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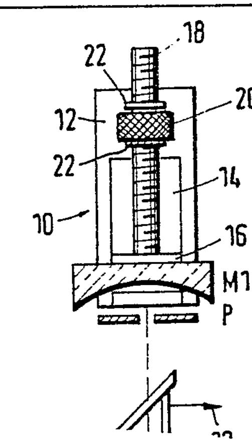
(56) Documents cited **None**
(58) Field of search **H1C**

(71) Applicants
Max-Planck-Gesellschaft Zur Foerderund Der Wissenschaften eV, Maria-Theresia-Strasse 22, Postfach 860260, D-8000 Munchen 86, Federal Republic of Germany.
(72) Inventors
Klaus J. Witte, Walter Scrlac, Ernst Fill.
(74) Agents
Kilburn and Strode, 30, John Street, London WC1N 2DD.

(54) Generation of variable duration pre-pulse free laser pulses

(57) The pulse duration of an iodine laser LK is adjusted between 400 ps and 20 ns primarily by changing the resonator length (L) M1, M2 in the range of about 2 cm to about 100 cm and secondarily by the ratio of excitation energy to threshold energy of the laser. Iodine laser pulses without pre-pulse and temporal substructure are achieved by adapting the gas pressure of the laser gas of the iodine laser to the resonator length in order to limit the band width $\Delta\nu$ of the amplification and thus the band width of the pulse to be produced, specifically such that $\Delta\nu = C/2L$. A prerequisite for the above results is that the excitation of the iodine laser occurs extremely rapidly, specifically the duration of excitation is less than the laser pulse build up time. This is advantageously achieved by photodissociation of a perfluoroalkyl iodide as CF_3I by means of laser providing sufficiently short output pumping pulses, e.g. an excimer laser, or a KrF laser or XeCl laser, or a frequency-multiplied Nd-glass or Nd-YAG laser, or a N_2 laser (in combination with $t\text{-}C_4F_9I$ as laser medium).

Fig.1



PATENTS ACT 1977

SPECIFICATION NO 2095463A

The following corrections were allowed under Rule 91 on 21 December 1982:

Front page, Heading (71) Applicants *below* Applicants *delete* whole lines *insert* Max-Planck-Gesellchaft Zur Foerderung Der Wissensthaften e.v. Bunsenstrasse 10, D-3400 Goettingen, Federal Republic of Germany.

THE PATENT OFFICE
27 January 1983

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SPECIFICATION AMENDED - SEE ATTACHED SLIP

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D-8000 Munchen 86,
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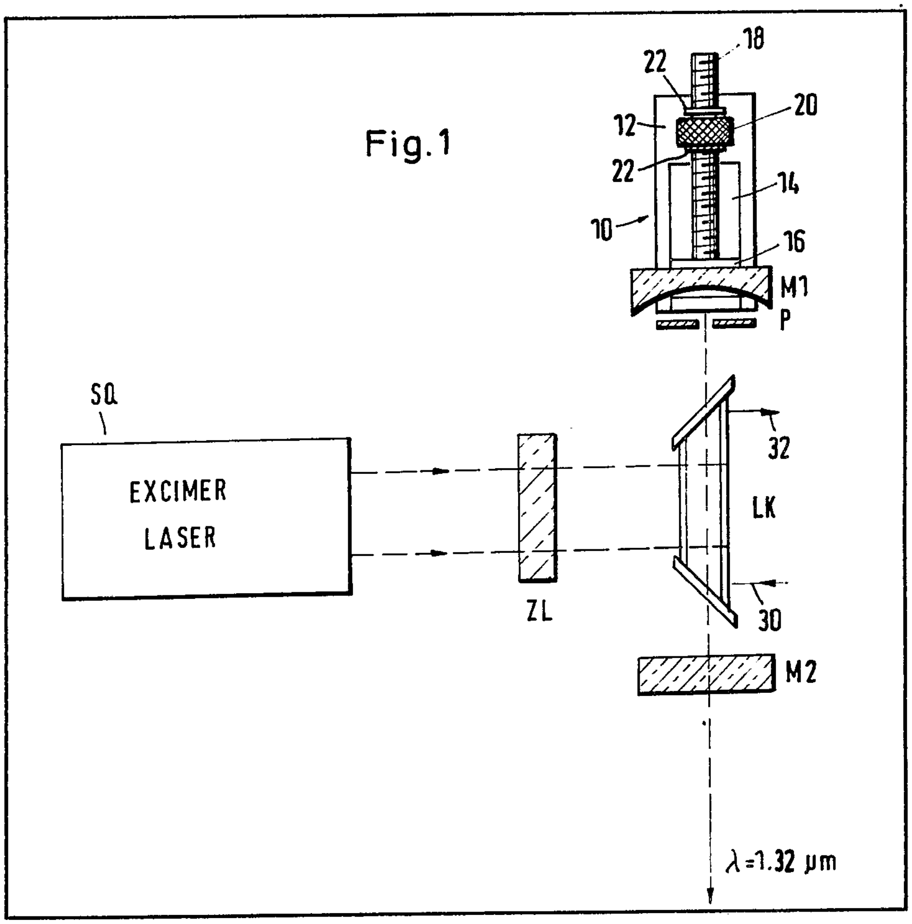

