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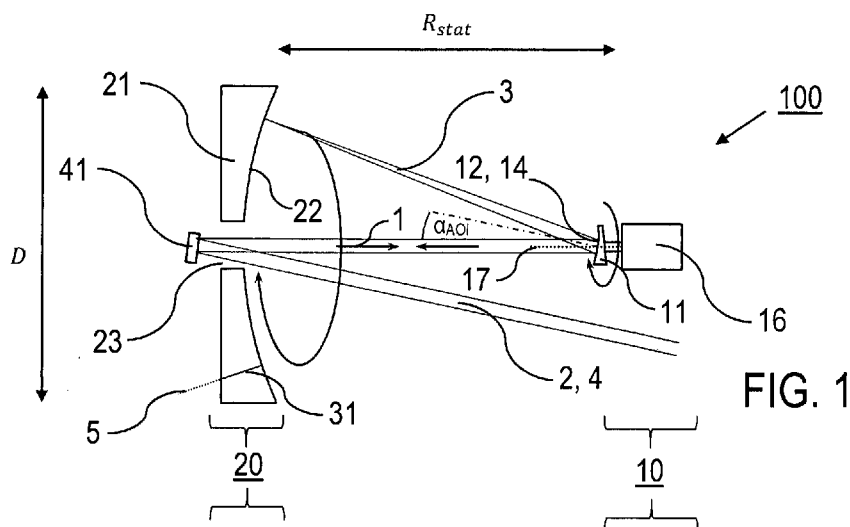
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(57) Abstract: A beam switch apparatus (100), for deflecting a laser beam (1) from an input beam path (2) along a deflection beam path (3) to an output beam path (4), comprises a rotating mirror device (10) having at least one rotating mirror (11) which can be rotated in a range of rotational angles, wherein the rotating mirror device defines an input mirror surface (12) and an output mirror surface (14) of the beam switch apparatus, and a stationary mirror device (20) having at least one stationary mirror (21), wherein the deflection beam path (3) is spanned from the input mirror surface (12) of the rotating mirror device (10) via the at least one stationary mirror (21) to the output mirror surface (14) of the rotating mirror device (10), and the deflection beam path (3) has a variable spatial course determined by the current rotational angle of the at least one rotating mirror, wherein the at least one rotating mirror (11) and the at least one stationary mirror (21) are configured such that the input mirror surface (12) is imaged in at least one plane onto the output mirror surface (14), and wherein at least one coupling element (31) is arranged in the deflection beam path (3) for coupling at least one temporal laser beam section (5) into and/or from the deflection beam path (3) per rotation of the at least one rotating mirror (11). Furthermore, a regenerative amplifier device and an enhancement cavity device, including the beam switch apparatus, and a beam switching method are described.

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**Optical beam switch apparatus, beam switching method and
applications thereof**

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Technical field

The present invention relates to an optical beam switch apparatus and an optical beam switching method for deflecting a laser beam from an input beam path along a variable deflection beam path to an output beam path. Furthermore, the present invention relates to a laser device having a resonator cavity, like a regenerative amplifier device or an enhancement cavity device, including the beam switch apparatus in the resonator cavity for in- and/or out-coupling laser light into and/or out of the resonator cavity. Applications of the invention are available e. g. in the fields of operating laser devices, in particular for in- or out-coupling laser light into or out of a resonator cavity.

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Technical background

In the present specification, reference is made to the following prior art illustrating the technical background of the invention.

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- [14] US 2015/0016479 A1;
- [15] US 4 998 259; and
- [16] US 5999555 A.

Directly coupling laser pulses into or out of optical resonators is highly desirable for many applications, such as cavity dumping or regenerative amplification. To this end, optical switches that are able to switch on the timescale of the repetition rate of the resonator are employed. Typically, the repetition rate of laser resonators is in the range of a few MHz to several hundreds of MHz, given by the resonator length. Laser systems that amplify laser pulses with a high pulse energy and peak power typically work at repetition rates that are orders of magnitude lower than those of the seeding oscillators. To reduce the repetition rate, the optical switches should be fast enough to pick individual pulses from a MHz pulse train for subsequent amplification. Depending on the application, these switches might need to exhibit a very high transmission in at least one switch state, and work in a broad optical bandwidth. In some applications, they also need to tolerate high average powers without inducing

thermal lensing or other thermal effects, and high peak powers without inducing nonlinear effects or being damaged.

