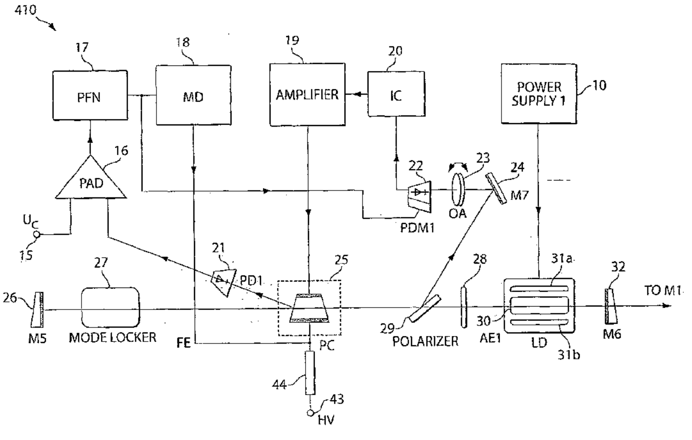

Fig. 4

(57) Abstract: In one aspect, a laser system is provided. The laser system comprises an oscillator comprising an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons, a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons, and a pulse generator for generating first pulsed laser radiation at a first wavelength and having a micro-macro pulse structure, and a conversion stage coupled to the oscillator stage to receive the first pulsed laser radiation, the conversion stage configured to amplify the first pulsed laser radiation and convert at least some of the amplified pulsed laser radiation to a second wavelength, the conversion stage providing second pulsed laser radiation at the second wavelength and having the micro-macro pulse structure, wherein the micro-macro pulse structure includes a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the picosecond scale.

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INFRARED LASER METHODS AND APPARATUS

RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application Serial No. 60/995,097 entitled “MID-INFRARED LASER SYSTEMS AND METHODS,” filed on September 24, 2007, which is herein incorporated by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to laser systems in the infrared range, and more particularly, to diode-pumped laser systems.

BACKGROUND

Conventional surgery is often characterized by a number of general risk factors including blood loss, wound complications such as infection, damage to surrounding tissue and other organs in the operative area, and development of blood clots in the legs which may result in pulmonary embolism, pneumonia, and heart complications (e.g. heart attack). The application of new and innovative laser-based surgical instruments may drastically reduce some of these risk factors by, for example, reducing the operating time and the damage to surrounding tissue and organs.

Lasers have tremendous potential as precise surgical instruments due to their small spot sizes and the ability to select specific wavelengths that are strongly and/or selectively absorbed by the target tissue. A goal of laser surgical applications is to remove a defined volume of tissue by a process called ablation, while leaving the surrounding tissue biologically viable. Minimizing collateral damage, which results from the laser interacting with the surrounding (e.g., healthy) tissue, is often a chief concern when contemplating laser surgical applications.

In various forms of surgery, for example, in neurosurgery, the ability to incise or remove tissue in close proximity to sensitive (frequently compromised) neural and vascular structures may be critical to the success of the surgery. For example, preserving adjacent tissue structures may be particularly important when ablating nerve or ocular tissue. To resect a brain tumor, a surgeon’s aim is to remove the entirety of cancerous cells but none of the benign cells of the surrounding tissue. Damage to surrounding cells may lead to a loss of neurons and thus to a loss of brain function. Due to their physical nature, lasers will typically cause some level of collateral cell damage through a multitude of different mechanism, e.g. cell damage due to stark thermal heating or due to induced shock waves disrupting the tissue.

In general, the effect of laser radiation on the tissue depends on the optical absorption properties of the tissue and subsequent energy dissipation. The latter may lead to tissue overheating and explosive vaporization, which inevitably harms the adjacent cells. The optical absorption properties of tissue are governed by electronic, vibrational and rotational structures of the constituent biomolecules, and are therefore typically dominated by the absorption of proteins, DNA, melanin, hemoglobin and water. The wide spread spectroscopic transitions of these tissue chromophores across the electromagnetic spectrum enables optical excitations of tissue in various spectral regions from the ultraviolet (UV) to the infrared (IR) range. Hence, relatively intense laser radiation tuned to specific absorption bands in these spectral regions has a potential for carrying out ablation in biological tissues and, when generated appropriately, may provide a mechanism for precise surgical operations. Excimer lasers, which operate in the UV range, have proven to be particularly adept at carrying out effective tissue ablation in corneal stroma. The usage of UV radiation, however, raises serious concerns about cell mutations due to DNA photo damage, which severely limits the applicability of UV lasers. Due to the absence of mutagenic risks, lasers in the infrared (IR) range may hold special promise for medical applications.

There are a number of relevant properties to consider for lasers that are employed for tissue ablation including sufficiently high average power and safe performance and operation. Conventionally, high-power lasers (more than 1 W) used for tissue manipulation in the mid-IR range have most commonly been gas-discharge CO and CO2 lasers, which provide relatively large amounts of energy at numerous mid-IR laser lines. However, the thermal tissue damage radius using the main CO2 wavelength (10.6 μm) is substantial. For example, in the case of continuous-wave (cw) CO2 lasers, thermal damage can be in the order of 200–1,000 μm. When operated in a rapid scanning or a pulsed mode with short pulses (~ 180 nanoseconds (ns)), thermal damage may be reduced to a range of 70–160 μm and ~60 μm, respectively. However, in many surgical applications, even this reduced thermal tissue damage radius is unacceptable. In addition, due to the larger penetration depth, approximately 12 μm at 10.6 μm wavelength, it may not be possible to achieve the reduced thermal damage that is found at other IR wavelengths where the tissue absorption is stronger. Therefore, gas-discharge lasers may have only limited applicability as a surgical instrument.

It has been discovered that two specific mid-IR wavelengths, 6.1 and 6.45 µm, are particularly effective for performing tissue ablation with generally minimal collateral damage. This is due in part to the fact that radiation at these wavelengths is absorbed dominantly by the protein in the tissue and partially by the water in the tissue. The specifically identified wavelengths coincide with the amide-I and amide-II vibrational bands of the peptide bond (O=C-N-H), which is a constituent of protein molecules. The amide-I and amide-II groups link the amino acids which form the proteins. In addition, these wavelengths overlap with the bending mode of water, which has an absorption peak at approximately 6.1 µm.

The efficacy of using radiation at 6.1 and 6.45 µm for tissue ablation has been demonstrated using a free electron laser (FEL). In particular, the Mark III FEL at Vanderbilt University in Nashville, Tennessee is capable of producing a pulsed laser having the relatively high average power and high peak power needed for tissue ablation at the identified wavelengths. The Mark III FEL is further capable of emitting a pulse structure having macro pulses, i.e., trains of picosecond micro pulses separated by approximately 350 picosecond with approximately 12,000 micro-pulses per macro-pulse, each having a duration between 4 and 5 µs, generating up to 30 macro pulses per second. A pulse structure wherein a macro-pulse that corresponds to the envelope of a plurality of micro-pulses is referred to herein as a micro/macro pulse structure.

Despite the advantageous properties of the Mark III FEL, such systems have significant drawbacks. In particular, the underlying physical principles that permit FELs to produce the above described pulse sequences include a relativistic electron beam propagating through a periodic magnetic field wherein electrons are ejected from a linear accelerator or provided by a storage ring (synchrotron). As a result, FELs are large-scale facilities requiring substantial costs to build and highly qualified personal to operate and maintain. Accordingly, such facilities may be prohibitively expensive and are generally unsuitable for broad clinical usage.

Medical and surgical applications may also benefit from other laser properties. For example, it has been recognized that using lasers as a surgical tool is accompanied by a relatively high degree of blood clotting (coagulation) and minimal wound bleeding. However, the wavelengths for generally optimal coagulation are different than those for effective tissue ablation. Accordingly, while the intrinsic properties of FELs make them well suited for tissue ablation, the same intrinsic properties render FELs generally unsuitable for coagulation.

SUMMARY OF THE INVENTION

Some embodiments according to the present invention include an oscillator for generating a laser beam having a micro-macro pulse structure, the oscillator comprising an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons, a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons, and a pulse generator for generating a pulsed laser from the emitted photons, the pulsed laser including a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the pico-second scale.

Some embodiments according to the present invention include a laser system comprising an oscillator comprising an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons, a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons, and a pulse generator for generating first pulsed laser radiation at a first wavelength and having a micro-macro pulse structure, and a conversion stage coupled to the oscillator stage to receive the first pulsed laser radiation, the conversion stage configured to amplify the first pulsed laser radiation and convert at least some of the amplified pulsed laser radiation to a second wavelength, the conversion stage providing second pulsed laser radiation at the second wavelength and having the micro-macro pulse structure, wherein the micro-macro pulse structure includes a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the picosecond scale.

Some embodiments according to the present invention include laser instrument adapted to perform laser surgery, the laser system comprising a laser component adapted to generate a first laser beam at a first wavelength adapted to perform tissue ablation and to generate a second laser beam at a second wavelength adapted to perform coagulation an instrument output coupled to the laser component to output the first laser beam, the second laser beam or both simultaneously, and a mechanism for selecting whether the instrument output provides the first laser beam alone, the second laser beam alone or both the first laser beam and the second laser beam simultaneously.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a laser system, in accordance with some embodiments of the present invention;

FIG. 2A-2C illustrates a micro-macro pulse structure, in accordance with some embodiments of the present invention;

FIG. 3 illustrates an oscillator capable of generating a micro-macro pulse structure, in accordance with some embodiments of the present invention;

FIG. 4 illustrates an oscillator capable of generating a micro-macro pulse structure, in accordance with further embodiments of the present invention;

FIG. 5 illustrates an oscillator capable of generating a micro-macro pulse structure, in accordance with further embodiments of the present invention;

FIG. 6 illustrates a laser system capable of emulating at least some of the characteristics of the Mark III FEL, in accordance with some embodiments of the present invention;

FIG. 7 illustrates a laser system capable of emulating at least some of the characteristics of the Mark III FEL, in accordance with further embodiments of the present invention; and

FIG. 8 illustrates a laser system for emitting lasers having multiple wavelengths configured to perform tissue ablation, coagulation or both, in accordance with some embodiments of the present invention.

DETAILED DESCRIPTION

As discussed above, the properties of FEL lasers have been shown to be efficacious for tissue ablation. However, the cost of building and maintaining such systems coupled with the large size of such facilities renders FEL lasers generally unsuitable for widespread clinical use. Semi-conductor lasers such as diode-pumped lasers can be built at much lower cost and at substantially smaller sizes than FEL lasers. However, conventional diode-pumped lasers are typically not capable of generating pulse structures capable of performing tissue ablation. In particular, conventional diode-pumped lasers are not capable of generating the relatively high average power and high peak power pulse sequences necessary for tissue ablation. Additionally, conventional diode-pumped lasers are not capable of producing the relatively complex pulse structures shown to be efficacious for performing tissue ablation (e.g., the relatively complex micro/macro pulse structures generated by the Mark III FEL).