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Fig.1

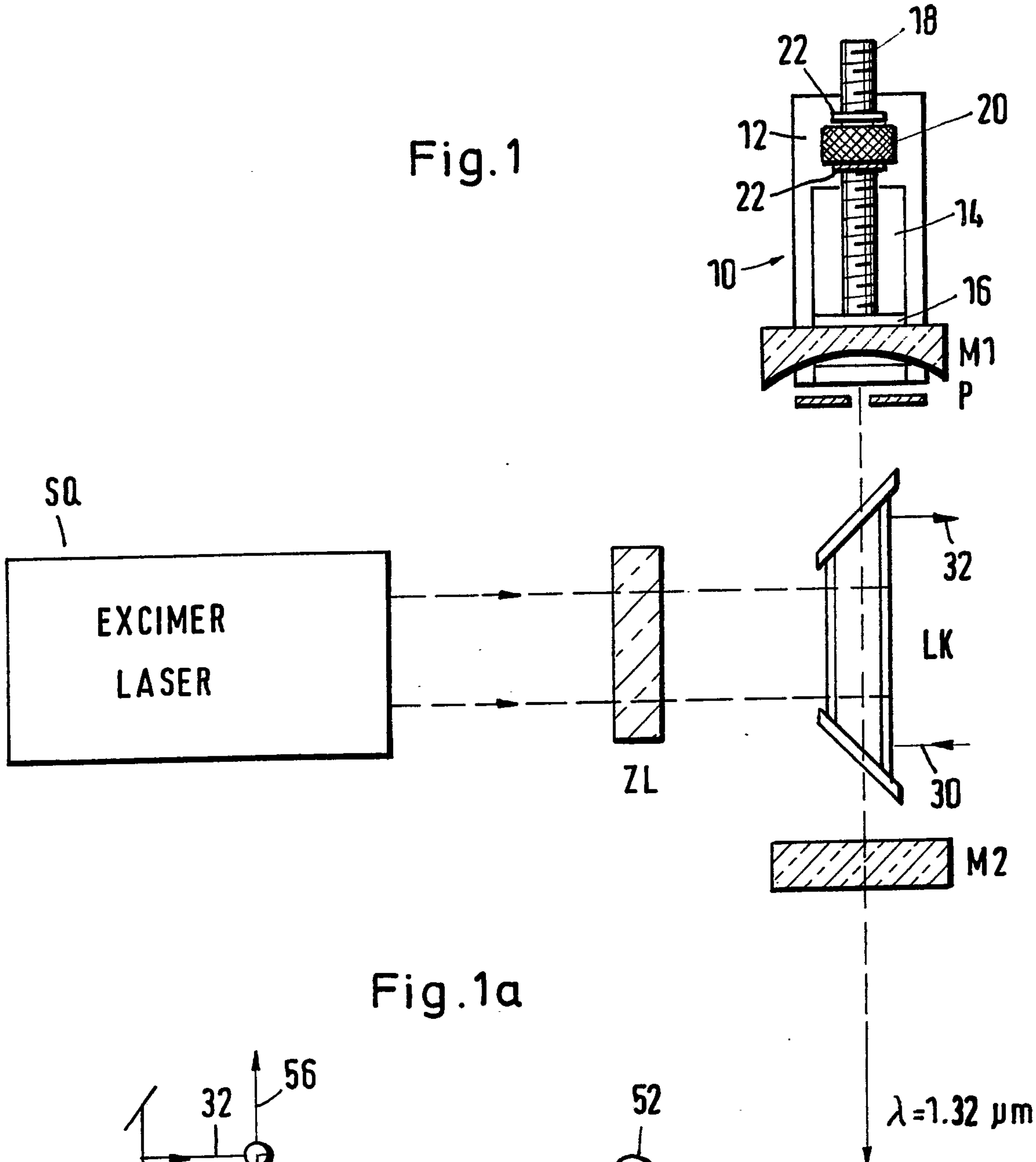

18
22
12
20
22
14
10
16
M1
P
SQ
EXCIMER
LASER
32
LK
ZL
30
M2
λ=1.32 μm

Fig.1a

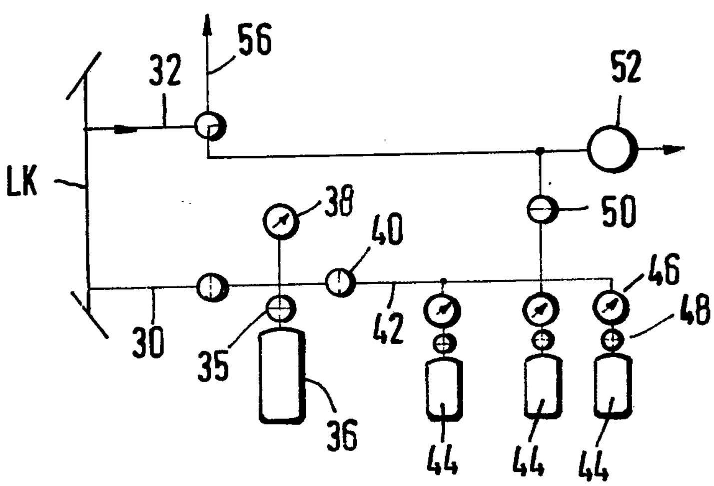

56
32
52
LK
38
50
40
46
48
30
35
42
36
44
44
44

Fig. 2

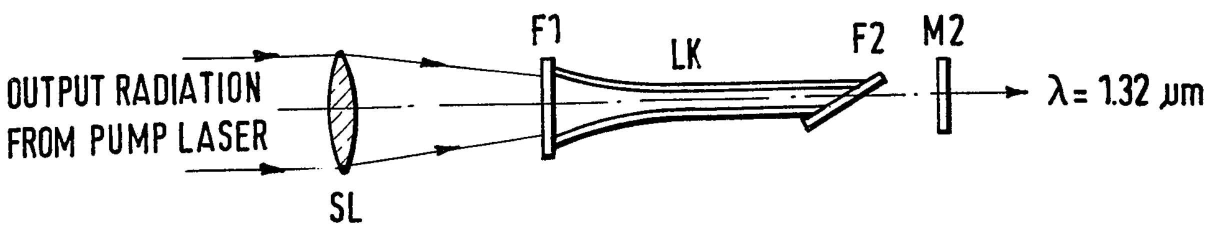
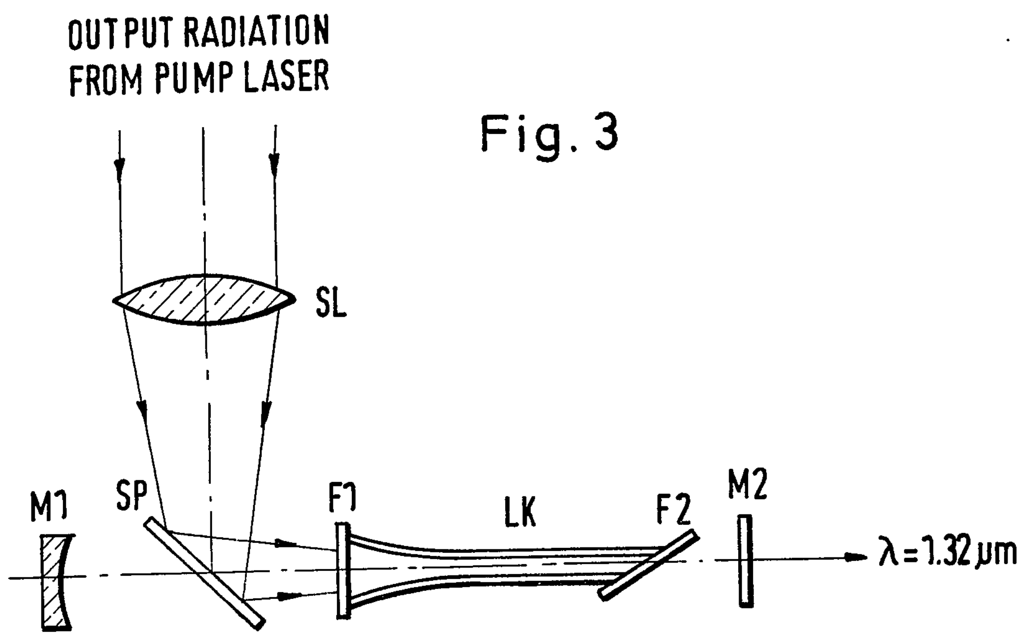

OUTPUT RADIATION
FROM PUMP LASER
SL
F1
LK
F2
M2
λ= 1.32 μm

Fig. 3


OUTPUT RADIATION
FROM PUMP LASER
SL
M1
SP
F1
LK
F2
M2
λ=1.32 μm

SPECIFICATION

Method and apparatus for the production of pre-pulse-free, smooth laser radiation pulses of variable pulse duration

The present invention relates to lasers, more specifically to method and apparatus for producing pre-pulse-free, smooth laser radiation pulses having substantially no temporal substructure, whose duration is adjustable between about 400 picoseconds and about 20 nanoseconds.

Pre-pulse-free smooth laser pulses having essentially no sub-structure and a duration freely selectible within a certain range are required for many purposes. For example, an iodine laser pulse ($\lambda = 1.325\ \mu m$) with a smooth envelope and without pre-pulse is required as the input pulses for an iodine laser amplifier cascade, in which the pulse duration should be continuously adjustable between 0.4 ns and 20 ns in order to be able to carry out experiments with the pulse amplified by the iodine laser amplifier cascade which should lead to the production of energy by nuclear fusion. Another use of such pulses is the measurement of short relaxation times in liquids or the distance measurement.

It is known in the art, that laser radiation pulses can be produced with a duration in the range of 1 ns and below by the technology of mode-locking. This technology fails, however at pulse durations about about 2 ns.

It is further known, that laser radiation pulses in the range of 1-20 ns can be produced by cutting out of a longer pulse. Generally electro-optical methods are used for this purpose. This method is however relatively expensive and leads in additions to small pulse energies and poor efficiencies since only a small portion of a longer pulse is utilized.