There are technologies that offer solutions for some combinations of these requirements. However, in particular for high-power applications, existing technologies are severely limited in their capabilities. In conventional regenerative amplifiers, for instance, the optical switch represents a bottleneck hindering further progress towards higher peak and average powers [1, 2, 6]. Another promising concept which would tremendously profit from a power-scalable and fast switch is cavity dumping from passive enhancement cavities ("stack and dump") [4, 5]. Here, the switch not only should be insensitive to thermal and nonlinear effects, but also should exhibit extremely low losses and a low dispersion for the pulses circulating in the cavity. A device that eliminates this bottleneck could be a key component for a new class of efficient lasers producing Joule-level pulse energies at repetition rates in the 10-kHz range [7, 8].

Optical switches in regenerative amplifiers typically comprise Pockels cells using the electro-optic effect in nonlinear crystals to rapidly rotate the polarization of the pulse train for input and output coupling. The thickness of the crystals, e. g. β -barium borate (BBO) crystals [3], is typically tens of millimeters, and their dispersion must be compensated. Scaling the aperture size of Pockels cells is not trivial because the necessary driving voltage increases with the aperture width. Thermal effects in the Pockels cell present a limitation to the average power [6], while nonlinear effects make the use of chirped-pulse-amplification (CPA) necessary to reach high pulse energies [1]. Typically, the average output power is limited to a few hundred watts, e.g.

resulting in a few tens of millijoules of pulse energy at ten kilohertz.

The combined losses as well as the dispersion caused by an electro-optic output coupler comprising the Pockels cell, a thin-film polarizer and wave plates make its use in high-finesse passive enhancement cavities impossible. For proof-of-principle demonstrations of the stack-and-dump concept, acousto-optic modulators (AOMs) have been employed [9 - 11].

The switching time and efficiency of these devices is linked to the beam size and propagation length in the material. A sufficiently short switching time to pick pulses from a megahertz pulse train requires the beam to be focused in the material and thus limits the achievable peak power.

Recently, a mechanical beam switch apparatus based on a chopper wheel has been proposed [5]. Here, only the picked pulse would interact with the switch, avoiding the losses, dispersion, birefringence, nonlinearities and thermal lensing associated with transmissive elements. However, the centrifugal forces that would occur in a chopper wheel rotating fast enough to intercept a single pulse - even in a tightly focused pulse train of just a few MHz repetition rate - poses a great technological challenge. If such a device is feasible, it would be bulky, expensive, and limited to relatively low repetition rates.

Further types of mechanical beam switch apparatuses are known, which however are not suitable for coupling laser pulses into or out of a resonator cavity ([14] to [16]). According to [14], a rotating mirror pair is included in the resonator cavity of a regenerative amplifier. By the rotation of the mirror pair, the incidence position of a light field on a gain medium is varied along a circle. The radius of the

circle described by the light field during one rotation is restricted to the size of the rotating mirror pair. Accordingly, the feasibility of the apparatus for output coupling single pulses from a resonator cavity is subject to the same mechanical limitation as the beam switch apparatus of [5].

The conventional beam switch apparatus 100' described in [15] is schematically illustrated in Figure 13 (prior art). The beam switch apparatus 100' includes a pair of rotating mirrors 11', 13' and a plurality of separate stationary mirrors 21', which are arranged for spanning a deflection beam path 3' being rotating around the rotation axis of the rotating mirrors 11'. A laser beam 1' created by the laser oscillator 210' with a high repetition frequency travels along an input beam path 2' to the first rotating mirror 11' and via the deflection beam path 3' through one of a plurality of amplifying gain media 220' to the second rotating mirror 13' and further to an output beam path 4'. The rotation of the rotating mirrors 11', 13' is synchronized with the repetition frequency of the laser beam 1' such that each subsequent laser beam pulse enters another amplifier gain medium 220'. After the amplification, the amplified pulses are recombined by the second rotating mirror 13'. A similar beam switch apparatus is disclosed in [16], including a rotating mirror sequentially distributing pump pulses to a plurality of stationary amplifier laser rods.