There are a number of laser characteristics that may impact the efficacy of a laser for use in a particular application. For example, in surgical applications (e.g., tissue ablation and/or coagulation), one or some combination of wavelength, pulse duration, distance between pulses, pulse repetition rate, average power, peak energy, spot size and spatial profile may impact the effectiveness of the laser. Conventional solid state lasers, and more particularly, diode-pumped lasers have been limited in their ability to generate one or more of the above parameters at desired values, for example, at values that are effective for laser surgery, either tissue ablation, coagulation or both.

As discussed above, the intrinsic properties of FELs result in a micro-macro pulse structure that has been shown to be particularly effective in performing tissue ablation. Conventional diode-pumped lasers do not naturally generate such a structure and have not been developed to do so. The inability of conventional diode-pumped lasers to generate such a pulse structure has prevented, at least in part, the use of such lasers for tissue ablation, particularly in surgical applications requiring precise tissue ablation and minimal collateral damage. In addition, conventional solid state lasers have not been capable of generating pulse structures having energy and power profiles suitable for various surgical applications. In particular, conventional diode-pumped lasers do not generate micro-pulses having sufficient peak energy and/or macro-pulses having sufficient average power to, for example, perform tissue ablation, and more particularly, to emulate the pulse sequences generated by the Mark III FEL.

Applicant has designed a diode-pumped laser system capable of generating a pulse structure that substantially emulates at least some characteristics of pulse structures previously capable of being generated solely through FEL systems. In some embodiments, the diode-pumped laser system is capable of generating a micro-macro pulse structure wherein the micro-pulse duration is on a pico-second scale and the macro-pulse duration is on a microsecond scale.

As discussed above, another generally beneficial property of lasers is the ability of lasers coagulate, thereby reducing bleeding. Wound bleeding is a significant complication in many surgeries, adding both to the difficulty and risk of performing the operation. Applicant has recognized the benefit of using lasers as a so-called “bloodless knife.” However, the wavelengths for lasers that are generally effective for tissue ablation are different than effective wavelengths for coagulation. Moreover, the lasers capable of tissue ablation with minimal collateral damage (i.e., FELs) do not generate laser beams at wavelengths effective for coagulation. Accordingly, lasers that can operate satisfactorily for both cutting and coagulation are not available from the same laser instrument.

Applicant has designed a laser system that performs both tissue ablation and coagulation. According to some embodiments, the laser system generates at least one laser beam having at least some portion of the laser energy at a wavelength adapted to perform tissue ablation and at least some portion of the laser energy at a wavelength adapted to perform coagulation. The two portions of the at least one laser beam may be generated substantially simultaneously to cause tissue ablation and coagulation to occur at approximately the same time. As a result, laser surgical cutting may be performed without the blood loss that typically accompanies both conventional knife surgery and conventional laser surgery.

Following below are more detailed descriptions of various concepts related to, and embodiments of, methods and apparatus according to the present invention. It should be appreciated that various aspects of the invention described herein may be implemented in any of numerous ways. Examples of specific implementations are provided herein for illustrative purposes only. In addition, the various aspects of the invention described in the embodiments below may be used alone or in any combination, and are not limited to the combinations explicitly described herein.

FIG. 1 illustrates a laser system in accordance with some embodiments of the present invention. Laser system 100 includes an oscillator 110 adapted to generate laser radiation at a first wavelength and according to a desired pulse structure to provide laser beam 117. Laser system 100 also includes a conversion stage 120 that includes amplification stage 130 and wavelength conversion stage 140. Amplification stage 130 is coupled to the oscillator to receive laser beam 117 and apply a gain thereto, thus converting the power characteristics of the laser beam to a higher power laser. Amplification stage may be provided to amplify the laser beam generated by oscillator 110 to generate amplified laser beam 125 having desired power characteristics, as discussed in further detail below.

Conversion stage 120 also includes wavelength conversion stage 140 which is coupled to the amplification stage 120 to receive amplified laser beam 125 and convert at least some of the laser radiation from the first wavelength to a second wavelength. For example, conversion stage 130 may convert amplified laser beam 125 from the first wavelength to a second wavelength more suitable for performing tissue ablation. In some embodiments, amplification stage 120 and conversion stage 130 are combined into a single stage that performs amplification and conversion simultaneously. Embodiments of each of the components identified above are described in further detail below.

As discussed above, oscillator 110 generates a laser beam 117 at a first wavelength and having a predetermined pulse structure. For example, oscillator 110 may be configured to produce a laser beam 117 having a parameter set that includes wavelength of the laser radiation, pulse duration of the laser pulses, distance between the pulses, and pulse repetition rate. Oscillator 110 may be designed to produce a laser beam having generally desirable values for each of the parameters in the parameter set. For example, oscillator 110 may be configured to produce a laser beam that emulates, to the extent possible, the pulse structure emitted by free electron lasers, and in particular, the Mark III FEL that have been shown to be effective at ablating tissue with relatively little collateral damage. However, oscillator 110 may be configured to generate other pulse structures, as the aspects of the invention are not limited in this respect.

Oscillator 110 includes a diode pumped laser source 115 to generate radiation that forms laser beam 117. The term diode pumped laser refers herein to a semiconductor laser mechanism wherein a laser diode is used to excite (pump) an active material responsive to the radiation emitted by the laser diode. Typically, the laser diode generates radiation that causes ions in the active material to achieve a higher energy state. When excited ions transition from the higher energy state to a lower energy state, photons are released into a resonator or optical cavity at wavelengths dependent in part on the active material type. The released ions may then be reflected back and forth in the optical cavity to form the desired laser beam, as discussed in further detail below. The released photons may contribute to further excite the active material to release additional photons that contribute to laser beam 117 generated by the oscillator 110.

There are numerous active materials that may be used as the source for laser radiation. Typically, the source material is an ion doped crystal or glass material. Source materials are often denoted using the notation *dopant* : *gain material*. For example, a neodymium (Nd) doped yttrium aluminum garnet (YAG) crystal is denoted as Nd:YAG. Other common crystals used as source material include yttrium, gadolinium or lutetium vanadate crystals ($YV0_4$,

$GdV0_4$ and $LuV0_4$, respectively), yttrium lithium fluoride (YLF) crystals, etc. Other common laser-active dopants include ytterbium (Yb), Erbium (Er), Thulium (Tm), Holmium (Ho) and Chromium (Cr). It should be appreciated that any combination of dopant and gain material may be used as the active material to generate radiation, as the aspects of the invention are not limited in this respect.

As discussed above, a limitation of conventional diode-pumped lasers is insufficient power to generate a laser beam suitable for medical purposes, such as tissue ablation. The pumping power of laser diodes relates, in part, to the degree of integration and density of the laser diodes. Single stripe, diode array, diode bar and diode stacks are examples of laser diode arrangements, listed above generally in order of increased degree of integration. Thus, diode stacks can produce relatively high power lasers due to the increased pumping power. Recent developments in high density laser diode arrays (which may then be stacked) has facilitated development of a diode-pumped laser having power characteristics that may be suitable for surgical applications. In some embodiments, the laser diode pump is formed from a relatively high density, highly integrated diode array, bar or stack capable of pumping active material at power levels suitable for generating radiation that can be transformed into a laser beam suitable for tissue ablation. However, any laser diode configuration may be used, as the aspects of the invention are not limited in this respect.

Also, as discussed above, the wavelengths lasers generated using a diode pump depends, at least in part, on the active material used to generate the laser. It should be appreciated that that a diode pump will release radiation in different quantities at multiple wavelengths that are clustered about a central wavelength at which the most significant portion of the radiation is emitted. When referring to a single wavelength emitted by an oscillator, it is to be understood that it is to the main wavelength that is generally being referred. In some embodiments, the active material includes Nd:YAG and the resulting photons have a wavelength of 1064nm. Thus, the laser beam generated by an oscillator using Nd:YAG will produce a laser beam having a wavelength of approximately 1 micron. However, other materials will result in laser beams having other wavelengths and the material may be chosen to provide a laser beam having a desired wavelength, as the aspects of the invention are not limited in this respect.

According to some embodiments, oscillator 110 produces a laser beam at a first wavelength having a pulse structure similar to the pulse structure illustrated in FIGS. 2A-2C.

FIG. 2A illustrates a train of macro-pulses, each macro-pulse having a width on a microsecond scale. The macro-pulse train may be comprised of a plurality of macro-pulses separated by a distance T1, which may be on the millisecond scale. For example, the distance between each macro-pulse may be in the range from 1 to 100 milliseconds. Applicant has appreciated that macro-pulses separated by approximately 33 milliseconds closely emulate the Mark II FEL macro-pulse structure and may be particularly suitable of surgical applications. However, other distances separating macro-pulses in a pulse train may be used, as the aspects of the invention are not limited in this respect.

FIG. 2B illustrates a more detailed view of the composition of each individual macro-pulse. As discussed above, each macro-pulse may correspond to the envelope of a plurality of micro-pulses. The duration T2 (e.g., the width) of each macro-pulse may be between 1 and 50 μs, and preferably between 1 and 10 μs for medical applications. Applicant has appreciated that macro-pulses between 3 to 6 μs closely emulate the macro-pulse structure of the Mark III FEL and may be particularly suitable for surgical applications. However, macro-pulses of other widths may be used, as the aspects of the invention are not limited in this respect.

FIG. 2C illustrates parameters of each of the micro-pulses that comprise the macro-pulse trains discussed above. Each micro-pulse may have a width T3 on a picosecond scale. For example, the width of each micro-pulse may be between .5 and 10 picoseconds. Applicant has appreciated that micro-pulses of approximately 1 picosecond closely emulate the pulse structure of the Mark III FEL and may be particularly suitable for surgical applications. However, micro-pulses of other widths may be used, as the aspects of the invention are not limited in this respect. The micro-pulses forming each macro-pulse may be separated by a distance T4 on a picosecond scale. For example, each micro-pulse may be separated by a distance between 10 and 1000 picoseconds. Applicant has appreciated that micro-pulses separated by approximately 350 picoseconds closely emulate the pulse structure of the Mark III FEL and may be particularly suitable for surgical applications. However, the micro-pulses may be separated by other distances, as the aspects of the invention are not limited in this respect.

Oscillator 110 may be configured to generate a laser beam having any of the pulse structures described above. In some embodiments, oscillator 110 generates a laser beam having a micro-macro pulse structure at a wavelength having substantial energy at approximately 1 micron. In some embodiments, the micro-macro pulse structure has macro pulse energy is in a range of 100 μJ – 4 mJ at a repetition rate of between 1 Hz and 1 kHz. However, oscillator 110 may generate micro-macro pulse structures having different wavelength and power characteristics, as the aspects of the invention are not limited in this respect.

