



- (51) International Patent Classification:
H01S 3/082 (2006.01) *H01S 3/11* (2006.01)
- (21) International Application Number:
PCT/EP2012/062209
- (22) International Filing Date:
25 June 2012 (25.06.2012)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
1113076.2 29 July 2011 (29.07.2011) GB
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- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,

[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR LASER PULSE CONTROL

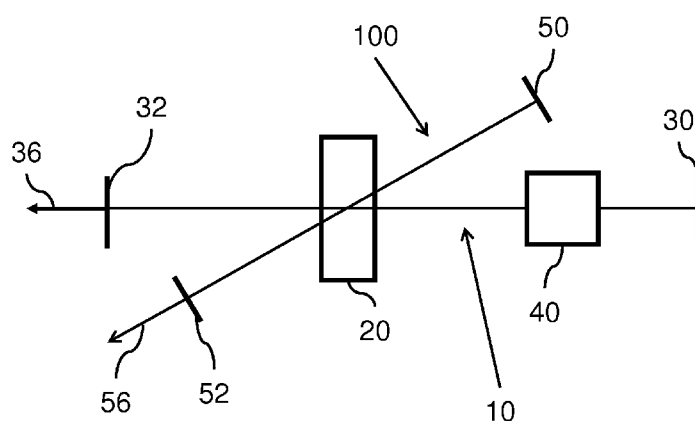


FIGURE 2

(57) **Abstract:** A method and apparatus for controlling the amplification of radiation in a laser gain are described. By using the controlling action of a secondary radiation path through the common gain element the gain, as seen by the primary radiation path, can be controlled or limited. In one particularly set of embodiments pertaining to laser pulse control of a laser cavity, a laser system is described that comprises first and second laser cavities each including a common laser gain medium. The first cavity incorporates a modulation element for variation of its cavity loss. A second cavity is employed that has a substantially distinct path or separable cavity mode from that of the first cavity. The laser threshold of the second cavity is set to a value intermediate to the extremes of the threshold for the first cavity, corresponding to the maximum and minimum loss available to the modulation element. As a result a more flexible control of laser pulsing and laser performance control is provided. Other embodiments of this invention allow improvement of laser performance through the control of the amplification of the output of a laser system through an external laser amplifier by utilising a secondary radiation path through the external amplifier.



TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

Method and Apparatus for Laser Pulse Control

The present invention relates to lasers, and more specifically although not exclusively to a method and apparatus for laser pulse control.

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Laser operation in a pulsed mode of output is desirable and commonly used in a very wide range of applications. In pulsed operation, the laser emits radiation intermittently, usually in the form of pulses with duration considerably shorter than the time between pulses. For example, pulsed lasers are commonly used for laser micromachining in industrial manufacturing and laser marking for product identification. In these applications, the pulses provide precise material removal or material interaction aided by the high peak power of the pulses with the short interaction time of pulse reducing the thermal damage to surrounding material. The laser can offer higher precision, control, speed and / or cost-effectiveness compared to other more traditional mechanical or chemical processes. Additionally, the high peak power of pulsed laser operation can also provide advantages for some nonlinear optical processes. For example, laser radiation at one frequency can be converted to new frequencies by harmonic generation in nonlinear optical crystals and the efficiency of the process can be enhanced by many orders of magnitude by using the high peak power of pulses.

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For implementation in applications, the benefit of the laser is enhanced if it can have flexibility of variation of pulse parameters including in terms of pulse repetition rate, pulse duration, and pulse energy. The pulse repetition rate may be required to be low in one application and high in another application. Some applications require variation of pulse rate in different parts of its operation, sometimes in a single step change and sometimes on a pulse-to-pulse basis.

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Another common application need is to have periods when the laser is required to emit no pulses or other radiation output at all, for an extended period.

5 A common method for controlling pulse delivery is the technique known as Q-switching. In this method, an element in the laser is used to modulate the loss of the laser cavity. During a period in which the modulation element provides high loss (low Q) the laser cavity can be prevented from lasing. By switching to a low loss (high Q) the laser can be rapidly switched to a state where it is considerably above threshold for laser action and the excitation energy stored
10 in the laser gain medium is emitted as a short duration pulse with high peak power. After emission of a pulse the cavity can be switched back to high loss and the process repeated. Temporal control of the loss in the modulation (Q-switching) element can therefore provide a method for obtaining short pulses with high peak power and control of the pulse repetition rate.

15 A serious problem can occur if the loss of the modulation element is insufficient to prevent laser action. This will be particularly true if the laser has high gain and / or the modulation element has poor ability to create high loss. High gain can occur if the gain medium is highly pumped by the external
20 excitation source. High gain will particularly develop when the modulator has to provide high loss for a long time period and the gain provided by the excitation source can build up to high values in the laser active element. This is especially true at low Q-switching repetition rates or if the laser is required to remain in the off state (with no emission) for an extended period. Even with
25 the modulation element operating with its maximum loss, the gain can grow to exceed the threshold for laser oscillation and laser output will occur even when this is not desired. The flexibility of the laser is thereby limited since the laser output pulse formation cannot be operated with full control at low repetition rates and the laser cannot be inhibited from producing laser emission.

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Reducing the pumping to the laser gain element may be necessary but that may result in considerable loss in the available output power or lasing efficiency, amongst other parameters. Additionally, the high gain provides advantages in the ability of the laser to attain higher pulse repetition rates and shorter pulses, so reduction of gain to attain better low repetition rate control adversely affects the pulse operation at higher repetition rates.

A further problem with pulse operation is pulse energy control. A flexible laser system should be capable of adjustment of pulse energy alongside adjustment of pulse repetition rate. In practice this is quite challenging. One solution is to adjust the excitation pumping rate delivered to the laser gain element. This solution however is not usually practical when pulse energy and / or repetition rate is required to be changed quickly since the pumping mechanism may not be able to be changed rapidly or undesirable effects can ensue (e.g. in diode-pumped solid state laser the diode pump wavelength can change with its excitation rate). In general, a continuously pumped Q-switched laser will emit higher energy pulses at lower repetition rates than at high rates due to the longer time and hence higher energy excitation that has been stored between pulses.

Another associated problem with pulse operation is the variability of the thermally-induced lensing of the laser leading to unwanted variations in the spatial quality of the laser. The thermally-induced lensing can be a function of pulse repetition rate or change considerably between periods of lasing and when lasing is inhibited (non-lasing). The thermally-induced lens is due to the formation of a temperature distribution in the laser gain element due to heat deposited by the excitation mechanism for laser action. The temperature dependence of the material refractive index leads to the optical lensing and also lead to other aberration effects in the materials. In solid materials, the

temperature distribution can lead also lead to stress effects that can cause other optical effects, including birefringence of the material and depolarisation of the laser radiation. The heat deposition, and hence strength of the thermal lens and other optical non-uniformities, can be affected by how much the excitation in
5 the laser gain element is extracted by the laser cavity radiation. The extremes are when the laser cavity is inhibited from lasing (no lasing) and when the laser is continuously operated at full laser power. Intermediate to these cases, at low pulse rates the laser medium is left unextracted for long periods compared to high pulse rates, and thermal lensing strength can change continuously across
10 attainable repetition rate of the laser leading to unwanted and / or unexpected spatial quality change with repetition rate.

By way of example, Figure 1 shows a prior art laser system for producing pulsed laser output. The laser system 10 has a laser gain medium 20
15 incorporated in a laser cavity formed by a high reflectivity mirror 30 and a partially reflecting mirror 32. The cavity also incorporates a modulation element 40 that is responsible for pulse formation of the laser radiation. An output beam 36 is produced by the partial transmission through mirror 32. The laser gain medium provides amplification at the laser wavelength when
20 excitation energy is provided by an external pumping source. By way of example, the gain medium can be a solid-state material such as Nd:YAG or Nd:YVO₄ and the pumping mechanism can be a discharge lamp or diode pump. Also by way of example, the modulation element can be an acousto-optic modulator that provides externally-controlled diffraction-induced losses
25 by delivery of an RF signal or by an electro-optic modulator that provides polarisation-induced losses by application of an externally-applied electric field.

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When operating in a Q-switching mode for pulsed output, the modulation element is switched from a high loss state (“closed” state) which inhibits the onset of laser oscillation to a low loss state (“open” state) leading to a build up and emission of a pulse of laser radiation. In general, pulse energy is a function of pulse repetition rate. In a case of very high gain laser the closed state of the loss modulation may not be sufficient to inhibit onset of laser oscillation.

In US Patent No. 6,683,893 a method of pulse control is disclosed that involves a more complex time scheme of opening and closing of the modulation element. In one method, the modulation element is left open after the emitting of a pulse and a period of continuous wave (CW) output is allowed to occur for an interval between subsequent pulses. The period of CW emission is used to control the energy removal from the laser gain element and thereby control the pulse energy of a subsequent sequence of Q-switching operation where the modulation loss is closed for a fixed period and then opened. This method can control the pulse operation but has a major disadvantage of the CW radiation being present between pulses. Although for some applications, the low power of the CW radiation may be below processing threshold whilst the high peak power of the pulses is above processing threshold, this is more generally undesirable. In many applications this CW radiation, which may contain a high fraction of the total laser output power would be totally unacceptable.