Deviating from [14], the rotating deflection beam path 3' covers a region larger than the dimension of the rotating mirrors 11', 13', so that it is suitable for obtaining an increased rotation speed of the light field and separating and recombining laser pulses. However, the current deflection beam path 3' including a pair of stationary mirrors 21' and an amplifier gain medium 220' provides a separate branch of

the complete system, requiring a separate adjustment and stabilization. Furthermore, due to the size of the stationary mirrors 21' and the amplifier gain media 220', the number of separate deflection beam paths 3' is restricted and they require a relatively large radial distance from the rotation axis of the rotating mirrors 11' and a relatively large mutual azimuthal distance. Accordingly, the system of [15] has disadvantages in terms of a limited number of deflectable pulses per full mirror rotation and/or complexity of the optical set-up.

Objective of the invention

The objective of the invention is to provide an improved beam switch apparatus and beam switching method for deflecting a laser beam from an input beam path via a rotating deflection beam path to an output beam path, avoiding the limitations of the conventional techniques and in particular being capable of coupling light into and/or out of a resonator cavity with reduced complexity, reduced requirements on adjustment and stabilization and/or an improved separability of subsequent laser beam sections. Furthermore, the objective of the invention is to provide an improved laser device, including the beam switch apparatus device and avoiding limitations of conventional laser devices, in particular avoiding the limitations resulting from the use of transmissive optical switches.

Summary of the invention

According to a first general aspect of the invention, the above objective is solved by a beam switch apparatus, which is adapted for deflecting a laser beam from an input beam path along a rotating deflection beam path to an output beam

path. The beam switch apparatus comprises a rotating mirror device having at least one rotating mirror, which can be rotated relative to a predetermined rotation axis, covering a range of rotational angles, e.g. a full circle or a portion thereof. The rotating mirror device, in particular the at least one rotating mirror thereof, defines an input mirror surface and an output mirror surface of the beam switch apparatus. With a first embodiment of the invention, wherein the input and output beam paths coincide, the rotating mirror device has one single rotating mirror only. With a second embodiment of the invention, wherein separate input and output beam paths are provided, the rotating mirror device has two rotating mirrors.

Furthermore, the beam switch apparatus comprises a stationary mirror device having at least one stationary mirror being arranged relative to the at least one rotating mirror such that the deflection beam path is formed between the input mirror surface of the rotating mirror device via the at least one stationary mirror to the output mirror surface of the rotating mirror device. Due to the rotation of the at least one rotating mirror, the deflection beam path is rotating around a central axis (deflection beam rotation axis), e. g. coinciding with or being parallel to the rotation axis of the rotating mirrors, resulting in a variable spatial course, which is determined by the current rotational angle of the at least one rotating mirror. With the first embodiment of the invention, the stationary mirror device has one single stationary mirror only. With the second embodiment of the invention, the stationary mirror device has two stationary mirrors. In both cases, the stationary mirror(s) has/have a larger diameter than the rotating mirror(s).

According to the invention, the at least one stationary mirror and optionally also the at least one rotating mirror is a curved imaging mirror. The configuration of the at least one rotating mirror and the at least one stationary mirror is adapted for imaging the input mirror surface in at least one of the sagittal and tangential light field planes of the deflection beam onto the output mirror surface. Accordingly, the rotating and stationary mirrors are formed and arranged such that a light field distribution on the input and output mirror surfaces is equal (or scaled with an imaging factor) with regard to the at least one light field plane considered.

Imaging of the input mirror surface onto the output mirror surface means that the arrangement of the at least one rotating mirror and the at least one stationary mirror fulfils the imaging equation, i.e. all beam components in one single location of the input mirror surface are recombined in one single location on the output mirror surface. The input mirror surface provides an object plane, while the output mirror surface provides an image plane with regard to at least one light field plane.