As discussed above, the conversion stage of laser system 100 includes amplification stage 120 that amplifies the radiation generated by the oscillator such that the laser radiation has desired power characteristics. For example, amplification stage 120 may include one or more amplifiers arranged to achieve average power and peak power characteristics suitable for tissue ablation. In some embodiments, amplification stage 120 includes at least one optical amplifier that achieves laser amplification based on stimulated emission. In particular, amplification stage 120 may include a pumped gain material capable of increasing the power of the input laser (i.e., the laser generated by oscillator 110). According to some embodiments, amplification stage 120 includes a multi-stage amplifier.

For example, amplification stage 120 may include one or more regenerative amplifiers in series with one or more multi-pass amplifiers, or amplification stage 120 may include one or more chirped-pulse amplifiers, as discussed in further detail below. However, amplification stage 120 may include any amplifier capable of achieving a desired gain, as the aspects of the invention are not limited in this respect. In some embodiments, the amplification achieves ten fold power increase or more, wherein the macro-pulse energy is in a range of 50-100 mJ. However, other amplifications may be achieved, as the aspects of the invention are not limited in this respect.

The conversion stage of laser system 100 also includes a wavelength conversion stage 140 that converts the laser radiation emitted at the first wavelength associated with the oscillator to one or more different wavelengths. As discussed above, the wavelength of the laser radiation generated by oscillator 110 typically depends, in part, on the properties of the active material being pumped. While a range of wavelengths may be achieved by selecting the appropriate material, some desired wavelengths may not be achievable directly from the oscillator. Accordingly, wavelength conversion stage 130 converts the wavelength of the laser generated by the oscillator to a desired wavelength. In some embodiments, one or more optical parametric oscillators (OPO) and/or one or more optical parametric amplifiers (OPA) are employed to convert the wavelengths of the laser beam generated by the oscillator into one or more different wavelengths. In some embodiments, the conversion stage includes two conversion steps, a first step of which converts wavelengths of the laser from the oscillator to intermediate wavelengths and a second step of which converts the intermediate wavelengths into final output wavelengths, as discussed in further detail below. However, any components capable of converting the wavelengths of laser beam 117, 125 may be used, as the aspects of the invention are not limited in this respect.

Laser system 100 may be tunable to achieve a range wavelengths suitable for a desired application. In some embodiments, laser system 100 is designed as a table-top laser suitable for general use in clinical settings. In particular, laser system 100 may be constructed to a size suitable for use in a variety of existing operating rooms and/or typical operating conditions and settings. Laser system 100 may be configured to generate a laser having wavelength and power characteristics suitable for surgical applications. For example, laser system 100 may be configured to generate one or more lasers capable of performing tissue ablation, coagulation or both. Various embodiments of the laser system described above are discussed in further detail below.

As discussed above, conventional diode-pumped laser systems have been incapable of generating pulse structures that can be transformed into lasers suitable for performing laser surgery, particularly with the minimal collateral damage requirements of precision surgeries such as neurosurgery and vascular surgery. In particular, conventional diode-pumped laser systems have been unable to generate micro-macro pulse structures that can be converted to lasers having the appropriate energy and power characteristics suitable for tissue ablation and/or coagulation.

Among diode-pumped solid state lasers up to 2.1 μm, only continuous-wave (CW) mode-locked laser systems have temporal pulse structures similar to those of FEL trains. However, the construction of such a CW mode-locked laser system with subsequent synchronously pumped optical parametric oscillator (SPOPO) that could reach output energies and average power similar to the FEL with up to 4 microsecond durations would require pump lasers with more than 10 kW. However, this exceeds by far the technology limits for CW mode-locked lasers of 10-100W. Peak powers and pulse energy achieved by various other conventional semiconductor lasers are very modest and generally require cryogenic cooling for efficient operation. Therefore their application is limited to low - power applications, e.g. chemical sensing and other diagnostic tasks.

Applicant has appreciated that relatively high density and highly integrated laser diode arrays may be able to obtain suitable pumping powers. In addition, by using a negative feedback mechanism in combination with a suitable mode locking component, a diode-pumped laser system capable of generating a micro-macro pulse structure suitable for surgical applications may be obtained.

FIG. 3 illustrates an oscillator capable of generating pulse structures such as those described above, in accordance with some embodiments of the present invention. For example, oscillator 310 may be used as the oscillator 110 illustrated in connection with laser system 100 of FIG. 1. Oscillator 310 may be constructed as a diode-pumped short-cavity laser including mirrors 305a and 305b, a negative feedback control 320, a diode pump 315, and a passive mode locking component 330. Diode pump 315 generates photons that oscillate back and forth in the resonator or optical cavity between mirrors 305a and 305b. Negative feedback control 320 and the passive mode locking component operate in connection to generate the generally desirable pulse structures, as discussed in further detail below.

Recent developments in solid state lasers have made available high-power diode pump lasers. For example, high-power laser diode arrays developed for space technology applications have recently become available commercially. Accordingly, laser diode array 318 may be formed from a high density stack of laser diode arrays capable of pumping the active medium 316 to produce photons that can be formed into pulse structures suitable for converting into laser beams capable of performing, for example, tissue ablation and/or coagulation. In particular, laser diode array 318 may be capable of pumping active material 316 to generate macro pulse energy in a range from 100μ-4mJ at a repetition rate of 1 Hz to 1KHz. For example, 1mJ pulses at 1 kHz may be a suitable pulse train that can be converted into a laser beam (e.g., via an amplification/wavelength conversion stages) capable of performing tissue ablation and/or coagulation.

As discussed above, the laser diode-pump 315 generates photons at a wavelength corresponding to the type of material being pumped. For example, Nd-doped materials will generate photons having a wavelength of approximately 1 micron. However, active material 316 can be formed from any suitable material generating photons at any wavelength. The photons generated by active material 316 may be confined in an optical cavity or resonator and reflected multiple times between mirrors 305a and 305b. Due to constructive interference effects, only certain patterns of radiation will be sustained by the resonator, with the others being suppressed by destructive interference. The most stable radiation patterns, known as modes, will be formed in the resonator.

Mirrors 305a and 305b define the extent of the optical resonator and generally determine the type of the resonator used. In particular, the curvature of the mirrors will determine the type of resonator forming the optical cavity. Typical types of resonators include plane-parallel, concentric, confocal, hemispherical and concave-convex resonators. The type of resonator chosen may depend on the characteristics and properties of the laser beam being generated. It should be appreciated that any type of resonator may be used, as the aspects of the invention are not limited in this respect.

As discussed above, the light reflecting back and forth between the mirrors will stabilize according to the modes of the resonator. However, the various modes will each oscillate independently with no fixed relationship between each other. Passive mode-locking compont 330 operates to force a fixed phase relationship between the modes oscillating in the optical cavity causing the light to form into relatively intense pulses. That is, when the fixed phase relationship is induced, the modes will periodically interfere constructively to produce a laser pulse. The laser pulses occur periodically separated by a duration that depends, in part, on the properties (e.g., length) of the optical cavity or optical resonator to produce a train of pulses. While oscillator 310 is illustrated as including a passive mode-locking component to form the pulse train, an active mode-locking component or other component capable of generating a pulse train from the light emitted by the diode pump may be used, as the aspects of the invention are not limited in this respect.

Compared to a continuous wave (cw) mode-locked laser oscillator, pulsed mode-locked solid state lasers offer the advantage of increased output pulse energy, e.g., of about two orders of magnitude. Relatively high output energies and reduced requirements on mechanical stability of the resonator are the substantial advantages of using pulsed mode-locked lasers as a tool for ablation of different materials. Analyses have shown that the statistical nature of the light generation in the optical cavity and the effect of Q-switching often lead to substantial shot-to-shot variations of the pulse energy and duration. Moreover, ultrashort pulse train duration often do not exceed several hundreds of nanoseconds and individual pulse durations may be above the spectral transform limit.

Passive mode-locking typically uses a laser resonator element whose transmittance (or reflectivity) is changed with increasing intra-cavity light intensity, e.g. a semiconductor saturable absorber mirror (SESAM) or a solution of polymethylene dyes. The laser output depends on the properties of the amplification medium and the passive mode-locker. Since typical values for amplification cross section of solid state active materials (($10^{-19} - 10^{-22}$ cm^2) are smaller than the typical values for nonlinear absorption cross section (by several orders of magnitude) the intra-cavity single pulse intensity will often saturate the mode-locker without reaching saturation and maximal amplification. Therefore, the resonator losses drop with increasing pulse intensities which causes a simultaneous Q-switching effect.

Applicant has appreciated that feedback control may be used to stabilize the passive mode-locking of solid-state lasers by suppressing the inherent instabilities of these systems. The simultaneous Q-switching due to the bleaching of the mode-locker can be overturned by a passive or active negative feedback element which introduces additional losses and suppresses the change of the pulse energies. Thus, oscillator 310 also includes negative feedback control 320 to suppress the simultaneous Q-switching of the passive mode-locked pulse lasers. In particular, negative feedback control 320 includes a polarizer 322, a photodiode 324, a negative feedback module 325 and Pockels cell 326. This negative feedback control permits the formation of quasi-stationary pulses at higher pump energies with parameters that do not depend on the initial stochastic distribution of the electromagnetic field in the laser resonator.

FIG. 4 illustrates an oscillator having a resonator utilizing a mode-locker and negative feedback control to produce ultra-short pulse trains, in accordance with some embodiments. Oscillator 410 uses an electro-optical modulator for the realization of a feedback control, which offers an additional degree of freedom for the control of the resonator losses through dynamic changes of the HV bias applied to a Pockels cell. The change of the HV bias values and the feedback depth together enables a dynamic control of the quality factor (Q-factor). Oscillator 410 includes a resonator with dynamic control of the Q-factor and transversal pumping of the laser medium. The scheme for dynamic control of the Q-factor of a laser resonator comprises an electronic negative feedback control scheme and an optical modulator scheme, as discussed in further detail below.

The laser resonator in FIG. 4 comprises a mirror 26, mode-locking element 27, focusing element 28, Pockels cell 25, polarizer 29, active element 30 and output coupler 32. The active element is pumped by the laser diode arrays 31a and 31b, powered by the power supply 10. The negative feedback scheme contains the Pockels cell 25, dielectric polarizer 29, optical attenuator 23, p-i-n photodiode module 22, integration scheme 20 and broadband amplifier 19. The negative feedback control of the Q-factor functions as follows. The Q-factor of the resonator is reduced by applying a constant high voltage to the Pockels cell (through the constant high-voltage source 43 and the ballast resistor 44). With the process of generation developing, part of the emitted radiation, reflected by the surface of the polarizer 29, is reflected by the mirror 24, passes through the optical attenuator 23 and activates the p-i-n photodiode module 22. The produced electrical signal is then integrated by the integration scheme 20 and amplified by the broadband amplifier 19, and applied to the other Pockels cell electrode.