A further method of controlling pulse formation is to modulate the pumping mechanism. However, this method may be impractical or undesirable. In some cases the speed of change of the pumping cannot be effected on a fast timescale (e.g. on the order of the pulse repetition time). The variation of the pumping will also lead to changes in the heat deposition into the laser gain

element and this can lead to unwanted changes in spatial quality in the laser output, amongst other variations.

5 The present invention is set out in the claims.

The present invention allows for greater control of laser radiation in laser oscillator and laser amplifier systems and in particular when operation is in a Q-switched pulse mode. The inventive features we disclose allow for creation
10 of lasers with much greater flexibility of operation and elimination of unwanted problems that can happen in lasers operating with high gain. We show that besides the primary path of a beam through a laser gain medium, by providing a secondary path of radiation through the same laser gain material, the gain and operation of a laser amplifier or laser oscillator can be controlled.

15 In a laser oscillator, if the gain of the laser material is too high for the loss modulator to suppress onset of laser threshold in the primary laser cavity, this invention shows how the provision of a secondary laser cavity is employed to clamp the gain at a level that the loss modulator can suppress. In this way it is
20 shown that a laser whose gain was too high to be operated with controlled pulsing operation (e.g. due to maximum loss of modulation element being insufficient) can be brought under control. Additionally, by adjusting the parameters of the secondary cavity the gain level and hence pulse energy of the primary cavity can be controlled and over a wide range of repetitions rates. All
25 this extra control adds considerable flexibility and improved performance to the laser. The excess gain removed by the secondary cavity is not emitted in the direction of the primary cavity beam (or can be separated by polarisation or frequency from the primary radiation) and hence the quality and flexibility of the pulsing is put into effect in this invention without unwanted radiation

artefacts on the primary output beam. This maintains high contrast between on-operation (pulse output period) and off-operation (no pulse / emission period) in the laser output used for application process. One further benefit of this invention is that the laser can be operated with a modulation element with limited loss and that may have practical advantages (by way of example, modulator with low amplitude of maximum loss but higher speed of modulation) or cost benefit (by way of example, lower cost modulator product or technology). A particular benefit of this invention is that the laser can be operated with a high excitation pump rate and this provides a laser gain medium with ability to operate with higher pulse repetition rates and also provides shorter pulses with higher peak power, compared to a lower pumping rate. Such a highly pumped laser would find difficulty to be operated at lower repetition rates due to the resulting high gain without the benefit of this invention.

This invention further teaches that its inventive features can also be employed to provide enhanced control of laser amplification of radiation passing through an external laser gain medium (laser amplifier). The gain experienced by a primary path of radiation (e.g. output of a laser oscillator) may be too high at some period in the laser operation due to previous period of non-extraction. Changing the pumping rate to the amplifier to lower the gain may be too slow to employ or involve unwanted consequences such as spatial quality changes due to change in thermal lensing. Using this invention, the gain can be controlled by employing passage of a secondary beam through the amplifier that, by way of example, follows a different path to the primary beam being amplified. In particular, this invention teaches how it can be accomplished in various ways including use of a secondary laser cavity path with the laser amplifier as its cavity element. Many practical benefits are derived from this inventive feature in a laser amplifier. One practical benefit is the reduction of

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amplified spontaneous emission that may follow the path of the main laser beam. When the amplifier is not extracted by the primary laser beam, the gain can build up to high levels where the spontaneous emission of radiation can be amplified to unwanted high levels. The inventive features can be employed to
5 limit the gain such that a reduced and controlled level of the amplified spontaneous emission can be achieved at more acceptable levels. Another benefit is the limiting of the amplification level of a primary beam with low repetition rate pulses that would otherwise experience such high gain that their high peak power can cause damage or unwanted consequences to the optical
10 system of the laser or the external application.

The control of the gain (and hence amplification properties) in the laser gain material of the laser oscillator or external laser amplifier employed by this invention give a further added benefit of establishing a more constant thermal
15 loading to the laser gain material, over a wide pulsing range. This means that the spatial quality of the laser system can be better maintained as the thermal loading can affect the spatial propagation properties of the laser radiation. By way of example, the thermal loading in a solid-state laser gain medium can result in a temperature distribution in said gain medium that leads to it acting
20 with the properties of a lens whose strength and aberrations are heat load dependent.

It will be clear to the reader skilled in the art that the inventive features and embodiments of this invention provide manifold and substantive benefits to
25 practical control of laser operation particular under pulsed Q-switched operation. Since there is a need for cost effective, less complicated and more flexible control of parameters of pulsed laser operation (in particular to advanced industrial machining and marking application) the inventive features of this invention provide substantial benefit in laser-based tools.

Embodiments of the inventions will now be described, by way of example, with reference to the following figures, of which:

5 Figure 1 is a schematic diagram embodying a prior art pulsed laser system incorporating a modulation (Q-switch) element;

Figure 2 is a schematic representation of one embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with path angularly separated from the primary cavity to assist the pulse control of
10 that cavity;

Figure 3 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with polarisation and / or frequency separation from the primary cavity to assist its pulse control;

15 Figure 4 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with its own modulation element to assist the pulse control;

Figure 5 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to
20 assist the pulse control of the primary cavity and additionally to utilise the secondary output to control the amplification of the primary laser output in an external amplifier element;

Figure 6 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to
25 control the amplification in an amplifier element of an angularly separated primary beam path;

Figure 7 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to

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control the amplification in an amplifier element where the secondary cavity and primary beam path are separated by polarisation and / or frequency;

Figure 8 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with modulation element to control the amplification of a primary beam path in an amplifier element; and

Figure 9 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to assist the pulse control of the primary cavity and a further secondary cavity to simultaneously control the amplification in an external amplifier element.

Figure 2 is a schematic representation of one embodiment of a laser system, according to the present invention. A primary laser cavity 10 consists of a laser gain medium 20 together with a modulation element 40 within a laser cavity formed by high reflectivity mirror 30 and a partially reflecting output coupling mirror 32 that allows transmission of a primary output beam 36. A secondary laser cavity 100 consists of the same laser gain medium 20 but within a secondary cavity formed by mirrors 50 and 52 where the path through the gain medium 20 is at some angular offset with respect to the path of the primary cavity. A partial transmission of mirror 52 provides a secondary output beam 56. The secondary laser provides a means for clamping the gain of element 20 as seen by the primary laser. If the primary laser cavity 10 is inhibited by its modulation element 40 from oscillation for an extended period, the gain would build up to a higher value than if it was allowed to oscillate more frequently. In this embodiment, the secondary cavity 100 is arranged to have the threshold gain of element 20 for onset of its oscillation set to a value that is lower than the maximum gain level that the primary cavity can reach in the absence of secondary cavity. When secondary cavity reaches its threshold for oscillation,

its operation will act to clamp the gain to a level at, or close to, its threshold gain level. In this way the secondary cavity suppresses the onset of unwanted gain levels seen by primary cavity and this allows greater control and flexibility of the laser.

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For the sake of clarity, particularly for those not skilled in the art, we present a brief and basic formulation to define better some of the laser terminology used in this invention description and also clarify the principles underpinning the invention. A laser cavity has a threshold for laser action when the sum of gain and loss elements in the cavity, after a round-trip, is equal to unity. This threshold condition for a linear laser cavity can be described by the following equation:

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$$r_1 r_2 (1 - L) G_{RT} = 1 \quad (\text{equation 1})$$

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where r_1 and r_2 are the reflectivities of the cavity end mirrors, G_{RT} is the roundtrip gain as seen by the oscillating laser cavity mode due to double-pass laser amplification by the laser gain medium, and L is a roundtrip loss factor which can have values from $L = 0$ (for no loss) to $L = 1$ (for infinite loss). The terminology of cavity mode (or radiation cavity mode) is used in some descriptions of this invention, and is well-known to those skilled in the art, to denote a self-reproducing spatial and spectral radiation distribution that exists in a laser after multiple round-trips of the cavity. Many spatial or spectral modes can exist. The term cavity mode, as used in this description, is assumed to encompass the case of single mode operation or multiple mode operation of the laser cavity.

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The roundtrip loss L can be due to a large number of physical phenomena including absorption losses and surface reflection losses of intracavity

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components, scattering and diffraction losses, and actively imposed losses due to a modulation element. In the latter case, the losses of a modulation element can impose a time-dependent loss factor $L(t)$. When the time-dependent loss has the form of a step function this produces what is known as a Q-switching of the cavity and is commonly employed for pulse formation, by switching from a high threshold state to a low threshold state after a high inversion (high gain G_{RT}) has been established.