Advantageously, the imaging is kept constant independently on the current rotational angle of the at least one rotating mirror. This allows for the at least one stationary mirror device to have one single, non-segmented (continuous) reflecting surface that provides the imaging function for all rotation angles of the rotating mirrors. The at least one stationary mirror preferably is a compact mirror made of a single piece reflector. Thus, for all or a continuous range of rotation angles, a laser beam input on the input mirror surface side of the beam switch apparatus is provided with reproduced spatial and temporal structure at the output mirror surface side of the beam switch apparatus. This feature

represents an essential advantage in particular for the application of the beam switch apparatus in laser systems, like regenerative amplifiers or enhancement cavities. Compared with the conventional techniques, this results in a facilitated adjustment of the beam switch apparatus and allows deflecting a substantially increased (theoretically unlimited) number of laser pulses per rotation.

The imaging function of the inventive beam switch apparatus is in contrast to the beam switch apparatuses of [14] to [16], which use plane mirrors ([14], [15]) or apply imaging of light beams into the laser rods [16] only. Advantageously, the problems of the conventional techniques are overcome in particular by the imaging function used according to the invention. Imaging the input mirror surface onto the output mirror surface advantageously results in an independency of the cross-section of a circle described by the deflection beam path from the size of a rotor, a capability of free selection of the number of pulses that can be recombined with the beam switch apparatus, and an improved stability of the beam switch apparatus. The beam switch apparatus can be adjusted with the at least one rotating mirror in a resting state as the adjustment is kept in the rotating state of the at least one rotating mirror. Furthermore, compared with the conventional techniques, the beam switch apparatus is less sensitive against mutual misalignments of the stationary and rotating mirrors. As a further advantage of the imaging function of the beam switch apparatus, the intensity of the light field on the stationary mirror surface(s) can be reduced by broadening the light field along at least one direction.

According to a further feature of the invention, the beam switch apparatus includes at least one coupling element, which is arranged for in- and/or out-coupling at least one

temporal laser beam section into and/or out of the deflection beam path per rotation of the at least one rotating mirror. The beam switch apparatus allows the formation of geometrically disjoint beam paths for subsequent roundtrips. The beam can be focused in the beam switch apparatus, e. g. inside of a resonator cavity, to avoid spatial overlap of subsequent pulses at one location along the deflection beam path. Advantageously, the coupling element allows a separation and/or an introduction of the at least one temporal laser beam section, like e.g. one single laser pulse or a sequence of laser pulses or a section of a cw laser beam, from and/or into the deflection beam path at a predetermined rotation state of the at least one rotating mirror. Using the imaging function of the beam switch apparatus and/or shaping of the light field by a laser device including the beam switch apparatus, the coupling element can be arranged at a location (focus position) along the deflection beam path, where the travelling light field has a minimum cross-sectional dimension in at least one direction of the plane of the light field (dot or line focus).

The combination of the rotating and stationary mirror devices shares the advantages of the chopper wheel [5] in that it avoids any kind of transmissive optics. However, in contrast to the chopper wheel, no mechanical part needs to move at a speed that is sufficient to intercept an isolated pulse from the pulse train. Here it is the deflection beam path that fulfils this requirement. By using the beam path as a lever, the mechanical rotor needs to be just big enough to provide a sufficient aperture for the beam. Compared to a chopper wheel, this by far more compact rotor will permit a better performance in terms of rotation speed and pulse separation, at a significantly lower cost.

According to a second general aspect of the invention, the above objective is solved by a regenerative amplifier device, comprising a regenerative amplifier resonator including at least one gain medium, which is adapted for amplifying laser pulses, and further comprising the beam switch apparatus according to the above first general aspect of the invention.

According to a third general aspect of the invention, the above objective is solved by an enhancement cavity device, comprising an enhancement cavity, which is adapted for coherently adding laser pulses, and further comprising the beam switch apparatus according to the above first general aspect of the invention.

Advantageously, the beam switch apparatus facilitates the coupling of amplified pulses out of the regenerative amplifier device or coherently enhanced laser pulses out of the enhancement cavity. The limitations of conventional beam switch apparatuses, like Pockels cells, are avoided.

With further applications of the invention, the beam switch apparatus can be used for coupling laser pulses into the resonator cavity of the regenerative amplifier resonator or the enhancement cavity, respectively.

According to a fourth general aspect of the invention, the above objective is solved by a beam switching method for deflecting a laser beam from an input beam path along a rotating deflection beam path to an output beam path, wherein a rotating mirror device with at least one rotating mirror and a stationary mirror device with at least one stationary mirror are used. Preferably, the beam switching method is conducted with the beam switch apparatus according to the above first general aspect of the invention.