The transmission of the combination of the Pockels cell 25 and the polarizer 29 suppresses the natural amplification of the pulse in the resonator. After several hundred passes of the pulse through the resonator its parameters reach quasi-stationary values provided the time characteristics of the negative feedback scheme comply with the following criteria: 1) the voltage applied to the Pockels cell 25 is proportional to the integral value of the intra-cavity radiation intensity; and 2) the value of the integration constant of the feedback is larger than the time duration for a double pass through the resonator, and smaller than the characteristic time for changes of the integral intra-cavity laser intensity. The optimal time period for electronic integration of the detected intra-cavity intensity is set by the integration constant of the integration electronic circuit 20.

The output of the broadband amplifier 19 is connected to the electrode of the Pockels cell. The depth of the negative feedback is regulated via control of the intensity of the light pulses on the p-i-n photodiode 22 by setting the transmission of the optical attenuator 23. The negative feedback scheme is capable of generating a long train of picosecond pulses with pulse energies between 0.01 and 10 μJ and train durations between 1 and 100 μs. The repetition rate of the picosecond trains can be varied from 1 Hz to several kHz. The generation of ultra-short pulses with substantially higher energies from such a laser system is possible through combination of the negative feedback scheme with a Q-factor modulation system. The modulation circuit is used for switching the Q-factor after the formation of the quasi-stationary pulse. Thus, the rest of the energy stored in the active medium 30 may be used for the amplification of the pulse, and provides a short train of 5 to 10 pulses with energies of one to two orders of magnitude higher than those obtained in long pulse train durations.

The modulation scheme consists of a fast p-i-n photodiode 21, pulse amplitude discriminator 16, programmable-delay pulse generator 17 and a control module 18. When the output signal of the photodiode 21 reaches a certain threshold, defined by the control voltage 15, the amplitude discriminator 16 triggers the pulse generator, which forms a time delay in the range of 1-50 ms. Afterwards, a control pulse is fed into the Q-factor control module 18. Depending on the control voltage 15, the level of the Q modulation can be smoothly regulated. The output pulse of the pulse generator 17 is applied to the photodiode module, disabling the negative feedback simultaneously with the Q-factor control high-voltage pulse generated from control module 18. The time for the negative feedback disabling is several resonator roundtrips and corresponds to the time of extraction of the rest of the energy stored in the active medium 30.

FIG. 5 illustrates a laser oscillator 510, according to some embodiments, having negative feedback with longitudinal pumping of the laser active element replacing the transverse pumping illustrated in FIG. 4. In particular, the resonator of oscillator 510 is comprised by the high-reflectance surface active element 34, polarizer 29, Pockels cell 25, concave high-reflectance mirror 33, concave high-reflectance mirror 41, a nonlinear passive mode-locker 42 and an output coupler 43. The surface 35 of the active element 34 has high reflectance for the wavelength of laser generation and high transmittance for the wavelength of the optical pumping and serves as a rear mirror of the laser resonator. The laser medium 34 is optically pumped by a diode laser 40, which emission is transferred through a fiber 39 and optical coupling 38 to a collimating lens 39. The collimated laser beam is focused to the active element by the focusing lens 36. The scheme for dynamic control of the Q-factor of the laser resonator includes similar or the same elements as described in connection with oscillator 410 in FIG. 4.

Accordingly, oscillators 310, 410 and 510 may produce a variety of pulse structures, including a micro-macro pulse structure that substantially emulate at least some pulse characteristics of the Mark III laser and/or is capable of producing other generally desirable characteristics. In particular, the above described oscillators are capable of generating a train of macro-pulses on the microsecond scale, each representing the envelope of a train of micro-pulses on the pico-second scale. For example, such oscillators may be capable of generating trains of picosecond pulses with total energy of 100 mJ near 1 μm. Any of oscillators 310, 410 or 510 may generate a pulse structure that satisfies the pulse duration, pulse repetition and high beam quality characteristics of a laser that may be converted (e.g., via a conversion stage as illustrated in FIG. 1) into a laser capable of performing tissue ablation, coagulation, or both, as discussed in further detail below.

There are a number of characteristics that may contribute to the efficacy of a laser system in surgical applications including laser wavelength, pulse energy, pulse duration, average power, pulse repetition and beam quality. To closely emulate the Mark III FEL, a laser should be capable of wavelength tunability between 5.75 and 6.5 μm, pulse energy on the order of about 2 mJ in order to reach the threshold for laser tissue ablation (assuming a practical spot diameter above 300 μm), pulse duration shorter than the thermal relaxation time of the biological tissue, which is typically in the range of 10 – 30 μs, average power of the laser in a range of 1 W to guaranty a reasonably high throughput in laser surgery. The pulse repetition rate of an emulating pulse sequence may match the FEL frequency (30 Hz or above), and have generally high beam quality (spatial profile) of the laser to allow focusing at relatively small spot diameters.

FIG. 6 illustrates a laser system for generating a laser that emulates at least some of the properties of the Mark III FEL, in accordance with some embodiments of the present invention. Laser system 600 includes an oscillator 610 that uses a diode-pump to generate laser beam 617. Oscillator 610 may be similar to the oscillator described in connection with any of FIGS. 1 and 3-5. One example of a suitable diode pumped oscillator generates a laser beam 617 having significant energy at 1 micron wavelength and have pulse energy from 100μJ-4mJ at a repetition rate in a range between 1 and 1000 Hz. However, any diode-pumped oscillator capable of generating a laser having desired characteristics (e.g., any wavelength and/or energy characteristics) may be used. Laser system 600 also includes an amplification stage 630 and wavelength conversion stage 640. Amplification stage 630 includes a first amplifier 633 and a second amplifier 635 to achieve desired power characteristics. According to some embodiments, the amplifiers utilize diode side-pumping geometry and are capable of achieving an average power of approximately 90 W at 1 kHz.

Amplification stage 630 may be constructed as a master-oscillator preamplifier power-amplifier implementation. In particular, amplification stage 630 may include a preamplifcation stage (e.g., first amplifier 633) having one or more multi-pass preamplifiers (e.g., a four or two-pass amplifier) capable of amplifying the pulse energy of the input laser (i.e., laser 617), for example, up to 10 mJ. Amplification stage 630 may also include a power amplification stage (e.g., second amplifier 635) having one or more multi-pass amplifiers capable of amplifying the laser energy from the preamplification, for example, to 50-100mJ. Such amplification may be suitable for achieving desired energy and power characteristics of the laser beam after the wavelength conversion stage due to conversion inefficiencies, as discussed in further detail below.

Laser system 600 also includes wavelength conversion stage 640 to convert wavelengths in the laser beam provided by the oscillator and/or amplification stage to one or more different wavelengths. Wavelength conversion stage 640 may include a cascade scheme of OPO/OPAs. The first OPO/OPA stage 643 may convert wavelengths of the radiation provided by the oscillator (which may be tunable, for example, between 1-2 microns) at the output of the amplification stage to wavelengths, for example, between 2-3 microns. The second OPO 645 stage may convert wavelengths between 2-3 microns to wavelengths between 5-7 microns. The stages may be controllable (e.g., by rotating the nonlinear crystals) such that the resulting laser beam is tunable between 5 and 7 microns, as discussed in further detail below.

The construction of this system can be done by employing contemporary achievements of mid-IR nonlinear crystal technology capable of supporting multi-watt operation of a mid-IR OPO pumped by 2-3 μm radiation. A cascade scheme of OPO/OPAs may be preferable because of the lack of nonlinear crystal materials suitable for conversion from wavelengths generated by common active materials (e.g., established Nd- (Yb and Tm) lasers) to wavelengths longer than 4 μm (e.g., to convert the laser beams from the oscillator/amplifier to wavelengths in the region of interest, such as between 5 - 7 μm suitable for tissue ablation).

The OPO/OPA stages convert by using nonlinear crystals to convert radiation at a first wavelength to radiation at a second wavelength. Nonlinear crystals suitable for the first and second stage high-average power OPO may be selected based upon transparency range, damage threshold, thermal conductivity, phase matching possibility, mechanical hardness, nonlinear figure of merit and crystal availability. Conventional materials such as $AgGaSe_2$ (AGSe) and $AgGaS_2$ (AGS) suffer from low damage thresholds and poor thermal conductivity, though these materials may be used. Due to improvements in growth techniques, $ZnGeP_2$ (ZGP) materials are available as nonlinear crystals and may be particularly suitable for some embodiments of a laser system described herein. ZGP has a relatively high nonlinearity, good thermal conductivity and acceptable damage thresholds. The short wavelength transmission cut-off is near 2 μm. The overall conversion efficiency of the system also depends on the parameters of the input laser. Accordingly, in some embodiments the nonlinear crystals for the OPO/OPA stages includes ZGP. However, any suitable non-linear crystal may be used, as the aspects of the invention are not limited in this respect.

FIG. 7 illustrates a laser system in accordance with other embodiments of the present invention. As shown, laser system 700 is configured differently than laser system 600 and has different operating parameters. In laser system 700, the wavelength conversion stage includes a first OPO/OPA stage 12 that converts laser radiation from the amplifier to wavelengths in a range between 2 and 4 microns, and a second OPO stage that converts wavelengths from the first stage to wavelengths between 5 and 8 microns. In some embodiments, the laser radiation emitted by the laser system has the corresponding laser structure and properties shown in FIG. 7. However, the illustrated wavelength, energy, power, and repetition values shown are merely exemplary and do not limit the aspects of the invention.

OPO/OPA stages typically convert photons of a first wavelength into multiple photons having a greater wavelength and therefore less energy. Because of the conversion inefficiencies, each OPO/OPA stage typically reduces the energy of the output laser beam. Accordingly, the parameters of the amplification stage may be designed such that a resulting converted laser energy has suitable energy and power characteristics satisfactory for the particular application for which the laser is to be used.

For example, using the illustrated amplification stages in FIG. 7, assuming ~ 20 % conversion efficiency in the first OPO/OPA stage, radiation at 8-20 mJ with wavelengths at 2-4 μm may be obtained. And, assuming >30 % conversion efficiency for the second OPO stage, radiation of more than 1mJ with wavelengths above 4 microns (e.g., 4-8 μm) may be obtained at the output, which is suitable for at least some medical applications. The above parameters for the OPO/OPA stages are merely exemplary and do not limit the aspects of the invention.

In addition, some radiation will pass through each OPO/OPA stage with wavelengths that remain unchanged. That is, the OPO/OPA stages will not convert the wavelengths of 100% of the input laser radiation. Accordingly, the OPO and/or OPA stages may include one or more filters to filter out radiation having wavelengths that are not desirable at any given stage of the wavelength conversion process (e.g., after each cascaded OPO/OPA stage). It should be appreciated that the particular implementation of the amplification stage and wavelength conversion stage may depend on the characteristics of the laser emitted by the oscillator, which may in turn depend on the type of active material and resonator that is used.