For a fixed loss factor L , we can consider a threshold gain G_{th} which satisfies equation 1. In this case the gain just balances all the other losses of the cavity. When threshold gain is even slightly exceeded the laser will oscillate. It is noted that if the gain threshold is exceeded and laser oscillation occurs, the laser radiation will saturate the gain by extracting stored energy. Steady state is established, after a short transient period, when the gain is saturated back to its threshold value. This property of the laser can be considered as clamping the gain to its threshold level and is a key aspect incorporated in this invention. The gain clamping action is employed in this invention by the inventive feature of the secondary cavity and the inventive manner this cavity is employed to benefit the primary laser system.

The gain threshold for secondary cavity can be set by adjustment of a number of cavity parameters that control the cavity losses, which can include but is not limited to: the reflectivity of the cavity mirrors 50 and 52; the alignment of the mirrors 50 and 52; the alignment path through the gain medium 20; adjustment of the match of the frequency or polarisation of the secondary cavity mode to the laser transition of the gain element; inclusion of an additional loss element in the secondary cavity.

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The benefits of this inventive feature utilising a secondary cavity are manifold. The threshold of the secondary laser cavity provides additional control of the primary laser cavity. One of the benefits is to allow the primary cavity to operate with a modulation element which would not have had sufficient loss amplitude to inhibit its oscillation at the maximum gain, by way of example, when operating for long periods without emitting laser radiation or pulses, such as at low laser Q-switch repetition rates. One major advantage of this invention embodiment is that the control is passive, in that once the secondary cavity is incorporated it needs no external controls to initiate it. Unwanted high gains are extracted by the secondary cavity, but if the high gains are not attained during the primary cavity operation (by way of example at high pulse repetition rates) then the secondary cavity is not activated (no output occurs from secondary cavity). No external means are needed to “switch-off” the secondary cavity. Another benefit of this inventive feature is that the thermal loading of the laser material is better stabilised across different repetition rates. Without this inventive feature, operation at lower repetition rates leaves the gain medium unextracted for long periods and can in some materials lead to a different heat loading to when it is extracted such as at high repetition rates. The onset of oscillation in the secondary cavity ensures that the gain medium is extracted even when the laser gain element is unextracted for long periods by the primary cavity. The combination of oscillation in both the primary and secondary cavities results in a more uniform extraction at both high and low repetition rates. Since the thermal loading can lead to optical effects such as thermally-induced lensing, stress-induced birefringence and other refractive index aberrations the more uniform thermal loading leads to a more constant spatial quality independent of repetition rate. This spatial consistency is essential for many practical applications of the laser.

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Figure 3 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with polarisation and / or frequency separation from the primary cavity to assist the pulse control. The previous embodiment showed a secondary cavity where the beam path was different through the gain element compared to the primary cavity. This embodiment teaches that the path through the gain need not be different so long as the primary and secondary cavity can be made distinct. Figure 3 shows a primary cavity 10 formed by gain element 20, modulation element 40 and cavity mirrors 30 and 32. The secondary cavity 100 is formed by gain element 20 and cavity mirrors 50 and 52 and additionally separation elements 57 and 58. The separation elements 57 and 58 may be polarisers in which the primary and secondary cavities oscillate with different polarisations and while following near identical paths through gain element 20 have distinct cavity paths and distinct outputs 36 and 52, for the primary and secondary cavities, respectively. In a similar way, the separation elements 57 and 58 may be frequency selective elements and the primary and secondary cavities oscillate with different frequencies while following near identical paths through gain element 20. By way of example the frequency selective elements 57 and 58 can be dichroic mirrors reflective at one frequency and transmissive at another, or diffraction gratings that separate wavelengths by angle, or dispersive refracting elements, such as prisms, that separate wavelengths by angle. The secondary cavity can be set in threshold as with the embodiment of Figure 2, and accrue the same benefits. The separation of secondary cavity by polarisation or frequency can be beneficial if it is impractical or impossible to separate by angle. An example is in a single mode optical fibre amplifier in which angular separation is not possible, since only one spatial path is possible.

Figure 4 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with

its own modulation element to assist the pulse control. In this embodiment the secondary laser cavity 100 of this invention also contains a modulation element 70. The modulation element can be externally controlled to set the level of loss of the secondary cavity. Hence its lasing threshold can be varied continuously and a continuous range of gain clamping of the laser gain element 20 achieved. This adjustable control allows added benefit to the flexibility of the laser. By way of example, the gain can be clamped at one level prior to one pulse and at another level prior to another pulse. The available gain will be different for the two pulses and they will emit different pulse energies. The adjustable modulation element 70 thereby provides a variable pulse energy control, for example at a constant repetition rate output. Alternatively, when the pulse repetition rate is varied the pulse energy will vary due to the different pump energy stored between pulsing, but adjusting the loss modulator 70 can allow each pulse to emit the same energy across a range of repetition rates. This is beneficial if the process application requires precise pulse energy but due to scan speed changes or other processing features requires the pulse rate to vary. A further benefit that derives from this last inventive feature is first pulse suppression. When the laser is not operated for a long period, the energy stored in the laser gain element can be very high. The first pulse emitted after this period will tend to be much more energetic than the subsequent train of pulses and can even result in damage to the application process or laser itself. By using the modulation of the secondary cavity to provide additional suppression of the gain can eliminate the high energy of the first pulse and with suitable adjustment even ensure it is the same pulse energy as the later pulses in the train.

Figure 5 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to assist the pulse control of the primary cavity and additionally to utilise the

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secondary output to control the amplification of the primary laser output in an external amplifier element. The primary cavity 10, with laser gain element 20 and modulation element 40 and cavity mirrors 30 and 32 produces an output beam 36 that is then amplified in external laser gain element 80 to produce an amplified output 66. The inventive secondary cavity 100 is employed that emits output 56 when the gain in the common laser gain element 20 reaches a sufficiently high level, as described in reference to embodiment of Figure 2. In this present embodiment the gain of the external amplifier is controlled by passing the output of the secondary cavity 56 through the external gain element 80 via appropriate path changing optics 72 such as mirror(s). The benefit of this inventive feature is to suppress the gain of the external amplifier precisely when the primary laser is emitting pulses at a low repetition rate or is providing no output at all. By way of example, we shall consider the extreme case of no primary cavity output 36. In this case, the gain of the external amplifier can become too large due to lack of extraction and in this circumstance the spontaneous emission of this amplifier can be amplified to high levels. This is exacerbated by the fact that the amplified spontaneous emission in one direction through the amplifier 80 can be reflected by the mirror 32 or other optics of the primary laser cavity to see further amplification in the other direction through the amplifier. This double pass amplified spontaneous emission can be very large for a high gain amplifier. Further amplification may also be effected by feedback of amplified output beam 66 from the application process. This output 66 may be occurring just at the very time that no emission is required from the laser. In this embodiment it is noted that the strength of the secondary cavity output 56 is maximal when the primary cavity output 36 is minimal. The suppression of the gain of external amplifier 80 is therefore maximal just when the external amplifier 80 would be unloaded by output 36. Conversely, when the primary laser is emitting strongly or at high pulse rate the secondary output 56 is low or non-existent. In this way this embodiment

feature provides benefit of external amplifier gain suppression when most needed and no or little gain suppression when not required. It has the advantage of being passive in respect that it need not require external control to decide which state it is in.

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Figure 6 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to control the amplification in an amplifier element of an angularly separated primary beam path. This embodiment employs the inventive features of the secondary cavity to control the gain of an amplifier element rather than the oscillator. A laser system 110 provides an output beam 90 that is amplified in an external laser gain element 80 to provide an amplified output 92. The inventive feature of this embodiment is the use of an external secondary cavity 200 that incorporates the gain element 80 with cavity formed by mirrors 50 and 52 and a path at an angular separation to the primary output beam 90 and 92. One of the secondary cavity mirrors can be partially transmitting to provide an output 56. The secondary laser cavity 200 provides a means for clamping the gain of element 80 as seen by the primary beam 90. If the primary output is inhibited or is very low power for an extended period, the gain in amplifier 80 would build up to a higher value than if it was extracted more often or strongly. In this embodiment, the secondary cavity 200 is arranged to have the threshold gain of element 80 for onset of its oscillation set to a value that prevents the amplifier reaching its maximum gain level. When secondary cavity reaches its threshold for oscillation, its operation will act to clamp the gain to a level at, or close to, the threshold gain level of the secondary cavity. In this way the secondary cavity suppresses the onset of unwanted excessive gain levels seen by primary output 90 that might cause damage to optical system components or the application process as well as suppression of the development a high level

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of amplified spontaneous emission. This allows improved control and flexibility of the laser.

5 The gain threshold for secondary cavity can be set by adjustment of a number of cavity parameters that control the cavity losses. This can include but limited to: the reflectivity of the cavity mirrors 50 and 52; the alignment of the mirrors 50 and 52; the alignment path through the gain medium 20; adjustment of the match of the frequency or polarisation of the secondary cavity mode to the laser transition of the gain element; inclusion of an additional loss element in
10 the secondary cavity.

Figure 7 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to control the amplification in an amplifier element where the secondary cavity and primary beam path are separated by polarisation and / or frequency. The
15 previous embodiment showed a secondary cavity where the beam path was different through the gain element compared to the primary output beam 90. This embodiment teaches that the path through the gain need not be different so long as the primary output path and secondary cavity can be made distinct.