It is an object of the present invention to provide a method with which a laser radiation pulse with a smooth envelope, i.e. without substantial temporal substructure, and without pre-pulse can be produced without using frequency selective or active electro-optical elements in the optical resonator of the laser, in which the pulse duration should be continuously variable between about 0.4 ns and 20 ns.

This object is achieved in short by an excitation (pumping) of the laser medium, the duration of which is shorter than the build-up time of the stimulated laser radiation pulse emitted by the excited laser medium.

The laser medium should satisfy the following conditions:

(a) the half maximum amplitude width $\Delta\nu$ of the laser transition between the upper and lower energy laser levels is adjusted by pressure and/or temperature so that the condition $\Delta\nu = c/2L$ is fulfilled, in which c means the velocity of light and L the length of the optical resonator;

(b) the duration of the upper laser level (quench time) is greater than the duration of about 30 round trips of the radiation in the optical resonator, and

(c) the duration of the upper level as a consequence of spontaneous emission is greater than 100 nanoseconds (corresponding to an Einstein coefficient smaller than $10^7 s^{-1}$).

The length of duration of the pulse may be primarily determined by the resonator length of the laser. To a lesser extent the pulse duration may also be influenced by changing the relationship of the excitation energy ("pumping energy") to the threshold energy of the laser ("hard" or "soft" pumping). Thus if one selects the excitation duration, i.e. the duration of the pumping radiation, shorter than the build-up time of the emitted laser radiation pulse which corresponds approximately to 30 to 40 resonator round trips, the duration of the emitted pulse may be thus primarily determined by the resonator length, in particular preferably approximately equal to three to five times the length of the round trip time of the radiation in the resonator. In this manner the pulse duration can be varied between about 400 ps and 20 ns in dependence on the resonator length.

Conditions (a) to (c) set on the laser may be fulfilled preferably by an iodine laser, whose laser medium may contain an alkyl iodide, e.g. CF_3I, C_2F_5I, $i-C_3F_7I$, $n-C_3F_7I$ or $t-C_4F_9I$. Excimer lasers, e.g. a KrF laser or an XeCl laser, whose radiation duration is smaller than 100 ns, are particularly suitable as the excitation radiation source. Further useful excitation radiation sources are Nd-glass and Nd-YAG lasers (with frequency multiplication of the output radiation) and the N_2 lasers having sufficiently short output pulse duration.

In addition to the substantial advantage of the easy variability of the pulse duration the method in accordance with the invention has in addition a number of further advantages:

- pre-pulse-free rising of the laser pulse up to the maximum amplitude;

- exchange of the laser gas between two pulses ("shots") is not necessary at repetition rates up to about 1 per second;

- high pulse repitition rates up to kilohertz range obtainable (with exchange of the laser gas in the optical resonator);

- switching elements for isolation between a laser oscillator and a laser amplifier cascade for the purpose of avoiding parasitic oscillations are not as critical as with conventional flash-lamp pumped lasers.

In order to promote a fuller understanding of the above, and other aspects of the present invention, some embodiments will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 is a simplified view of an apparatus for carrying out a method embodying the invention, that operates with transverse irradiation of the exciting radiation;

Figure 1a is a schematic representation of a gas feed system for the apparatus of Figure 1;

Figure 2 is a representation of a part of a second apparatus for carrying out a method embodying the invention, that operates with longitudinal irradiation of the exciting radiation; and

Figure 3 shows a modification of the apparatus of Figure 2.

The preferred apparatus illustrated in Figure 1 includes a laser cuvette LK which is closed at each end by a respective Brewster window. The laser cuvette LK serves to accomodate a laser gas which contains or consists of an iodine compound from which excited iodine atoms can be produced by photo-dissociation which are capable of a stimulated emission (laser emission). The laser gas advantageously comprises essentially a perfluoralkyl iodide, preferable CF_3I; other useful compounds are C_2F_5I, $n-C_3F_7I$, $i-C_3F_7I$ and $t-C_4F_9I$. The laser cuvette LK is arranged in an optical resonator which is defined by two mirrors M1 and M2, whereby the one mirror M1 has as high a possible reflection at the emission wave-length (1.315 μm) of the iodine laser and can be a concave mirror, whilst the other mirror M2 has a certain transmission so that the radiation from the resonator can be coupled out, as known in the art.