The beam switching method includes the steps of directing the laser beam along the deflection beam path from an input mirror surface of the rotating mirror device via the at least one stationary mirror to an output mirror surface of the rotating mirror device and rotating the at least one rotating mirror so that the deflection beam path has a variable spatial course between the rotating mirror device and the stationary mirror device, wherein the spatial course is determined by the current rotational angle of the at least one rotating mirror. The deflection beam path is rotated (or pivoted) relative to a deflection beam rotation axis.

According to the invention, the input mirror surface is imaged by the configuration of the at least one rotating mirror and the at least one stationary mirror in at least one light field plane onto the output mirror surface. Furthermore, according to the invention, at least one temporal laser beam section, like e.g. one single laser pulse or a sequence of laser pulses or a section of a cw laser beam, is coupled into or out of the laser beam using a coupling element, which is arranged in the deflection beam path, e. g. on one of the stationary mirrors or in free space, e. g. between two stationary mirrors.

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Preferably, if a single laser pulse is to be coupled into or out of a pulsed laser beam travelling between the rotating and stationary mirrors, the repetition frequency of the pulsed laser beam, the rotation frequency of the rotating mirror(s) and the geometric dimensions of the rotating and stationary mirrors, in particular the angle of deflection by the rotating mirror(s), the diameter of the stationary mirror(s) and the dimension of the at least one coupling element are selected such that the single laser pulse is incident on

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the coupling element, while the directly preceding and/or the directly subsequent laser pulses travel without incidence on the coupling element.

5 Generally, the inventive method is based on one or two rotating mirrors that rotate at a high angular velocity about a rotation axis that is not orthogonal to its surface. The input laser beam is reflected from a rotating mirror into a deflection beam path that is determined by the rotational angle
10 of this mirror. Subsequently, one or two large fixed mirrors guide all beam paths for a range of rotational angles either back to the same, or to a second rotating mirror which rotates at the same frequency and with a fixed phase with respect to the first mirror. The system is designed such that a
15 fixed output laser beam, which reproduces the spatial and temporal structure of the input laser beam, is formed after the second reflection off a rotating mirror. The deflection beam path of the beam in between the rotating mirrors is rotating e. g. around the central rotation axis. The speed with
20 which the beam path is moving is determined by the distance r of the deflection beam path from the deflection beam rotation axis, and the rotation frequency of the mirrors f_{rot} . The paths of successive pulses in a pulse train with a repetition rate f_{rep} are then separated by $\Delta s = 2\pi r \cdot N$, with the number of
25 pulses per round-trip $N = f_{\text{rep}}/f_{\text{rot}}$. For using such a device as an optical switch, the pulse separation Δs preferably is greater than the beam size at some point along the deflection beam path in the system. To this end, the beam is focused within the system by the rotating and/or stationary mirrors
30 and/or the optics including the resonator to make the above requirement easier to meet. The beam can be focused in both of the sagittal and tangential light field planes, resulting in a round light field distribution in the focal plane, or in

only one light field plane, resulting in a line-shaped light field distribution.

According to a preferred embodiment of the invention, the stationary mirror device, in particular the at least one stationary mirror thereof is adapted for guiding the laser beam along the deflection beam path for a continuous, preferably for the full range of rotational angles of the at least one rotating mirror. Contrary to the beam switch apparatuses of [15] or [16], the conventionally used separate stationary mirrors are replaced by the at least one stationary mirror covering the continuous range of rotational angles. The stationary mirror comprises a compact concave mirror having a continuous mirror surface accommodating the deflection beam path at all or a continuous range of rotational angles. Accordingly, the stationary mirror may comprise a ring shaped mirror. Advantageously, the complete beam switch apparatus can be adjusted with a mutual adjustment of the at least one stationary mirror and the at least one rotating mirror.

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According to a further preferred embodiment of the invention, the at least one stationary mirror is a curved concave mirror, particularly preferred a spherical, parabolic or conic mirror. Advantageously, with the curved concave surface of the at least one stationary mirror, the imaging function of the beam switch apparatus is supported.

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As a further advantage of the invention, multiple options for providing the at least one coupling element are available.