Accordingly, some embodiments of a laser system described herein may be suitable for applications in a variety of biomedical areas, e.g. precision surgery, minimally invasive-surgery and endoscopy. Some embodiments of the laser system emulate at least some of the optical properties of the Mark III FEL, and due to its relatively small size and cost to manufacture, may enable surgeons and other health care providers to apply precision surgical techniques in almost any clinic or hospital. Minimally-invasive surgery would allow physicians to perform many kinds of major surgery with less patient trauma and pain, minimal scarring, faster recovery and shorter hospital stays.

For example, some embodiments of the laser system described herein may be suitable for neurosurgical applications on the spine. In the U.S. alone spinal surgeries cost ~$100 billion dollars per year and low back pain represents a growing health care problem with epidemic proportions. One very common side effect from typical lumbar disk surgery, of which there are hundreds of thousands per year, is epidural fibrosis, i.e., scarring around the nerve root. This often leads to chronic leg pain and disability. The conventionally used instruments to remove disk fragments are "biting" and "tearing" and leave a lot of frayed edges which are conducive to scar formation. Microdiskectomy using appropriate laser technology would reduce the amount of epidural fibrosis. Some embodiments of laser instruments described herein may be successfully used for a number of other medical applications, ranging from transdermal drug delivery to cholesterol removal in arteries.

As discussed above, the notion of a bloodless knife has many attractive properties for surgical applications. FIG. 8 illustrates a laser system capable of generating lasers comprised of multiple wavelengths, thus capitalizing on the different properties of the various wavelengths. As discussed above, the OPO and OPA stages are not 100% efficient, and the wavelengths of some of the radiation will remain unconverted after each conversion stage. Typically, filters are arranged after each conversion stage to filter out the unconverted radiation such that the resulting laser beam has energy at desired wavelengths. For example, filters 18 and 19 may be provided after OPO/OPA 12 and OPO stage 13, respectively, to remove radiation at unwanted wavelengths. Applicant has appreciated that this radiation may be used to provide a surgical instrument emitting multiple wavelengths, for example, one or more wavelengths adapted for tissue ablation, one or more wavelengths adapted for coagulation, or some combination of multiple wavelengths such that ablation and coagulation may occur simultaneously.

In some embodiments, optical fibers are provided to guide radiation at different stages of laser system 800 to provide a multiple wavelength surgical instrument along a main optical fiber 35. For example, an optical fiber tap 30 may channel radiation prior to conversion (e.g., prior to OPO/OPA stage 12) such that at least some of the radiation channeled in main optical fiber lead 35 includes radiation at wavelengths prior to conversion (e.g., radiation having a wavelength associated with the active material of the oscillator). Similarly, optical fiber taps 32, 33 and 34 may be provided to channel radiation of any desired wavelength to main optical lead 35. As a result, a surgical instrument can be constructed that can provide alone, or in any combination, radiation having wavelengths of approximately 1 micron, between 2 and 4 microns and between 4 and 8 microns. It should be appreciated that the optical taps illustrated are merely exemplary and in some cases redundant. For example, radiation at ~1 micron can be obtained either prior to the first conversion stage (e.g., via tap 30) or obtained from the radiation that remains unconverted after the conversion stage and prior to being filtered (e.g., via tap 31). Any combination of taps may be used to obtain radiation at any number of desired wavelengths, as the aspects of the invention are not limited in this respect.

In some embodiments, laser instrument 800 provides simultaneous availability of the multiple wavelengths including ~1 μm , ~1.6μm and around 3 μm for coagulation and at approximately 6 μm for cutting. The surgical hand-piece may be provided with one or more buttons that allow the surgeon to choose between different modes of operation including: 1) *Cutting*; 2) *Cutting & Coagulation;* and 3) *Coagulation.* As discussed above, the tunability around 6 μm requires only minor adjustments of the phase matching by slight rotation of the nonlinear crystal in the second OPO and allows tunability to be completely computer controllable so that the final product will provide turnkey tunability from 5.7-6.5 μm, as well as any other wavelengths generated by the laser system. With the selection of active material, resonator type, amplification and wavelength conversion stages, virtually any wavelength may be provided at the output of the surgical instrument.

A tunable surgical instrument allows for the selection of optimal laser parameters for laser surgery, i.e., per pulse, wavelength, pulse duration, repetition rate and scanning speed, which are, to some extent tissue-dependent, because the optical, thermal and mechanical properties vary for different tissues. In some embodiments, ablation efficiency as a function of the above laser parameters may be optimized. Ablation efficiency is defined as ablated thickness (or ablated volume) per pulse as function of the fluence in J/cm^2. All processes of laser ablation have a threshold nature, which usually start at around 2 J/cm^2. Above this threshold, the ablation efficiency increases linearly with increasing fluence. Usually at higher fluences saturation processes take place due to shielding the beam from ablated plume. The nature of this process is plasma formation in the plume or just absorption of upcoming beam from ejected debris. This shielding process depends on the energy per pulse, wavelength, pulse duration, repetition rate and scanning speed.

Another parameter that may be important to assess is thermal damage around surrounding tissue. Assessing this parameter may require histological analysis of the tissue after ablation by well developed procedures of fixing and staining the tissue by suitable dye. Measurements of the thermally damaged areas are conducted by examination of the samples using optical microscopy (having in mind different colors of thermally damaged and undamaged tissue). The dimension of the thermally damaged tissue is mainly dependent upon the energy per pulse, the wavelength and the pulse duration. Pulse duration should be smaller than the thermal relaxation time of the tissue, which is usually in the range of 10 – 60 μs. Mid IR lasers can be used as effective tool for high efficiency bone ablation with minimal or practically absent thermal damage around ablated areas. The hard bone tissue can be cut with efficiency of 85, 77 and 58 μm/pulse for wavelengths of 6.1, 6.45 and 3.0 μm correspondingly at 72 J/cm^2, based on the experiments done with Vanderbilt FEL.

The 5 - 7μm output beam from the second stage OPO along with the residual 2-3 micron emission from the first-stage OPA will be guided through a single thin fiber and applied simultaneously to cut and coagulate soft and hard tissue.

Various aspects of the present invention may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Accordingly, the foregoing description and drawings are by way of example only.

Use of ordinal terms such as "first", "second", "third", etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having," "containing", "involving", and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

What is claimed is:

CLAIMS

1. An oscillator for generating a laser beam having a micro-macro pulse structure, the oscillator comprising:

an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons;

a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons; and

a pulse generator for generating a pulsed laser from the emitted photons, the pulsed laser including a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the pico-second scale.

2. The oscillator of claim 1, wherein a duration of each of the plurality of macro-pulses is in a range from 1 to 50 μs.

3. The oscillator of claim 1, wherein an interval between each of the plurality of macro-pulses is in a range from 1 to 100 milliseconds.

4. The oscillator of claim 1, wherein a duration of each of the plurality of micro-pulses is in a range from .5 to 10 picoseconds.

5. The oscillator of claim 1, wherein an interval between each of the plurality of micro-pulses is in a range between 10 and 1000 picoseconds.

6. The oscillator of claim 1, wherein the pulse generator includes a mode-locking component and a negative feedback control.

7. A laser system comprising:

an oscillator comprising an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons, a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons, and a pulse generator for generating first pulsed laser radiation at a first wavelength and having a micro-macro pulse structure; and

a conversion stage coupled to the oscillator stage to receive the first pulsed laser radiation, the conversion stage configured to amplify the first pulsed laser radiation and convert at least some of the amplified pulsed laser radiation to a second wavelength, the conversion stage providing second pulsed laser radiation at the second wavelength and having the micro-macro pulse structure,

wherein the micro-macro pulse structure includes a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the picosecond scale.

8. The laser system of claim 7, wherein a duration of each of the plurality of macro-pulses is in a range from 1 to 50 μs.

9. The laser system of claim 7, wherein an interval between each of the plurality of macro-pulses is in a range from 1 to 100 milliseconds.

10. The laser system of claim 7, wherein a duration of each of the plurality of micro-pulses is in a range from .5 to 10 picoseconds.

11. The laser system of claim 7, wherein an interval between each of the plurality of micro-pulses is in a range between 10 and 1000 picoseconds.

12. The laser system of claim 7, wherein the pulse generator includes a mode-locking component and a negative feedback control.

13. The laser system of claim 7, wherein the first wavelength is approximately 1 micron.

14. The laser system of claim 13, wherein the second wavelength is between 5-7 microns.

15. The laser system of claim 14, wherein the conversion stage is controllable to selectively adjust the second wavelength to wavelengths between 5-7 microns.

16. The laser system of claim 7, wherein the conversion stage includes an amplification stage including at least one amplifier and a wavelength conversion stage having at least one optical parametric oscillator/amplifier (OPO/OPA).

17. The laser system of claim 16, wherein the wavelength conversion stage includes a first OPO/OPA stage configured to convert the first wavelength into an intermediate wavelength and a second OPO/OPA stage to convert the intermediate wavelength into the second wavelength.

18. A laser instrument adapted to perform laser surgery, the laser system comprising:

a laser component adapted to generate a first laser beam at a first wavelength adapted to perform tissue ablation and to generate a second laser beam at a second wavelength adapted to perform coagulation;

an instrument output coupled to the laser component to output the first laser beam, the second laser beam or both simultaneously; and

a mechanism for selecting whether the instrument output provides the first laser beam alone, the second laser beam alone or both the first laser beam and the second laser beam simultaneously.