The spacing of the mirror M1 and M2 is adjustable by means of an adjustment device 10. The range of adjustment is relatively large in contrast to that of the conventional laser mirror adjusting devices, generally larger than 25 cm, it can be up to 100 cm, and be arranged in particular for an adjustment of the resonator length of about 4 cm to 100 cm.

The adjustment device 10 illustrated schematically in Figure 1 includes a base plate 12 with a screw 14 in which a sliding member 16 carrying the mirror M1 is slidably mounted. On the sliding member 16 a micrometer spindle 18 is mounted on which a knurled nut 20 sits which is axially fixed between two rings 22 mounted on the base plate 12. The adjustment of the mirror M1 is effected by virtue of rotation of the knurled nut 20.

A light stop or diaphragm P is arranged in the resonator, preferably in front of the mirror M1, to limit the laser emission to the lowest transverse oscillation mode (TEM_{oo}).

The photo-dissociation of the iodine compound in the laser cuvette is achieved by an optical radiation from an excitation radiation source SQ. An important condition of the method in accordance with the invention resides in the fact that the excitation of the laser, that is to say the photo-dissociation of the iodine compound, occurs extremely rapidly. This can be achieved by the use of e.g. an excimer laser, as a KrF laser of an XeCl laser, as the radiation excitation source. Other useful sources for the exciting or pumping radiation are a Nd-glass or a Nd-YAG laser, both in combination with an output radiation frequency multiplier, of if the laser medium comprises $t-C_4F_9I$, a N_2 laser. The half maximum amplitude width of the laser radiation line must at least approximately satisfy the following condition:

$$\Delta v = c/2L$$

in which c means the velocity of light and L the length of the optical resonator of the laser.

The setting of the half width to the value required by this condition can be easily achieved by means of the pressure of the laser gas. The temperature also has a certain influence on the line width. The adjustment of the pressure of the laser gas can be effected in a known manner, the devices and connections of the laser cuvette necessary for this are shown for the sake of simplicity only in Figure 1a and there only schematically: the laser cuvette LK is provided with an inlet line 30 and an outlet line 32. The inlet line is connected via a valve 34 to a gas supply container 36 which can be shut off by a valve 35 and to a pressure measuring device 38 and via a further valve 40 to a line 42 to which pressurised gas bottles 44 for the required gases are each connected via a flow measuring device 46 and a valve 48. The line 42 is additionally connected via a valve 50 to the inlet of a vacuum pump 52. The outlet line 32 can be connected to a gas outlet 46 or the inlet of the pump 52 via a three-way valve 54. Alternatively, a known laser gas recirculating and regenerating system can be used.

In the apparatus shown in Figure 1 the exciting radiation (pumping radiation) is irradiated by the excitation radiation source SQ transverse to the optical axis of the actual iodine laser. The radiation emitted by the radiation excitation source SQ is focused for this with a cylinder lense ZL in the laser cuvette LK which contains the iodide. The transverse geometry shown in Figure 1 is distinguished by great simplicity and is preferred when one is primarily interested in a simple construction.

Exemplary embodiments of apparatus for carrying out the method in accordance with the invention are shown in Figures 2 and 3 in which the exciting radiation (pumping radiation) is irradiated longitudinally into the laser resonator. The excitation radiation source is not shown, as in the apparatus in accordance with Figure 1 it preferably comprises here also a laser of the type mentioned above.