According to a first variant, the coupling element comprises a coupling hole arranged in the body of the at least one stationary mirror. The coupling hole is arranged at a position of the deflection beam path for a predetermined rotation state (coupling/decoupling state) of the at least one rota-

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ting mirror. With the at least one rotating mirror in the coupling/decoupling state, the current laser beam section is transmitted through the coupling hole out of the beam switch apparatus or into the beam switch apparatus, e.g. for a further amplification or the like.

Alternatively, the at least one coupling element comprises a coupling mirror, which is arranged in the deflection beam path between the at least one rotating mirror and the at least one stationary mirror or between the two stationary mirrors. Particularly preferred, the coupling mirror is arranged with grazing incidence, in particular with an angle of incidence relative to the deflection beam path above 80° , preferably above 85° .

According to a particularly preferred embodiment of the invention, the rotating mirror device comprises one single rotating mirror, which simultaneously provides both of the input and output mirror surfaces (first embodiment of the invention). With the first embodiment, the stationary mirror device preferably comprises one single stationary mirror reflecting the laser beam along the deflection path from the rotating mirror via the stationary mirror back to the rotating mirror. Accordingly, the input beam path and the output beam path of the beam switch apparatus coincide as a common input and output beam path.

The first embodiment of the invention has particular advantages in terms of a compact structure of the beam switch apparatus. The beam switch apparatus can be provided as an end mirror in a resonator cavity. Due to imaging the rotating mirror onto itself, a temporal and spatial characteristic of laser pulses circulating in the resonator cavity are preserved. Due to the spatial variation of the deflection beam

path during the rotation of the rotating mirror, the coupling element can be included in the beam switch apparatus without an interfering deterioration of the resonator cavity operation.

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According to the first embodiment, the rotating mirror may comprise a plane mirror or a curved concave mirror focussing the laser beam onto the stationary mirror. With the second alternative, the rotating mirror is curved relative to one
10 direction of the light field plane (cross-section of the laser beam on the input beam path), e. g. a cylindrical rotating mirror, or relative to two orthogonal directions of the light field plane, e. g. a spherical or parabolic rotating mirror. Providing the curved concave shape of the rotating
15 mirror results in advantages for focussing the laser beam on the stationary mirror, thus providing an improved spatial separation of pulses of the laser beam on the stationary mirror surface. Alternatively, focussing the laser beam on the stationary mirror can be obtained by a combination of a plane
20 or curved rotating mirror and a curved folding mirror being arranged in the common input and output beam path and focussing the laser beam via the plane rotating mirror on the stationary mirror.

25 Preferably, the single stationary mirror of the first embodiment comprises a curved concave, in particular spherical or parabolic or conic mirror. The spherical or parabolic stationary mirror has advantages for providing a dot-shaped focus of the laser beam on the mirror surface, facilitating an
30 out-coupling of a temporal laser beam section through at least one coupling hole in the stationary mirror. The conic stationary mirror has advantages for creating a line-shaped focus on the mirror surface, thus reducing the intensity on the mirror surface.

According to a particularly preferred variant of the first embodiment, the single rotating mirror has a rotation axis parallel or tilted (e. g. tilted with an angle below up to 5 45°) relative to the common input and output beam path (in the following: first circular embodiment). With the first circular embodiment, the rotating mirror has one single reflecting mirror facet, which is tilted relative to the mirror rotation axis, preferably with an angle of inclination below 10 20°. The angle of incidence below 20° has advantages for reducing effects on polarization and astigmatism caused by the rotation of the angle of incidence with respect to a stationary laboratory plane.

15 According to the first circular embodiment, the rotation axis of the rotating mirror preferably provides a reference axis defining the common input and output beam path. The deflection beam path is rotated around the rotation axis, wherein the angle between the common input and output beam path and 20 the deflection beam path is determined by the angle of incidence on the single mirror facet and the shape of the single mirror facet. According to a full rotation of the rotating mirror, the deflection beam path encloses a cone between the rotating mirror and the stationary mirror.

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With an alternative variant of the first embodiment, the rotating mirror has a rotation axis perpendicular to the common input and output path (in the following: first planar embodiment). With the first planar embodiment, the rotating mirror 30 has at least one facet, preferably two, three or more facets, which are arranged parallel or inclined relative to the rotation axis of the rotating mirror. The at least one facet provides both of the input and output mirror surfaces at the continuous range of rotational angles of the rotating mirror

device. With an increasing number of facets of the rotating mirror, the effective rotation speed can be increased, in particular by using three or even more facets.