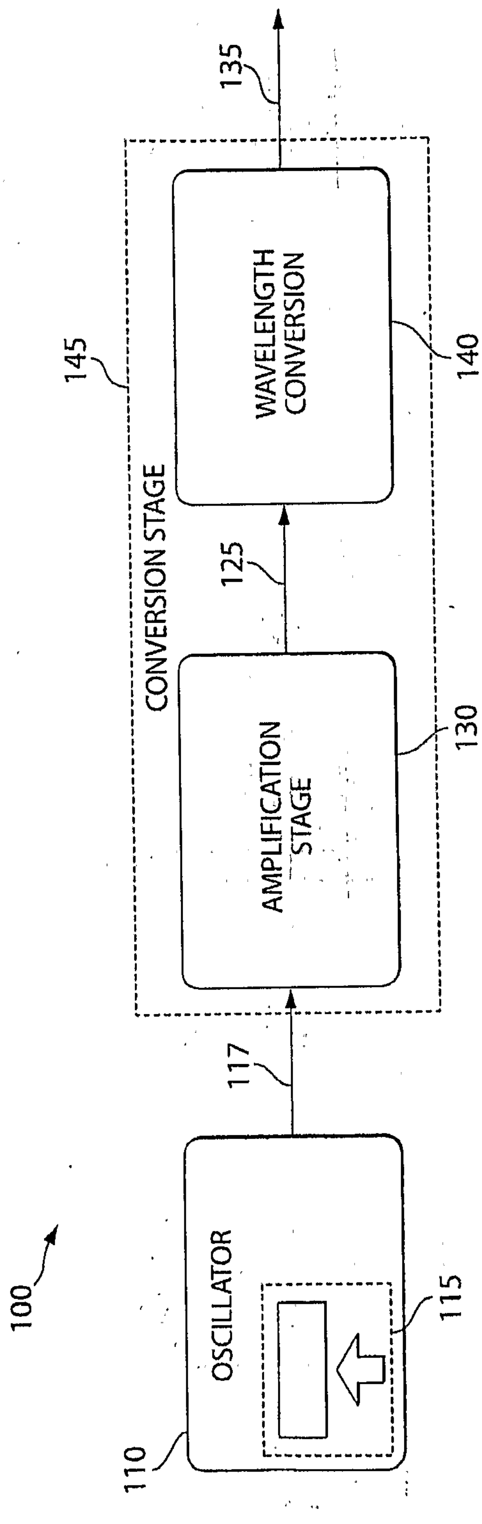
19. The laser instrument of claim 18, wherein the laser component comprises:

an oscillator comprising an active material for generating photons, the active material responsive to first laser radiation such that in response to the first laser radiation, the active material emits photons, a diode pump comprising at least one laser diode array arranged to provide the first laser radiation to the active material to excite the active material to emit the photons, and a pulse generator for generating first pulsed laser radiation at the first wavelength and having a micro-macro pulse structure; and

a conversion stage coupled to the oscillator stage to receive the first pulsed laser radiation, the conversion stage configured to amplify the first pulsed laser radiation and convert at least some of the amplified pulsed laser radiation to the second wavelength, the conversion stage providing the first laser beam and the second laser beam having the micro-macro pulse structure,

wherein the micro-macro pulse structure includes a plurality of macro-pulses having a duration on the millisecond scale, each of the plurality of macro-pulses comprising the envelope of a plurality of micro-pulses having a pulse duration on the picosecond scale.

20. The laser instrument of claim 19, wherein the conversion stage includes an amplification stage including at least one amplifier and a wavelength conversion stage having a first OPO/OPA stage configured to convert the first wavelength into an intermediate wavelength and a second OPO/OPA stage to convert the intermediate wavelength into the second wavelength.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WAVELENGTH CONVERSION
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Fig. 1

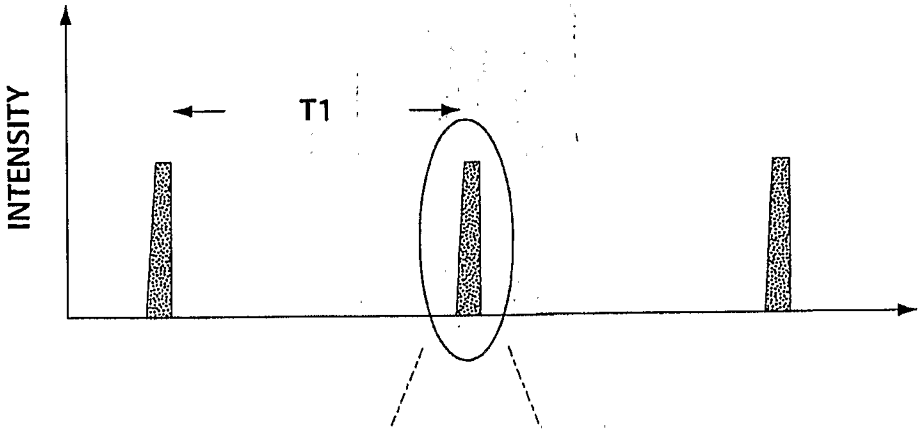


Fig. 2A

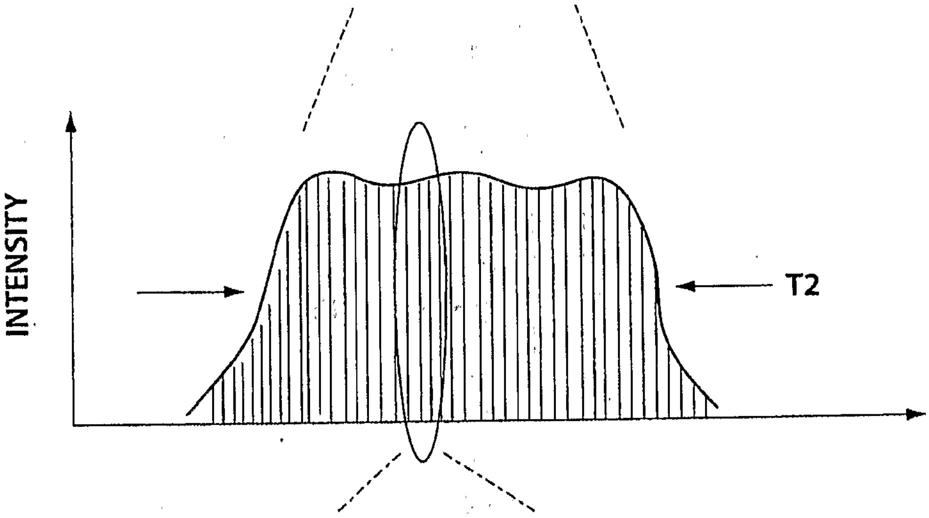


Fig. 2B

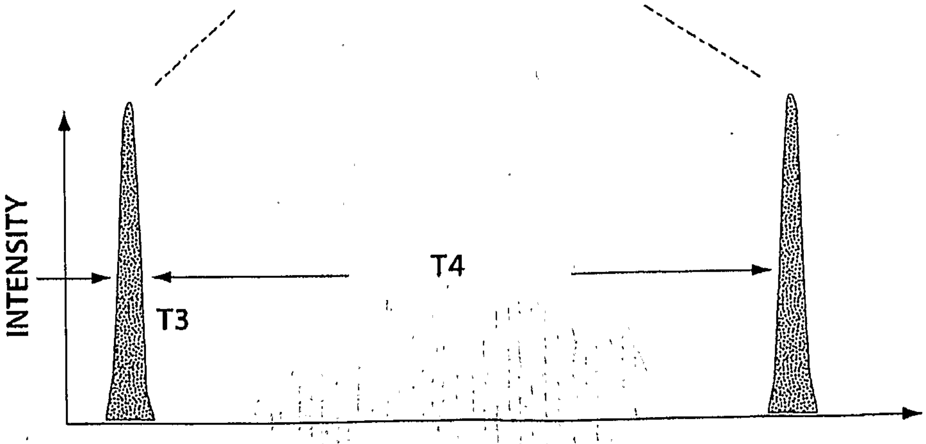
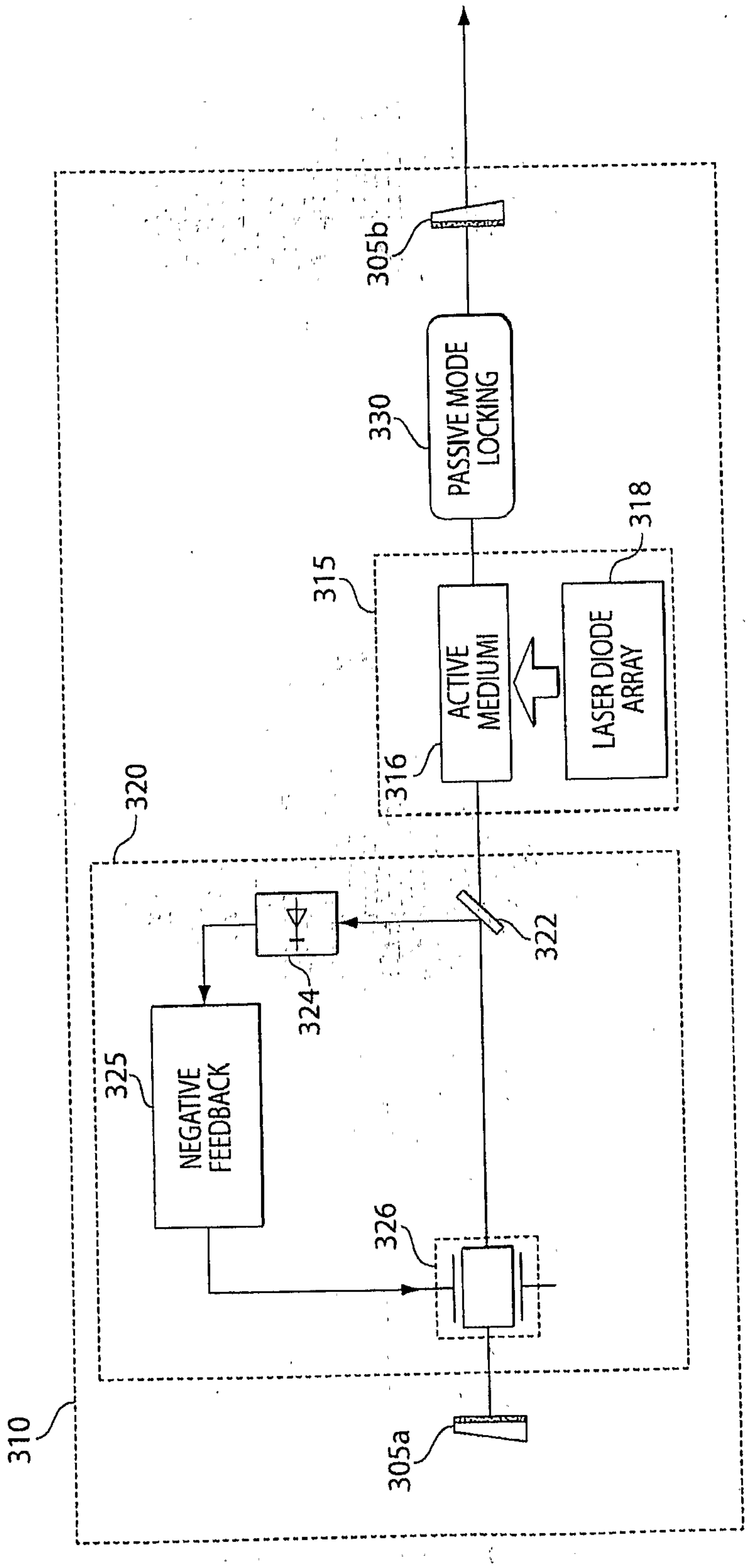