20 Figure 7 shows a primary output beam 90 emitted by laser system 110. The secondary cavity 200 is formed by gain element 80 and cavity mirrors 50 and 52 and additionally separation elements 57 and 58. The separation elements 57 and 58 may be polarisers in which the primary path and secondary cavities have radiations with different polarisations and while following near identical
25 paths through gain element 80 the overall secondary cavity path is distinct such that the secondary cavity does not substantially emit radiation into primary amplified output path 92 or back towards the laser system 110. In a similar way, the separation elements 57 and 58 may be frequency selective elements and the primary output radiation 90 and secondary cavity radiation mode

oscillate with different frequencies while following near identical paths through gain element 80. By way of example, the frequency selective elements 57 and 58 can be dichroic mirrors reflective at one frequency and transmitting at another, or diffraction gratings that separate wavelengths by angle, or
5 dispersive refracting elements, such as prisms, that separate wavelengths by angle. The secondary cavity can be set in threshold as with previous embodiment, and accrue the same benefits. The separation of secondary cavity by polarisation or frequency can be beneficial if it is impractical or impossible to separate by angle. An example is in a single mode optical fibre amplifier in
10 which angular separation is not possible, since only one spatial path is possible.

Figure 8 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity with modulation element to control the amplification of a primary beam path in an
15 amplifier element. A laser system 110 provides an output beam 90 that is amplified in an external laser gain element 80 to provide an amplified output 92. An external secondary cavity 200 incorporates the gain element 80 with cavity formed by mirrors 50 and 52 and a path at an angular separation to the primary output beam 90 and 92. One of the secondary cavity mirrors can be
20 partially transmitting to provide an output 56. The additional inventive feature of this embodiment is the incorporation of a modulation element 70 into the secondary cavity. The secondary laser cavity 200 provides a means for clamping the gain of element 80 as seen by the primary beam 90. The modulation element can be externally controlled to set the level of loss of the
25 secondary cavity. Hence its lasing threshold can be varied continuously and a continuous range of gain clamping of the laser gain element 20 achieved. This adjustable control allows added benefit to the flexibility of the laser amplifier. By way of example, the gain can be clamped at one level prior to one pulse emitted by laser system 110 and at another level prior to another pulse. The

available gain will be different for the two pulses and this can be used to control the amplified pulse energies. The adjustable modulation element 70 thereby provided a variable amplification control, for example for a constant repetition rate output. Alternatively, when the pulse repetition rate is varied the pulse energy will vary due to the different pump energy stored between pulsing, but adjusting the loss modulator 70 can allow each pulse to emit same energy across a range of repetition rates.

A further benefit that derives from this last inventive feature is first pulse suppression. This is a problem known to those skilled in the art. When the laser system 110 is not operated for a long period, the energy stored in the laser gain amplifier element 80 can be very high. When a pulse train is subsequently emitted, the first pulse emitted after this period will tend to be much more highly amplified than the subsequent train of pulses and can even result in damage to the application process or laser itself. By using the modulation of the secondary cavity to provide additional suppression of the gain it can reduce the high energy of the first pulse and with suitable adjustment even ensure it is the same pulse energy as the later pulses in the train.

Figure 9 is a schematic representation of another embodiment of a laser system, according to the present invention, that employs a secondary laser cavity to assist the pulse control of the main cavity and a further different secondary cavity to simultaneously control the amplification in an external amplifier element. In this embodiment the inventive features applied to a laser oscillator and the inventive feature applied to a laser amplifier are combined to obtained a fully controlled laser oscillator – power amplifier scheme. A primary laser cavity 10 consists of a laser gain medium 20 together with a modulation element 40 within a laser cavity formed by high reflectivity mirror 30 and a partially reflecting output coupling mirror 32 that allows transmission of a

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primary output beam 90. A secondary laser cavity 100 consists of the same laser gain medium 20 but within a secondary cavity formed by mirrors 50 and 52 where the path through the gain medium 20 is at some angle with respect to the primary cavity. A partial transmission of mirror 52 provides a secondary
5 output beam 56. The secondary laser provides a means for clamping the gain of element 20 as seen by the primary laser. If the primary laser cavity 10 is inhibited by its modulation element 40 from oscillation for an extended period, the gain would build up to a higher value than if it was allowed to oscillate more frequently. In this embodiment, the secondary cavity 100 is arranged to
10 have the threshold gain of element 20 for onset of its oscillation set to a value that is lower than the maximum gain level that the primary cavity can reach in the absence of secondary cavity. When the secondary cavity reaches its threshold for oscillation, its operation will act to clamp the gain to a level at, or close to, its threshold gain level. In this way the secondary cavity suppresses
15 the onset of unwanted gain levels seen by the primary cavity and this allows greater control and flexibility of the laser. The gain threshold for secondary cavity can be set by adjustment of a number of cavity parameters that control the cavity losses. These cavity parameter can include but is not limited to: the reflectivity of the cavity mirrors 50 and 52; the alignment of the mirrors 50 and
20 52; the alignment path through the gain medium 20; adjustment of the match of the frequency or polarisation of the secondary cavity mode to the laser transition of the gain element; inclusion of an additional loss element in the secondary cavity. The secondary cavity can also incorporate a modulation element, as illustrated in Figure 4, to provide additional control of the
25 oscillator, or incorporate frequency separation elements as illustrated in Figure 3. Additionally, Figure 9 shows the primary output beam 90 that is amplified in an external laser gain element 80 to provide an amplified output 92. An additional secondary cavity 200 is used that incorporates the gain element 80 with cavity formed by mirrors 120 and 122 and a path at an angular separation

to the primary output beam 90 and 92. One of the secondary cavity mirrors can be partially transmitting to provide an output 126. The amplifier secondary cavity 200 can also incorporate a modulation element, as illustrated in Figure 8, to provide additional control of the oscillator, or incorporate frequency separation elements in a similar way to those illustrated in Figure 3.

Although the invention embodiments shown in the figures depict particular layouts of elements it will be appreciated that these are for illustrative purposes and other variations can be used without affecting the key principles underlying these inventions. For example, additional optical components can be incorporated to improve performance. The various materials from which the laser mirrors and output coupler are formed are well known to the skilled reader and are not described herein. For example the mirrors can be glass substrates with dielectric coatings as is well known in the art. The laser cavities shown are linear formed by a pair of end mirrors but can readily be replaced by ring cavity arrangement. Alternatively, one or more of the cavity mirrors might be formed by a reflective surface on the laser gain medium itself.

The gain medium can be any of a large number of materials, including solid-state, fibre, semiconductor, gas or liquid, with suitable pumping to provide excitation and optical gain in the manner of a laser. In the case of a solid-state laser material, by way of example, Nd:YAG, the pumping might be from a discharge lamp, and the gain medium can be in the form of a rod or slab or disc. Alternatively, the gain medium might be Nd:YAG or Nd:YVO₄, with pumping by semiconductor diode lasers. The gain medium can be a fibre amplifier with either single mode or multimode doped core with diode pumping.

Claims

1. A laser system comprising:
 - a) a laser gain medium;
 - 5 b) a primary path of radiation that experiences amplification in said laser gain medium;
 - c) a secondary path of radiation that also experiences amplification in said laser gain medium but has a path that is distinct from the primary path or can be substantially separated from the amplified
10 radiation in the primary path; and
 - d) wherein, in use, the radiation in the secondary path is controlled to limit the gain experienced by the radiation in the primary path.
2. A laser system as claimed in Claim 1, comprising:
 - 15 a first laser cavity having:
 - a) said laser gain medium within said first laser cavity;
 - b) a loss modulation element within said first laser cavity; and
 - c) the modulation element being variable between a maximum value and a minimum value of optical loss for the laser mode of the first
20 laser cavity.
 - a second laser cavity having:
 - a) a common laser gain medium with said first laser cavity;
 - b) a radiation cavity mode that is substantially distinct from that of the first laser cavity such that any output of second laser cavity is
25 substantially separable from the output of the first laser cavity;
 - c) an optical cavity arrangement to set the threshold for laser oscillation of the second laser cavity at a level lower than that for the first laser cavity when the loss modulation element is at its maximum value of loss but at a level higher than the first laser

cavity when the loss modulation element is at its minimum value of loss.

5 3. A laser system as claimed in claim 2, where the loss modulation element is operated to produce a Q-switching action on the first laser cavity and creation of a laser pulse from the first laser cavity.

 4. A laser system as claimed in claim 2, where the loss modulation element is an acousto-optic modulator or an electro-optic modulator.

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 5. A laser system as claimed in claim 2, where the second laser cavity has a radiation cavity mode substantially distinct from that of the first laser cavity by following a path through laser gain medium that is angularly separated from that of the first laser cavity.

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 6. A laser system as claimed in claim 2, where the second laser cavity has a radiation cavity mode substantially distinct from the that of the first laser cavity by having a different polarisation from that of the first laser cavity.