- 5 The first planar embodiment of the inventive beam switch apparatus can have advantages in terms of a more compact structure compared with the first circular embodiment. Furthermore, as the deflection beam path can provide a stronger lever, allowing a separation of single pulses at a lower rotation frequency of the rotating mirror and/or a higher repetition frequency of the input laser beam.
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According to a preferred variant of the first planar embodiment, the stationary mirror and the at least one facet of the rotating mirror comprise cylindrical mirror. The cylindrical stationary mirror creates an image of the laser beam in the plane, which is spanned by the common input and output beam path and the deflection beam path. With the cylindrical rotating mirror, a line focus is created on the mirror surface of the stationary mirror, advantageously resulting in a local decrease of the intensity on the stationary mirror surface.

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According to an alternative embodiment of the invention, the rotating mirror device comprises a pair of rotating mirrors (second embodiment of the invention), wherein a first rotating mirror provides the input mirror surface and a second rotating mirror provides the output mirror surface. Both of the first and second rotating mirrors are arranged on a common rotation axis with the mirror surfaces facing in opposite directions. The stationary mirror device has a first stationary mirror being arranged in front of the first rotating mirror and a second stationary mirror being arranged in front of the second rotating mirror. With this embodiment of the invention, the first and second rotating mirrors are arranged for

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rotating with the same frequency and fixed mutual phase, e.g. on a common drive unit, like a common electric motor.

With the second embodiment, the first and second rotating
5 mirrors preferably comprise plane mirrors, while curved concave mirrors are not excluded. Plane mirrors may have advantages in terms of an easy adjustment of the rotating mirror device. The plane rotating mirrors are combined with spherical or parabolic or conic concave stationary mirrors.
10 Advantageously, in the second embodiment the beam can be focused in a plane between the two stationary mirrors, allowing for the light field distributions of successive pulses to overlap on the stationary mirrors. Accordingly, the intensity of the light field on the stationary mirror surfaces can be
15 reduced. Out- and input coupling can be facilitated in the focal plane between the stationary mirrors.

Preferably, the two stationary mirrors of the second embodiment comprise curved concave, in particular spherical or parabolic or conic mirrors. The spherical or parabolic stationary
20 mirrors have advantages for providing a dot-shaped focus of the laser beam in the focal plane between the stationary mirrors. The conic stationary mirrors have advantages for creating a line-shaped focus. A line shaped focus is advantageous to reduce the intensity on the coupling element.
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Preferably, the rotation axis of the first and second rotating mirrors is parallel to the input and output beam path, while the first rotating mirror is inclined relative to the
30 input beam path and the second rotating mirror is inclined relative to the output beam path. Alternatively, the rotation axis of the first and second rotating mirrors can be tilted relative to the input and output beam paths, respectively. In this case, the first rotating mirror is inclined relative to

the rotation axis thereof and the second rotating mirror is inclined relative to the rotation axis thereof. Advantageously, this embodiment of the invention allows an arrangement of the rotating mirror device outside the space between the first and second stationary mirrors. Accordingly, supporting the rotating mirror device without deteriorating the deflection beam path is facilitated.

According to an alternative embodiment of the invention, the rotation axis of the first and second rotating mirrors are perpendicular to the input and output beam paths, respectively (in the following: second planar embodiment). In this case, the rotating mirror device comprises a rotating plate having two opposite surfaces, which provide the first and second rotating mirrors. According to a preferred variant of the first planar embodiment, the stationary mirrors comprise cylindrical mirrors. With the cylindrical mirrors, a line focus is created in the focal plane, advantageously resulting in a decrease of the intensity on the output coupling element. The second planar embodiment of the inventive beam switch apparatus can have advantages in terms of a more compact structure compared with the second circular embodiment. Furthermore, the deflection beam path can provide a stronger lever, allowing a separation of single pulses at a lower rotation frequency of the rotating mirror and/or a higher repetition frequency of the input laser beam.