Fig. 2C


310
305a
305b
320
322
324
325
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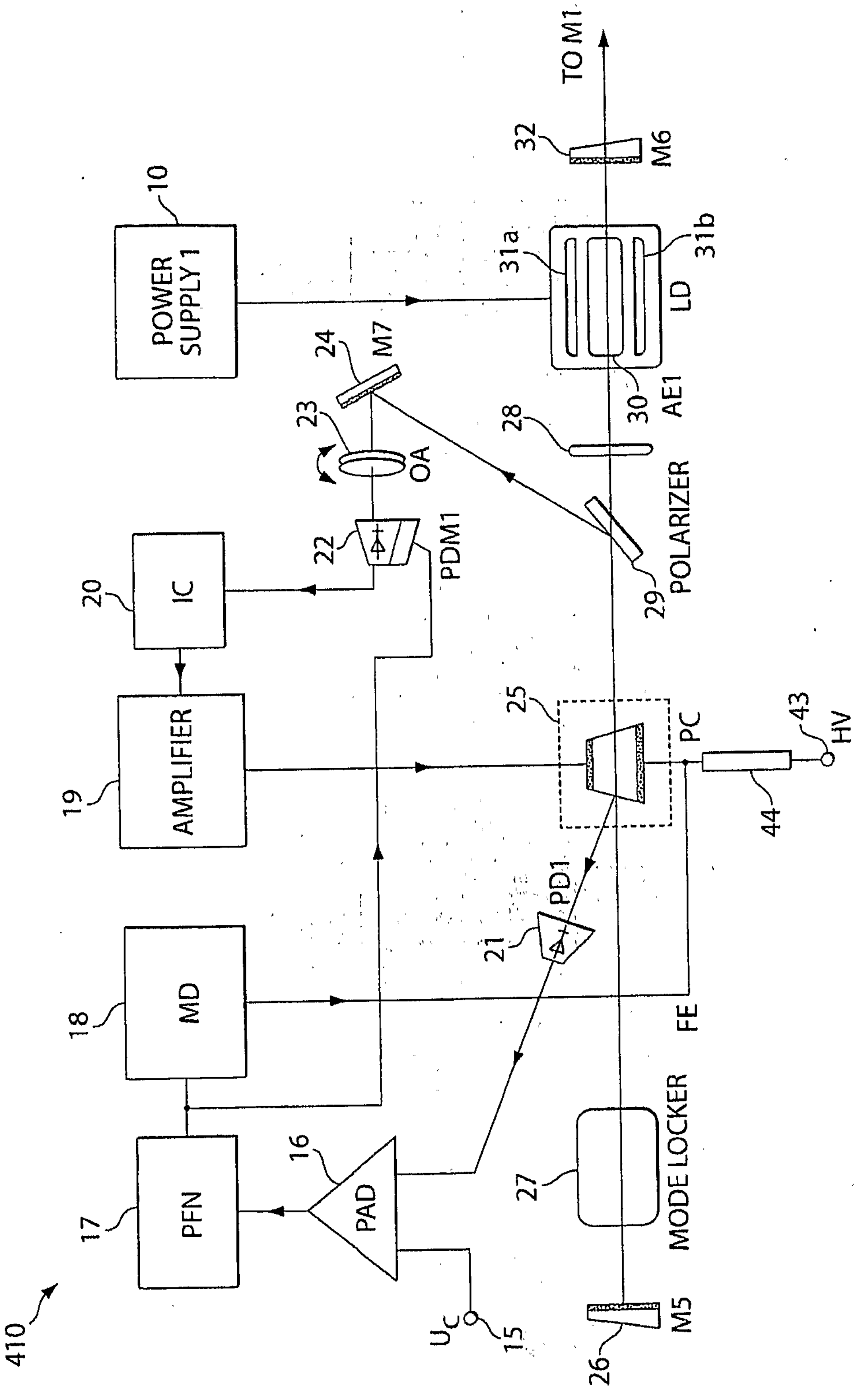
315
316
ACTIVE MEDIUM
318
LASER DIODE ARRAY
330
PASSIVE MODE LOCKING

Fig. 3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M6
10
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31b
LD
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M7
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29
22
PDM1
20
IC
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AMPLIFIER
25
PC
43
HV
44
21
PD1
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PAD
17
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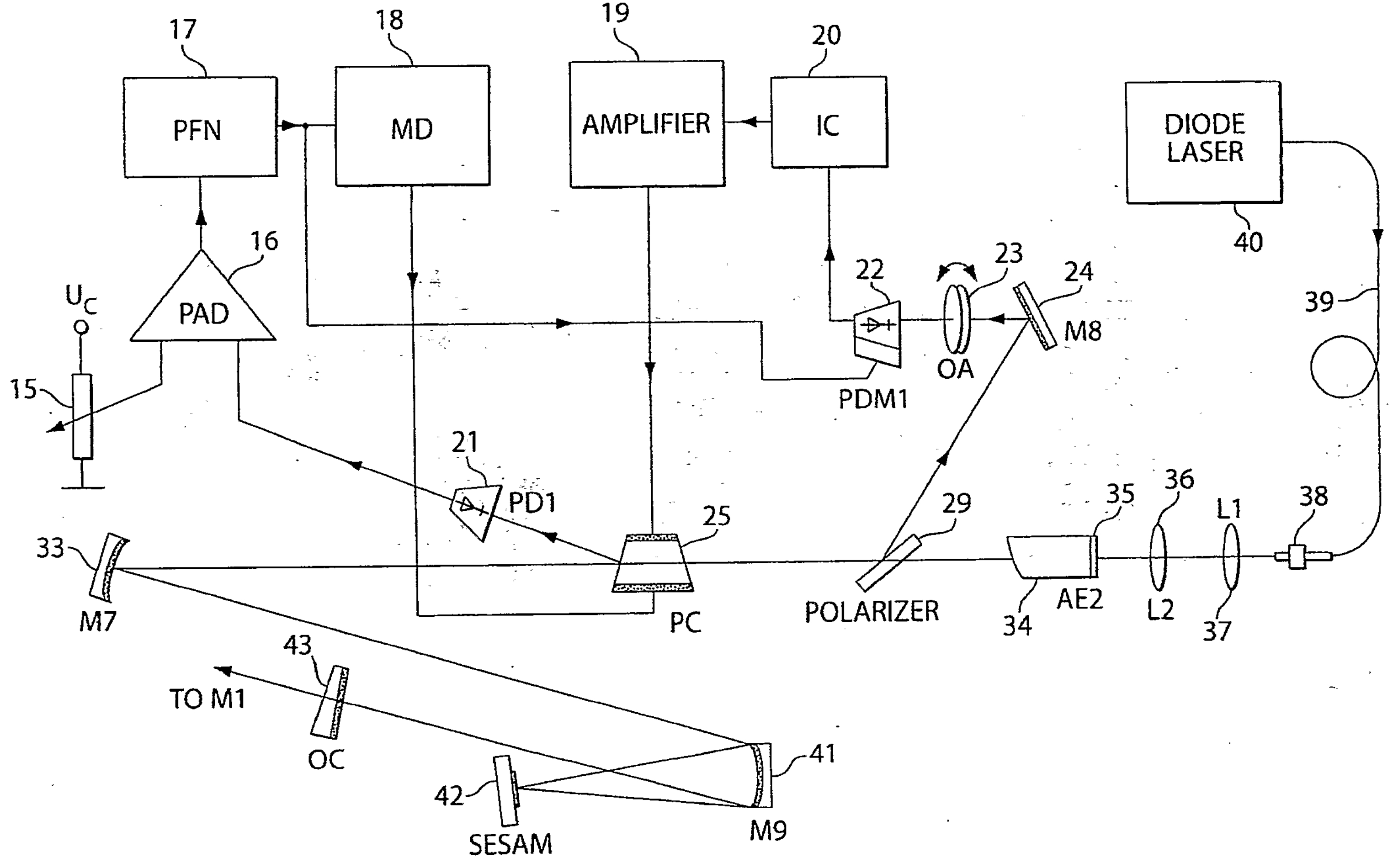
410
U_C
15
26
M5

Fig. 4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20
IC
DIODE LASER
40
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PAD
U_C
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OA
PDM1
39
21
PD1
25
PC
33
M7
29
POLARIZER
35
36
L1
38
34
AE2
L2
37
43
TO M1
OC
42
SESAM
41
M9

Fig. 5

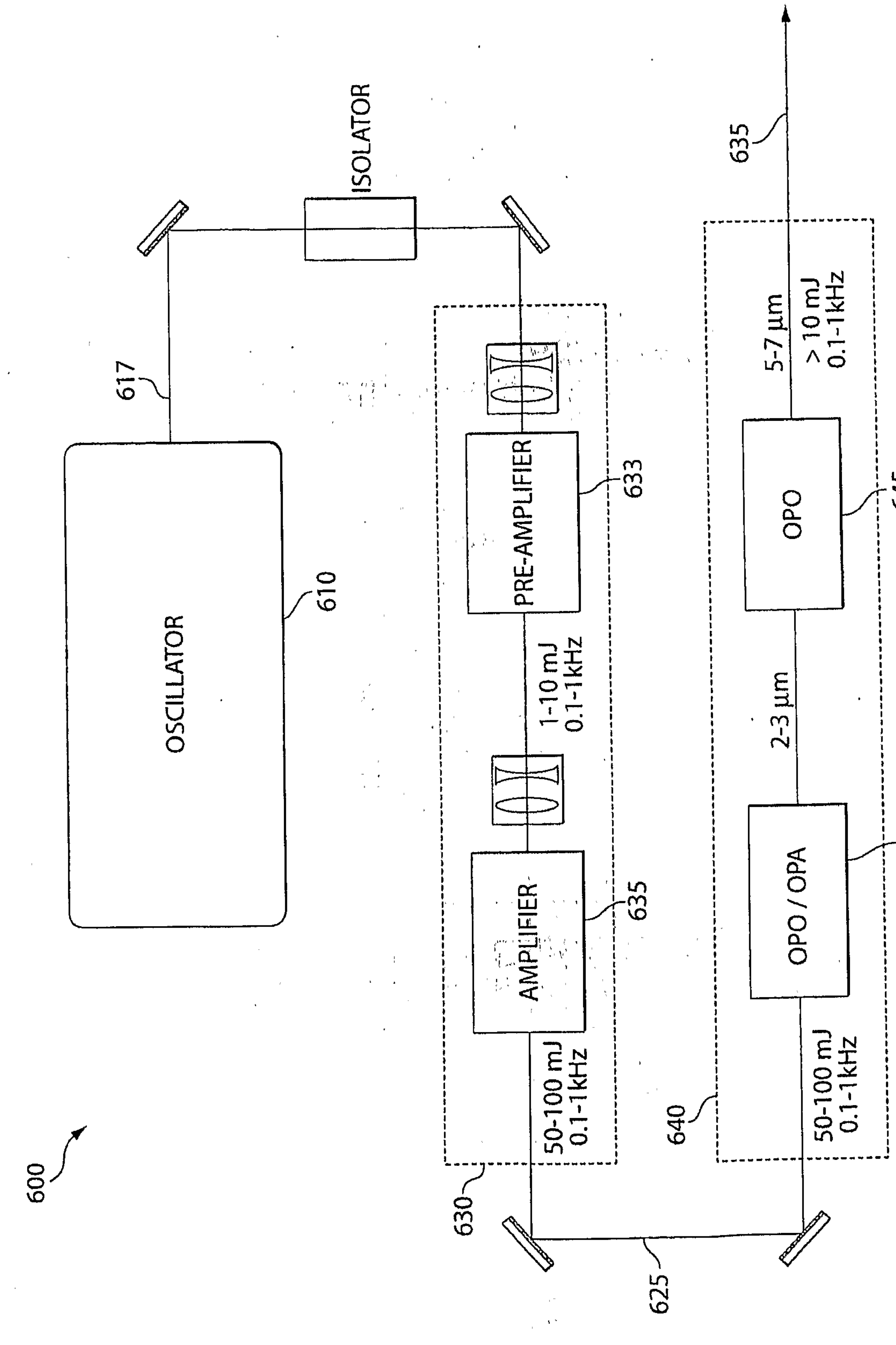
600
OSCILLATOR
610
617
ISOLATOR
PRE-AMPLIFIER
633
1-10 mJ
0.1-1kHz
AMPLIFIER
635
50-100 mJ
0.1-1kHz
630
625
640
OPO / OPA
643
2-3 µm
OPO
645
5-7 µm
> 10 mJ
0.1-1kHz
50-100 mJ
0.1-1kHz
635