The longitudinal arrangements in accordance with Figure 2 and 3 both have the advantage that the excited laser gas volume can be adapted to the volume of the lowest transverse oscillation type, whereby the necessity of a light stop is removed. Furthermore, with a cuvette length above 10 cm virtually all the exciting radiation is absorbed in the laser medium which results in a good utilisation of the exciting radiation. These arrangements, particularly that in accordance with Figure 3, are therefore preferred when a high effectivity of the exciting radiation is of particular importance.

In the apparatus in accordance with Figure 2 the exciting radiation from the pumping radiation source is focused by a spherical lens SL coupled into the iodine laser cuvette LK by means of a quartz disc F1 having no reflective coating. The quartz disc F1 acts at the same time as one end mirror for the optical resonator of the iodine laser. On the other side the cuvette is provided with a Brewster window F2. The optical resonator of the iodine laser is defined by the quartz disc F1 and a tuning mirror M2 whose transmission is freely selectible. The iodine laser cuvette LK can be constructed as a light guide in order to ensure a homogeneous distribution of the exciting radiation. This device also is relatively simple, however it has the disadvantage that only a fraction of the iodine laser radiation can be coupled out as useful output radiation.

In the apparatus shown in Figure 3 the excitation radiation is focused by a collecting lens SL and then reflected longitudinally into the laser cuvette LK of the iodine laser by means of a beam splitter or divider plate SP. The beam splitter plate SP should have as high a possible a reflection for the exciting radiation at 45° angle of incidence and as high a possible a transmission for the iodine laser radiation of 1.315 μm. A beam splitter plate with a hole of about 2 mm diameter can however also be used, then only a reflection for the exciting radiation must be large. The iodine resonator is defined by a concave end mirror M1 which should reflect the laser radiation as completely as possible and a tuning mirror M2 which is partially transmissive.

The iodine lasers described pumped by a laser providing extremely short output pulses have a number of substantial advantages over conventional iodine lasers excited with flash lights regardless of the direction of irradiation of the exciting radiation.

The pulse duration can be adjusted as desired within the range of 400 ps to 200 ns by changing the resonator length. Further, the pressure in the laser cuvette must be adapted to the resonator length in order to achieve a pulse without substructure, i.e. the longer are the pulses to be produced the lower must be the pressure in order to limit the band width of the amplification and thus the band width of the pulse to be produced. The dependence of the amplification band width on the pressure of the laser gas is known in principle from German patent specification 2409940.

In a preferred embodiment of the present method essentially undiluted C_3F_7I is used as laser gas. The pressure is about $4 \cdot 10^4$ Pa at a resonator length of 2 cm and is decreased to about $3 \cdot 10^3$ Pa when the resonator length is increased up to 1 m.

The laser gas may comprise a diluting gas, as argon. The intensity of the pulse increases monotonically up to the maximum amplitude and is free of secondary maxima (pre-pulses) before the primary maximum. Thus a pre-pulse-free individual pulse is ensured in a simpler manner and without critical additional active or passive elements.

An exchange of the laser medium (iodide) between two pulses is generally not necessary since by virtue of the rapid build-up time of the laser pulse up to initiation of the laser emission no quenching of the excited state by impurities or photolytically produced I_2 occurs.

After a large number of pulses replacing the laser medium is of course necessary since it is used up as a consequence of irreversable processes. Thus, when high pulse repetition rates are described, means for replacing or for recirculating, purifying and regenerating of the laser gas in the optical resonator should be provided.

The pulse repetition rate of the laser is substantially determined by the pulse repetition rate of the excitation radiation source (e.g. the excimer laser), which with the present state of the technology results in a substantially higher pulse repetition rate (up to the kilohertz range) than when using Xenon flash lamps as the excitation radiation source.

Energy and power of the iodine laser pulse produced by pumping laser radiation are substantially higher than the corresponding values with pulses produced by Xenon flash lamp pumping.