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 7. A laser system as claimed in claim 2, where the second laser cavity has a radiation cavity mode substantially distinct from that of the first laser cavity by having a different frequency from that of the first laser cavity.

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 8. A laser system as claimed in claim 2, where the second laser cavity has its laser threshold set at a value to ensure first laser cavity experiences gain that is limited to a level that allows first laser cavity to operate with lower amplitude of loss requirement from its modulation element when pulsing below a certain pulse repetition rate.

- 5 9. A laser system as claimed in claim 2, where the second laser cavity has its laser threshold set at a value to ensure first laser cavity experiences gain that is limited to a level that determines the pulse energy of the first laser cavity at a given pulse repetition rate.
- 10 10. A laser system as claimed in claim 2, where the second laser cavity has its laser threshold set at a value to ensure that laser gain medium is extracted with near constancy by the combined lasing of first and second laser cavities across a wide range of repetition rates.
- 15 11. A laser system as claimed in claim 2, where the second laser cavity has a loss modulation element contained within its said cavity, where loss modulator can be controlled to actively adjust the laser threshold of the second laser cavity.
- 20 12. A laser system as claimed in claim 2, where the second laser cavity has a loss modulation element contained within its said cavity, where loss modulator is actively adjusted to control the pulse energy of the first laser cavity at a given repetition rate.
- 25 13. A laser system as claimed in claim 2, where the second laser cavity has a loss modulation element contained within its said cavity, where loss modulator is actively adjusted to control the pulse energy of the first laser cavity over a range of repetition rates.
14. A laser system as claimed in claim 2, where the second laser cavity has a loss modulation element contained within its said cavity, where loss

modulator is actively adjusted to maintain the same pulse energy of the first laser cavity over a range of repetition rates.

5 15. A laser system as claimed in any preceding claim further comprising where the output of the second laser cavity is directed to pass through a second laser amplifier that is being used to amplify the output of the first laser cavity, and where the path of the first and second output beams are substantially distinct, or the beams able to be substantially separated, after amplification through the second laser amplifier.

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16. A laser system as claimed in claim 2, where one or more surfaces of the laser gain medium is used as one or more of the cavity reflecting mirrors for either, or both, of the first or second laser cavities.

15 17. A laser system as claimed in claim 2, where the laser gain medium is a solid-state laser material.

20 18. A laser system as claimed in claim 2, where the laser gain medium is a solid-state laser material has one or more of the following active laser ions: neodymium, ytterbium, thulium, titanium, chromium, holmium erbium.

19. A laser system as claimed in claim 2, where the laser gain medium is a solid-state laser material with a rod, slab or disc geometry.

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20. A laser system as claimed in claim 2, where the laser gain medium is a diode-pumped solid-state laser material.

21. A laser system as claimed in claim 2, where the laser gain medium is a diode-pumped solid-state laser material operating in a single bounce or multiple bounce amplifier geometry where a bounce of the laser mode is a grazing incidence total internal reflection from a diode-pumped side face of the laser material.
22. A laser system as claimed in claim 2, where the laser gain medium is a fibre amplifier.
23. A laser system as claimed in claim 2, where the laser gain medium is a semiconductor, gas, liquid or chemical amplifier.
24. A laser system as claimed in claim 1, comprising:
a first laser device for producing an output laser beam which passes through the laser gain medium and experiences amplification, the laser gain material being external of the first laser device;
a secondary laser cavity having:
a) a common laser gain medium with said first-laser device;
b) a radiation cavity mode that is either substantially distinct in path from the amplification path of the laser output beam or such that any output of the secondary laser cavity is substantially separable from the amplified output of the first laser device; and
c) an optical cavity arrangement to set the threshold for laser oscillation of the secondary laser cavity at a gain level of the external laser gain material below its maximum gain attainable, as would occur when no output beam from the first laser system is present.
25. A laser system as claimed in claim 24, where the secondary laser cavity has a radiation cavity mode substantially distinct in path by angular

separation through external laser gain medium compared to the path of amplification of the first laser output beam.

5 26. A laser system as claimed in claim 24, where the secondary laser cavity has a radiation cavity mode substantially able to be separated from the amplified first laser output beam by having a different polarisation from that of the first laser system.

10 27. A laser system as claimed in claim 24, where the secondary laser cavity has a radiation cavity mode substantially able to be separated from the first laser output beam by having a different frequency from that of the first laser system.

15 28. A laser system as claimed in claim 24, where the secondary laser cavity has a loss modulation element contained within its said cavity, where the loss modulator can be controlled to actively adjust the laser threshold of the secondary laser cavity.

20 29. A laser system as claimed in claim 24, where the secondary laser cavity has a loss modulation element contained within its said cavity, where loss modulator can be controlled to actively adjust the laser threshold of the secondary laser cavity in order to control the pulse energy or average power of the amplified output beam of the first laser system.

25 30. A laser system as claimed in claim 24, where one or more surfaces of the external laser gain medium is used as one or more of the cavity reflecting mirrors for the secondary laser cavity.

31. A laser system as claimed in claim 24, where the laser gain medium is a solid-state laser material.
- 5 32. A laser system as claimed in claim 24, where the laser gain medium is a solid-state laser material has one or more of the following active laser ions: neodymium, ytterbium, thulium, titanium, chromium, holmium, erbium.
- 10 33. A laser system as claimed in claim 24, where the laser gain medium is a solid-state laser material with a rod, slab or disc geometry.
34. A laser system as claimed in claim 24, where the laser gain medium is a diode-pumped solid-state laser material.
- 15 35. A laser system as claimed in claim 24, where the laser gain medium is a diode-pumped solid-state laser material operating in a single bounce or multiple bounce amplifier geometry where a bounce of the laser mode is defined as a grazing incidence total internal reflection from a diode-pumped side face of the laser material.
- 20 36. A laser system as claimed in claim 24, where the laser gain medium is a fibre amplifier.
- 25 37. A laser system as claimed in claim 24, where the laser gain medium is a semiconductor, gas, liquid or chemical amplifier.
38. A laser system as claimed in claim 1, the system having a first laser device comprising:
a first laser cavity having:

- a) said laser gain medium within said first laser cavity;
- b) a loss modulation element within said first laser cavity;
- c) the modulation element being variable between a maximum value and a minimum value of optical loss for the laser mode of the first laser cavity.

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a second laser cavity having:

- a) a common laser gain medium with said first laser cavity;
- b) a radiation cavity mode that is substantially distinct from that of the first laser cavity such that any output of the second laser cavity is substantially separable from the output of the first laser cavity;
- c) an optical cavity arrangement to set the threshold for laser oscillation of the second laser cavity at a level lower than that for the first laser cavity when the loss modulation element is at its maximum value of loss but at a level higher than the first laser cavity when the loss modulation element is at its minimum value of loss

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whereby the first laser device generates an output beam that is amplified in the laser gain medium, said laser gain medium being external;
the laser system further including a secondary laser cavity including:

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- a) a common laser gain medium with said first and second laser cavities;;
- b) a radiation cavity mode that is substantially distinct from the amplification path of the output beam or such that any output of the secondary laser cavity is substantially separable from the amplified output of the first laser device; and
- c) an optical cavity arrangement to set the threshold for laser oscillation of the secondary laser cavity at a gain level below the maximum gain attainable when no output beam from the first laser device is present

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39. A laser system as claimed in claim 38, where the second laser cavity has a radiation cavity made substantially distinct from the first laser cavity by following a path through laser gain medium that is angularly separated from that of the first laser cavity, or distinguishable in polarisation or frequency from the first laser cavity.
40. A laser system as claimed in claim 38, where either one or both of the second laser cavity or secondary laser cavity has a loss modulation element contained within its said cavity, where loss modulator can be controlled to actively adjust the laser threshold of the second or secondary laser cavity, respectively.
41. A laser system as claimed in any preceding claim and substantially as described herein with reference to Figures 2 to 9.
42. A method of operating the laser system of any one of the preceding claims.