Fig. 6

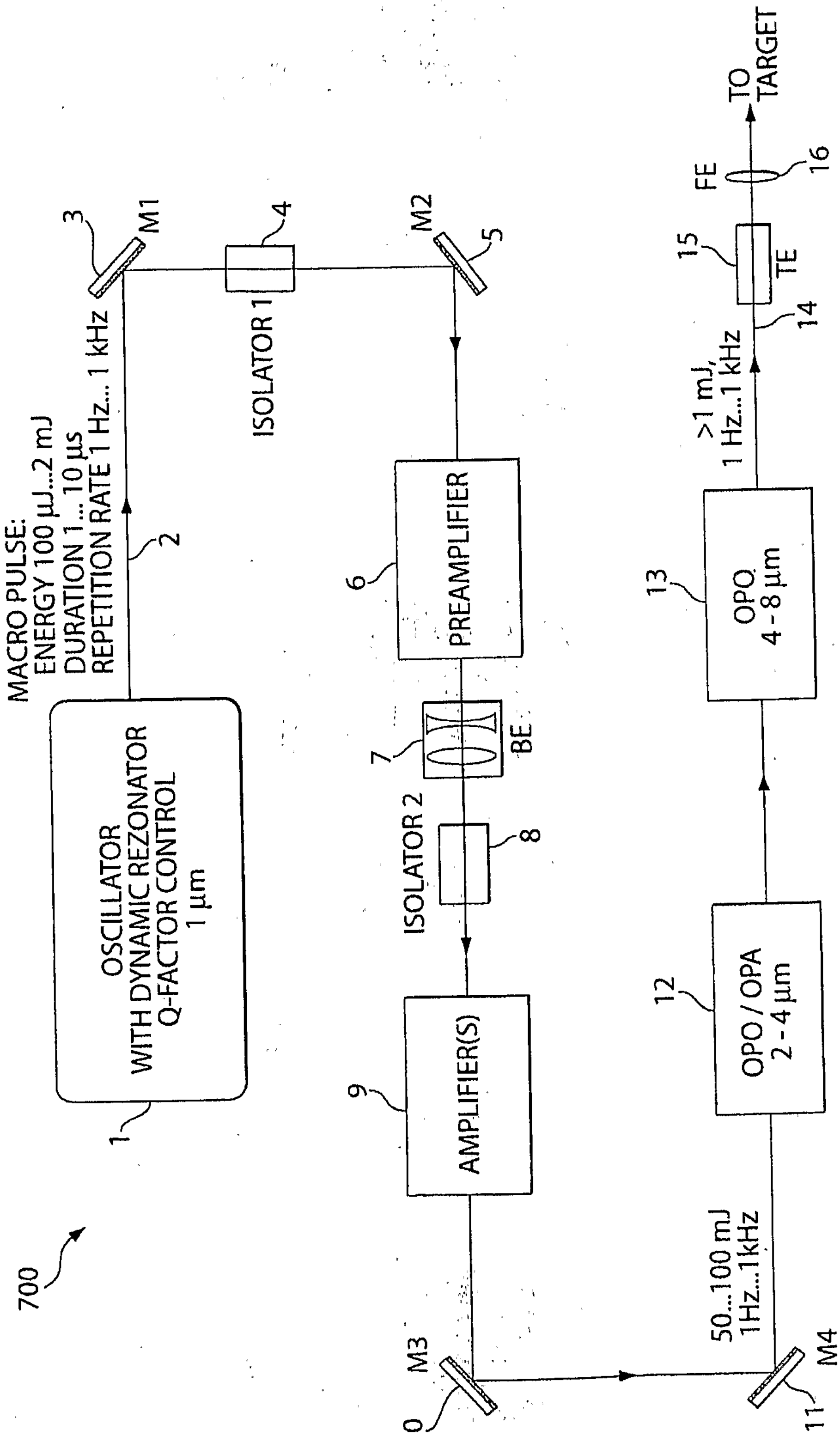
700
OSCILLATOR
WITH DYNAMIC REZONATOR
Q-FACTOR CONTROL
1 µm
1
MACRO PULSE:
ENERGY 100 µJ...2 mJ
DURATION 1... 10 µs
REPETITION RATE 1 Hz... 1 kHz
2
3
M1
ISOLATOR 1
4
M2
5
PREAMPLIFIER
6
BE
7
ISOLATOR 2
8
AMPLIFIER(S)
9
M3
10
50...100 mJ
1Hz...1kHz
M4
11
OPO / OPA
2 - 4 µm
12
OPO
4 - 8 µm
13
>1 mJ,
1 Hz...1 kHz
14
15
TE
FE
16
TO
TARGET

Fig. 7

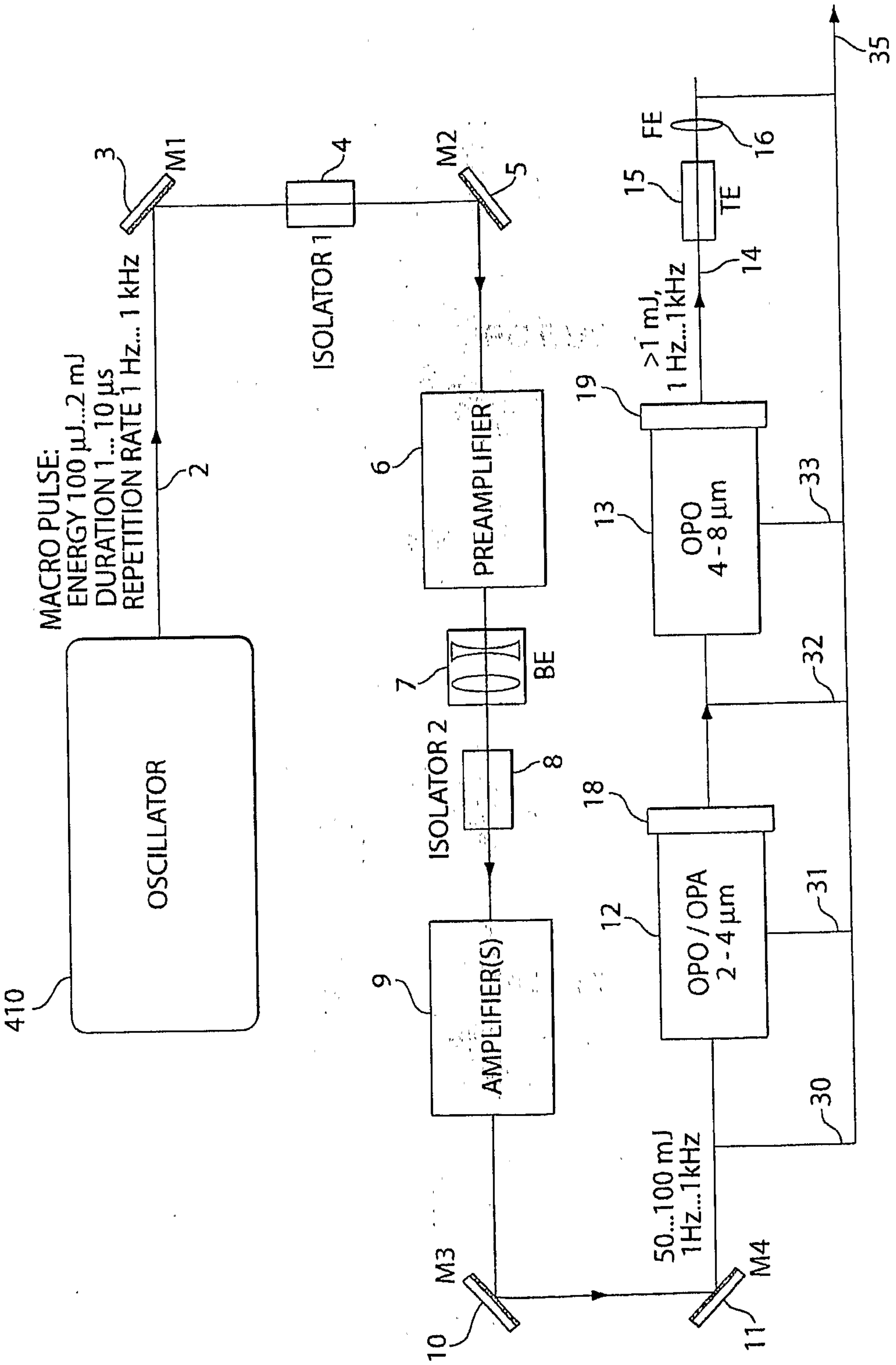
MACRO PULSE:
ENERGY 100 μJ...2 mJ
DURATION 1... 10 μs
REPETITION RATE 1 Hz... 1 kHz
410
OSCILLATOR
2
3
M1
4
ISOLATOR 1
M2
5
6
PREAMPLIFIER
7
BE
ISOLATOR 2
8
9
AMPLIFIER(S)
M3
10
M4
11
50...100 mJ
1Hz...1kHz
30
12
OPO / OPA
2 - 4 μm
31
18
32
13
OPO
4 - 8 μm
33
19
>1 mJ,
1 Hz...1kHz
14
15
TE
FE
16
35

Fig. 8