The invention is not limited to iodine lasers but can find application e.g. in a corresponding manner with a CO_2 laser also. Here also the adjustment of the half amplitude width by pressure and/or temperature of the laser gas is possible. The invention can also be realised with a ruby laser amongst others. The adjustment of the half amplitude width can be achieved by means of the temperature. Generally, the ruby rod should be operated at a temperature below 70 K.

CLAIMS

1. A method of producing pre-pulse-free, smooth laser radiation pulses having substantially no temporal substructure, whose duration is adjustable between about 400 picoseconds and about 20 nanoseconds, by means of a laser which includes an optical resonator, a stimulateable laser medium arranged in this having an upper and a lower level forming a laser transition and an excitation (pumping) source for populating the upper level of the laser medium and which satisfies the following conditions:

(a) the half maximum amplitude width $\Delta\nu$ of the laser transition is adjusted by pressure and/or temperature so that the condition $\Delta\nu = c/2L$ is fulfilled, in which c is the velocity of light and L the length of the optical resonator;

(b) the duration of the upper laser level (quench time) is greater than the duration of some 30 round trips of the radiation in the optical resonator, and

(c) the duration of the upper laser level as a consequence of spontaneous emission is greater than 100 nanoseconds (corresponding to an Einstein coefficient smaller than $10^7 s^{-1}$), in which the duration of the excitation is shorter than the build-up time of the stimulated laser radiation pulse emitted by the excited laser medium.

2. Method as claimed in Claim 1, in which the duration of the excitation is smaller than the duration of 30 round trips of the stimulated emitted radiation in the optical resonator.

3. Apparatus suitable for carrying out the method as claimed in Claim 1, comprising an iodine laser which includes an optical resonator, a cuvette positioned in said resonator and enclosing a laser gas including a photo-dissociable iodine compound, and an excitation radiation source for producing an optical radiation which produces excited iodine atoms by photo-dissociation of the iodine compound in the laser gas capable of a stimulated emission, in which the radiation excitation source includes a laser is arranged to deliver radiation pulses whose duration is smaller than the build-up time of an output pulse of the iodine laser produced by stimulated emission of the iodine atoms.

4. Apparatus as claimed in Claim 3, in which the excitation radiation source is arranged to have an emission duration per radiation pulse which is smaller than the duration of 30 round trips of the stimulated emitted laser radiation in the optical resonator.

5. Apparatus as claimed in Claim 3 or 4, in which the excitation radiation source includes as excimer laser.

6. Apparatus as claimed in Claim 3 or 4, in which the excitation radiation source includes a KrF laser.

7. Apparatus as claimed in Claim 3 or 4, in which the excitation radiation source includes an XeCl laser.

8. Apparatus as claimed in Claim 3 or 4, in which the excitation radiation source includes an N_2 laser.

9. Apparatus as claimed in anyone of Claims 3 to 8 in which the optical resonator has a length between 2 cm and 100 cm and that the pressure of the laser gas is of the order of $4 \cdot 10^4$ Pa at a resonator length of 2 cm and is decreased to about $3 \cdot 10^3$ Pa with an increase of the resonator length to 100 cm.

10. Apparatus as claimed in anyone of Claims 3 to 8, comprising a device for changing the length of the optical resonator, which permits an adjustment of the resonator length by an amount of at least 25 cm and a device for adjusting the gas pressure in the laser cuvette.

11. Apparatus as claimed in anyone of Claims 3 to 10, wherein said iodine compound is selected from the group of compounds comprising CF_3I, C_2F_5I, $i-C_3F_7I$, $n-C_3F_7I$, $t-C_4F_9I$.

12. Apparatus as claimed in anyone of Claims 3 to 11 characterised by a gas circulating circuit comprising said cuvette and means for regenerating said gas mixture.

13. A method of producing pre-pulse-free, smooth laser radiation pulses substantially as herein described with reference to the accompanying drawings.

14. Apparatus for producing pre-pulse-free, smooth laser radiation pulses substantially as herein described with reference to the accompanying drawings.

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