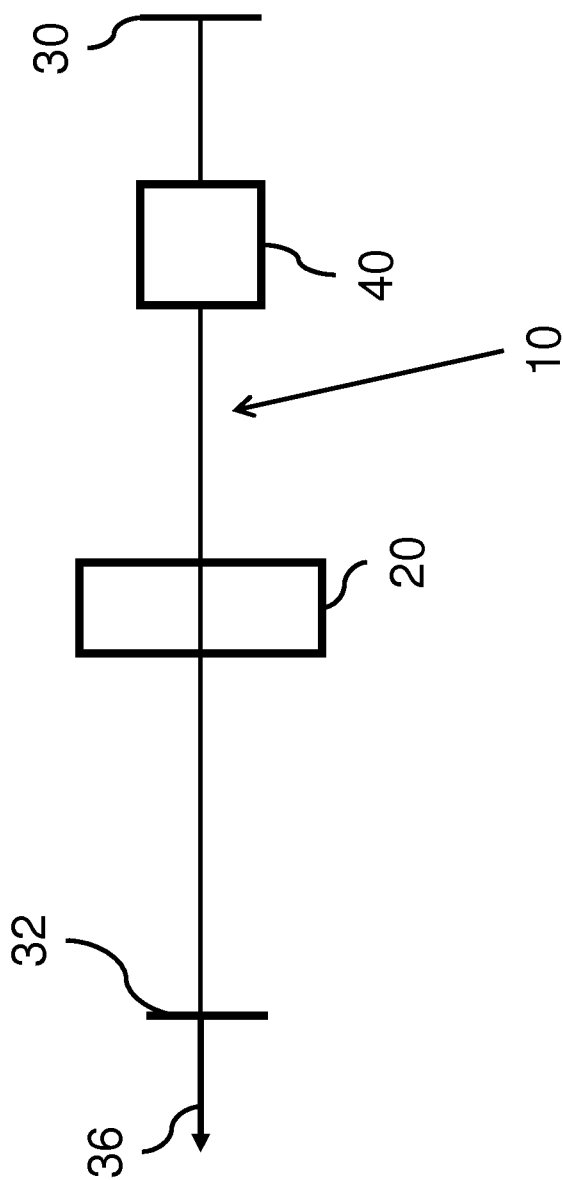


FIGURE 1
(PRIOR ART)

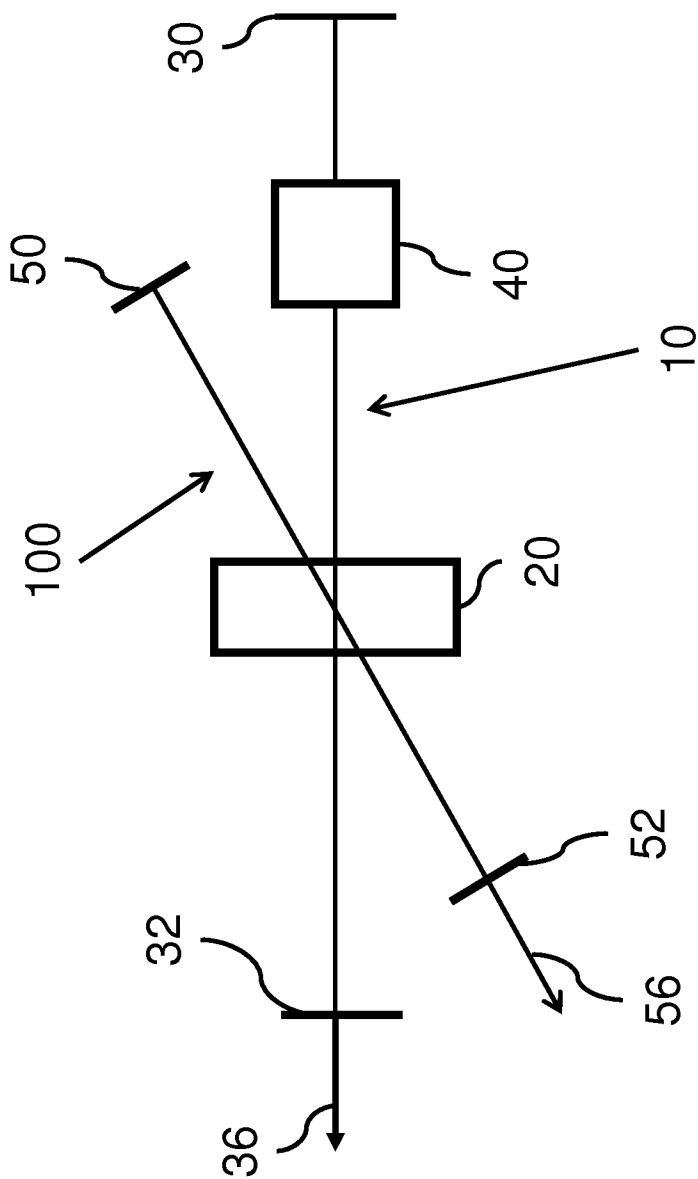


FIGURE 2

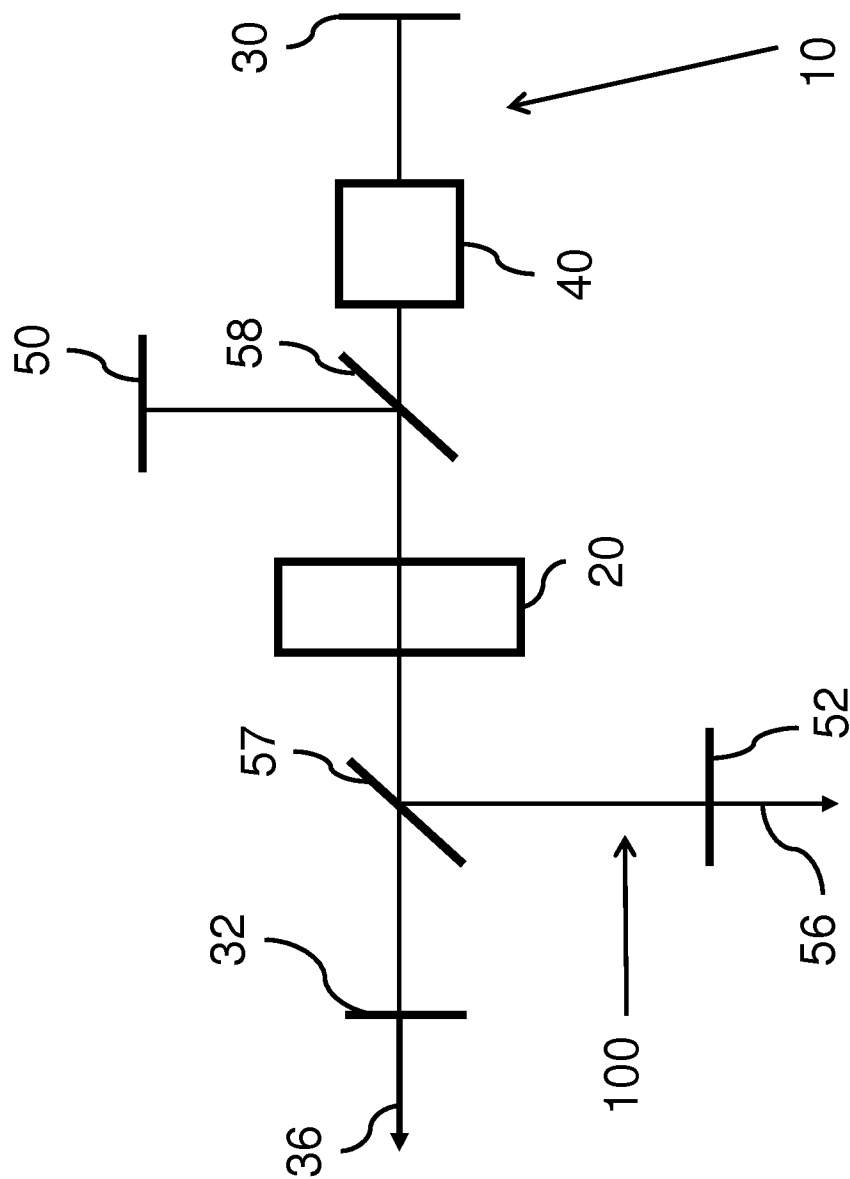


FIGURE 3

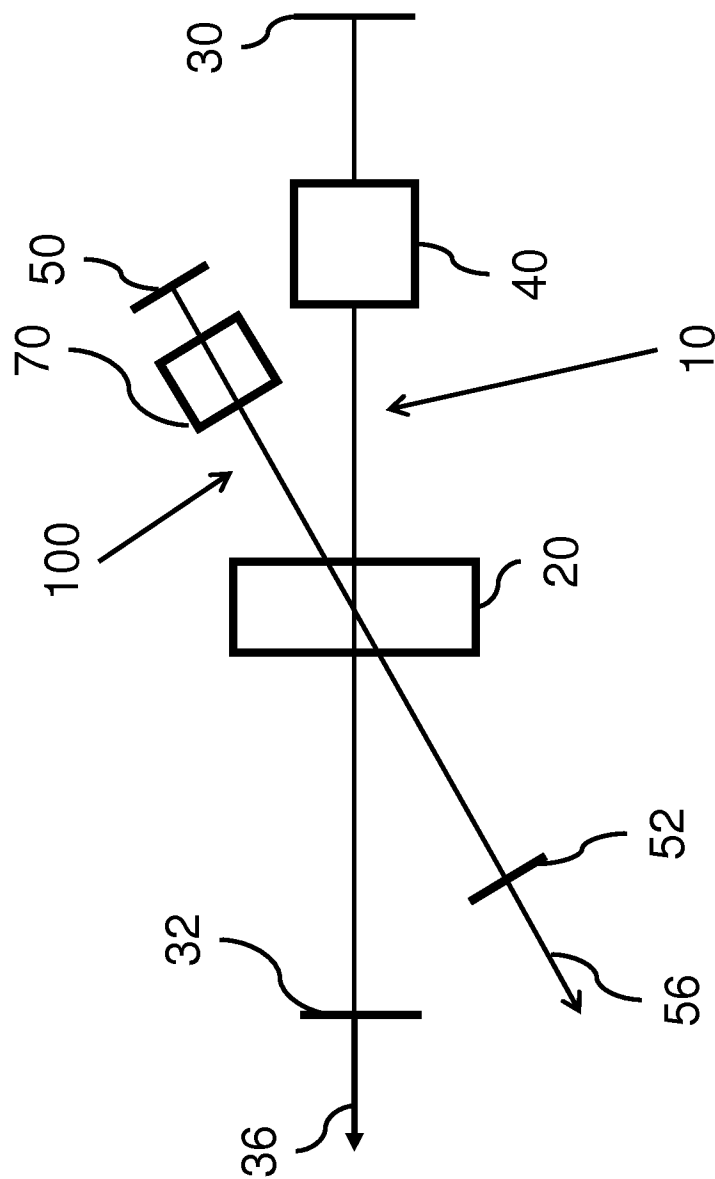


FIGURE 4

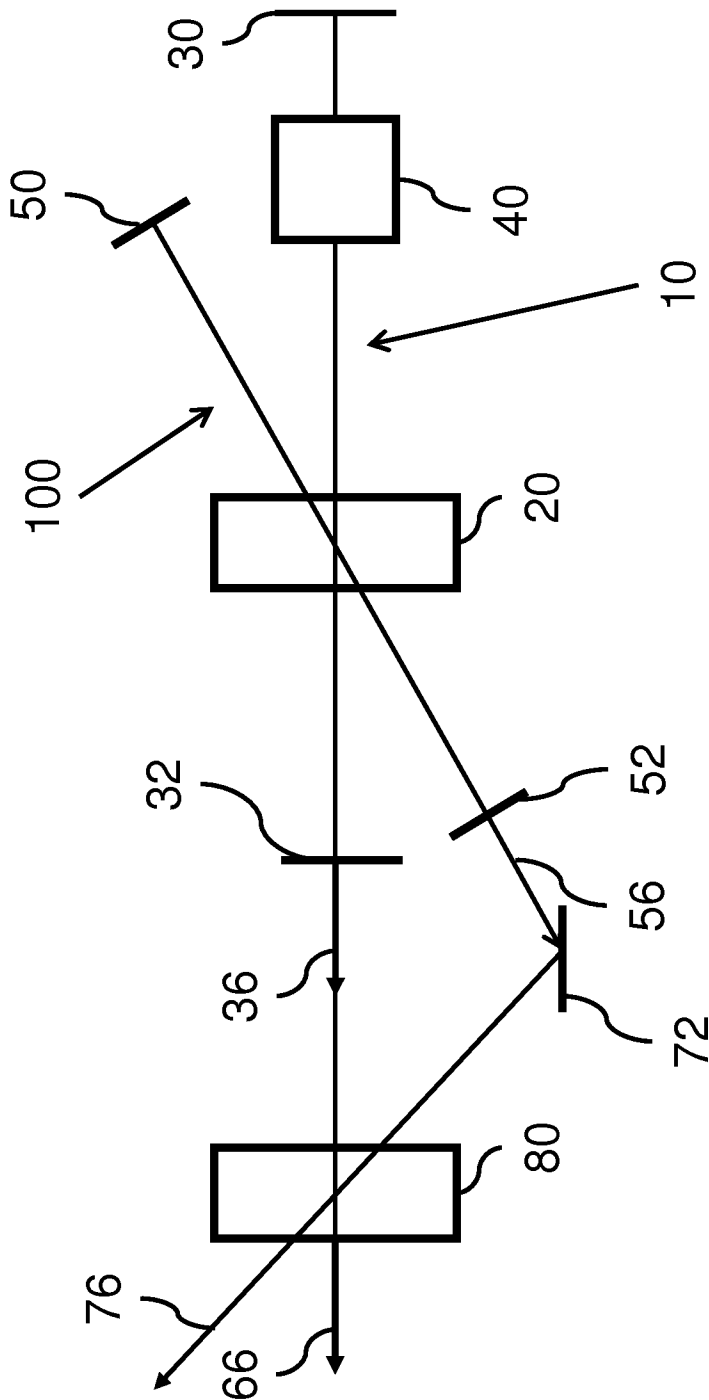


FIGURE 5

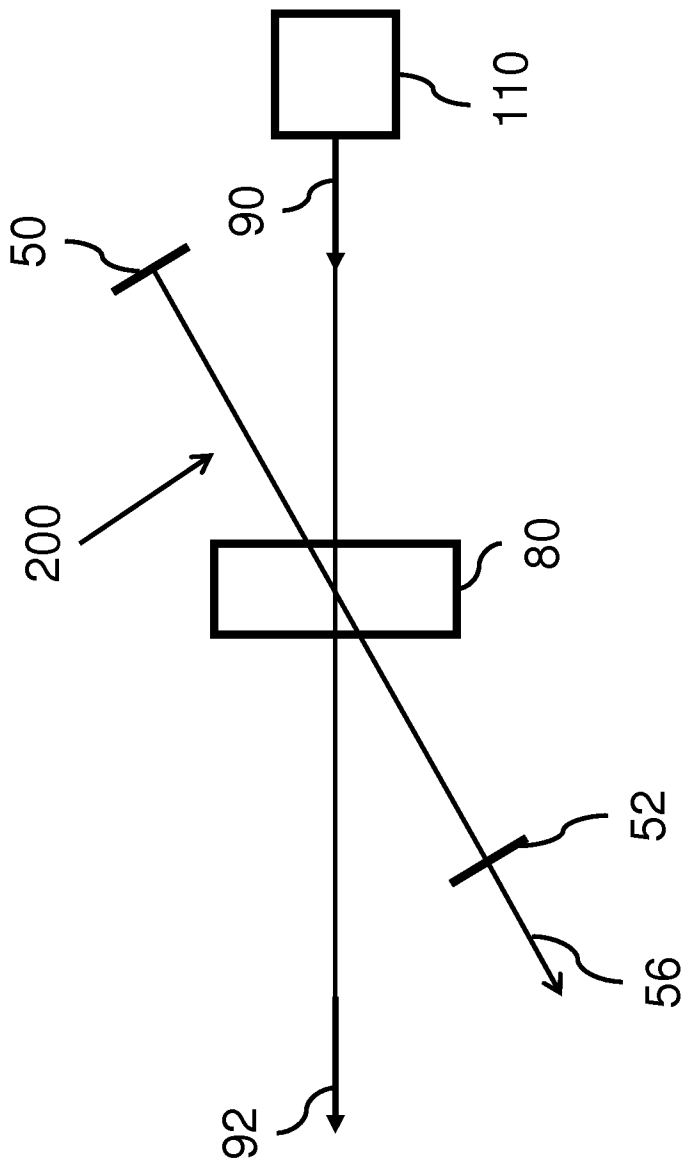


FIGURE 6

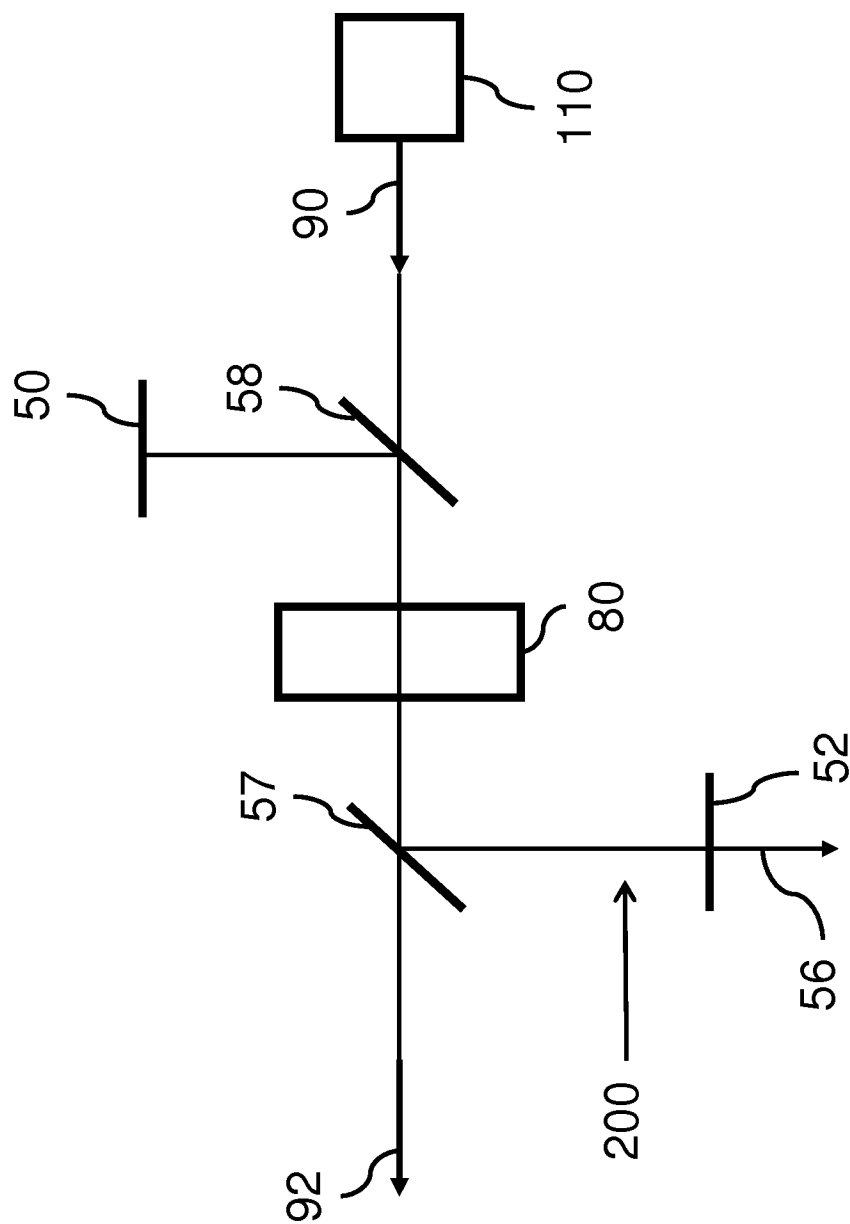


FIGURE 7

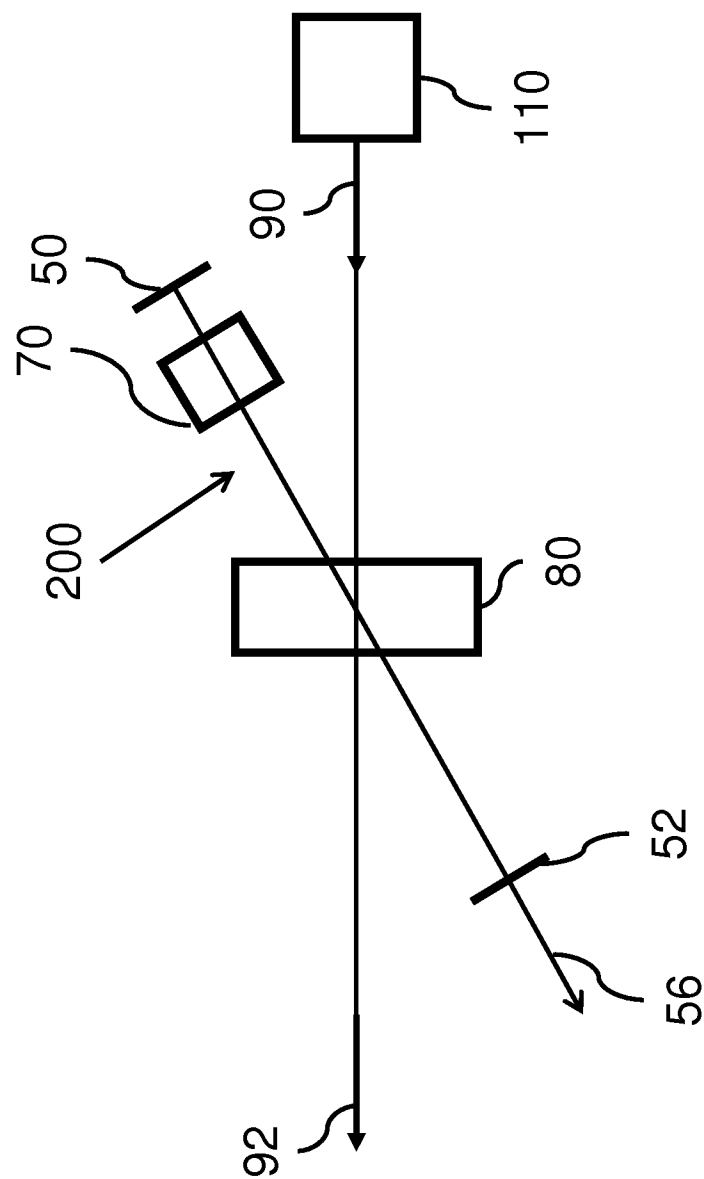


FIGURE 8

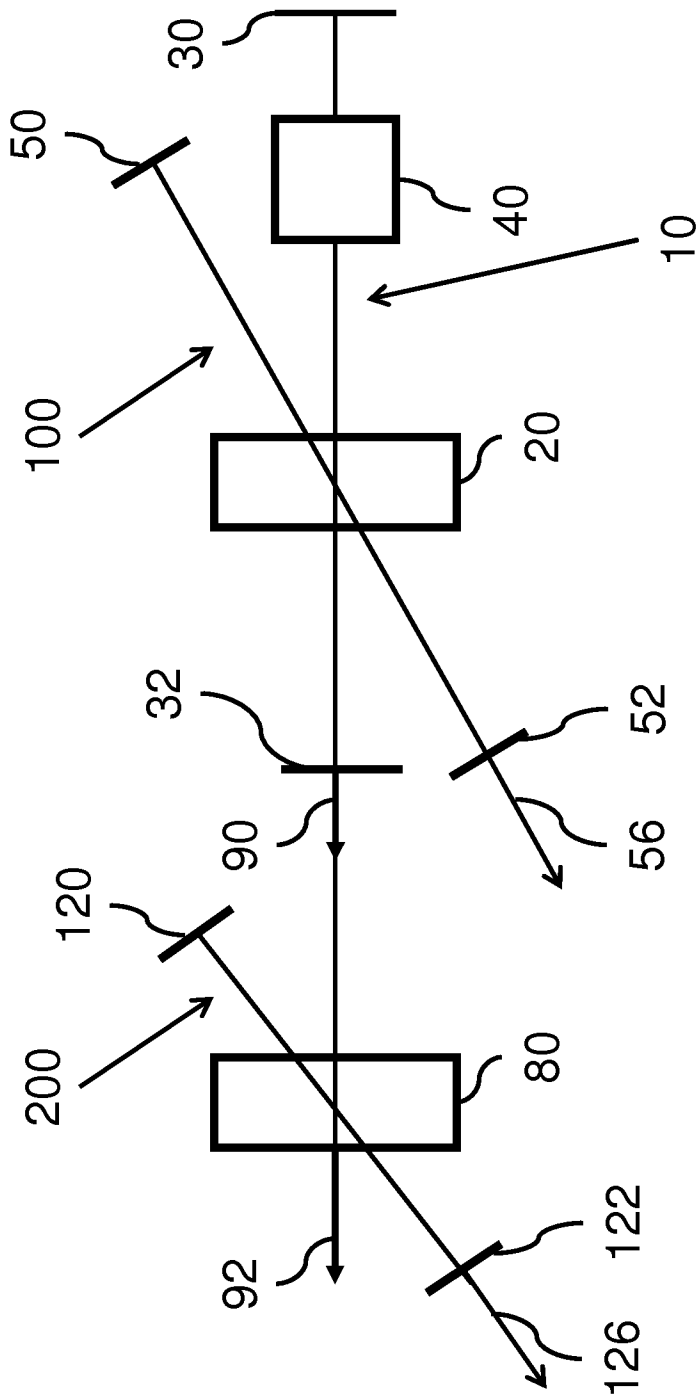


FIGURE 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/062209

A. CLASSIFICATION OF SUBJECT MATTER INV. H01S3/082 H01S3/11 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) H01S		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2008/060407 A2 (COHERENT INC [US]; CLUBLEY DAVID [GB]; BELL ANGUS SUTHERLAND [GB]) 22 May 2008 (2008-05-22) page 2, line 22 - page 3, line 5; figures 1,4,5,6 page 4, line 32 - page 5, line 14 page 8, line 21 - page 9, line 29; claims 1-5,16-20 -----	1-42
X	US 6 078 606 A (NAIMAN CHARLES S [US] ET AL) 20 June 2000 (2000-06-20) column 7, line 39 - column 8, line 54; figures 1,3 -----	1,7
A	US 2004/202207 A1 (WANG CHARLES XIAOYI [US] WANG CHARLES X [US]) 14 October 2004 (2004-10-14) the whole document ----- -/-	1-42
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 15 November 2012		Date of mailing of the international search report 23/11/2012
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Claessen, Michiel

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/062209

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BOCZAR B P ET AL: "NEW SCHEME FOR ULTRASHORT-PULSED ND3+:YAG LASER OPERATION: A BRANCHED CAVITY, INTERNALLY SEEDED REGENERATIVE AMPLIFIER", APPLIED OPTICS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC; US, vol. 22, no. 11, 1 June 1983 (1983-06-01), pages 1611-1613, XP000709227, ISSN: 0003-6935, DOI: 10.1364/AO.22.001611 the whole document	1-42
A	----- US 2009/046353 A1 (SEO HONG-SEOK [KR] ET AL) 19 February 2009 (2009-02-19) the whole document -----	1-42

INTERNATIONAL SEARCH REPORT

Information on patent family members

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			US 2009046353 A1 19-02-2009