Brief description of the drawings

Further details and advantages of the invention are described in the following with reference to the attached drawings, which show in:

Figure 1: a schematic cross-sectional view of the first circular embodiment of the inventive beam switch apparatus with a spherical stationary mirror;

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Figures 2 and 3: schematic cross-sectional views of the first circular embodiment of the inventive beam switch apparatus with a conic stationary mirror;

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Figure 4: a schematic top view of the first planar embodiment of the inventive beam switch apparatus with a spherical or cylindrical stationary mirror;

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Figure 5: a schematic cross-sectional view of the second circular embodiment of the inventive beam switch apparatus, combined with the resonator cavity of a laser device;

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Figure 6: a schematic illustration of deflection beam path positions during a full rotation of the rotating mirrors of the beam switch apparatus according to Figure 5;

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Figure 7: a further variant of the second circular embodiment of the inventive beam switch apparatus with spherical stationary mirrors;

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Figures 8 and 9: schematic cross-sectional views of the second circular embodiment of the in-

ventive beam switch apparatus with conic stationary mirrors;

Figure 10: a schematic top view of the second planar embodiment of the inventive beam switch apparatus;

Figures 11 and 12: schematic illustrations of applications of the inventive beam switching method; and

Figure 13: a schematic illustration of a conventional beam switch apparatus according to [15] (prior art).

Preferred embodiments of the invention

Features of preferred embodiments of the invention are described in the following with exemplary reference to beam switch apparatuses being adapted for applications in laser devices, like regenerative laser amplifiers or enhancement cavities (see in particular Figures 5, 11, 12 and 13). It is emphasized that the application of the beam switch apparatus is not restricted to these laser devices, but rather possible in combination with resonator cavities of other laser devices. Furthermore, exemplary reference is made to embodiments of the beam switch apparatus, which are adapted for out-coupling a single laser pulse or a sequence of laser pulses out of a resonator cavity. The beam switch apparatus can be provided in a corresponding manner for in-coupling a single laser pulse or a sequence of laser pulses into a resonator cavity, e. g. for in-coupling seed pulses into a regenerative amplifier. The application of the invention is not restricted

to the switching of laser pulses, but correspondingly possible with other temporal laser beam sections, e.g. of a continuous wave laser beam, e. g. having a duration in a range of 10 ns to 1 μ s.

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Some details of the beam switch apparatus, like the materials the mirrors, the support and adjustment thereof, can be provided as it is known from conventional optical set-ups, e. g. of laser resonators. Furthermore, the inventive beam switch apparatus can be operated in a vacuum environment, in an inert gas or in an atmospheric surrounding.

There is a large number of possible implementations of the invention. The stability of the system with respect to vibrations, misalignment and thermal effects strongly depends on the optical design of the beam switch apparatus. Other important properties of the beam switch apparatus are the beam size on its optics, astigmatism, polarization effects in the mirror coatings, and its footprint and complexity. Depending on the required optical bandwidth, peak and average power, resonator geometry and sensitivity to distortions, different applications will require different designs. For instance, in enhancement cavities, the circulating pulse train needs to overlap spatially, temporally and in terms of polarization with an incoming pulse train, resulting in a high sensitivity to any distortion of the circulating pulse. In regenerative amplifiers on the other hand, only the spatial overlap of the resonator mode with the pump spot in the gain medium needs to be conserved and its spectral bandwidth is typically limited by the gain medium. Accordingly, the embodiments of the invention can be adapted to the particular application thereof.

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Figure 1 represents a schematic cross-sectional view of the inventive beam switch apparatus 100 according to a first var-

5 iant of the first circular embodiment. The beam switch apparatus 100 comprises a rotating mirror device 10 with one single rotating mirror 11 and a drive unit 16, like an electric motor, and a stationary mirror device 20 with one single stationary mirror 21. The rotating mirror 11 is supported by a drive axis of the drive unit 16 defining the rotation axis 17 of the rotating mirror 11. The beam path spanned by the beam switch apparatus 100 comprises the input beam path 2 towards the rotating mirror 11, the rotating deflecting beam path 3 from the rotating mirror 11 to the stationary mirror 21 and back to the rotating mirror 11 and the output beam path 4 coinciding with the input beam path 2.

15 The rotating mirror 11 has a concave spherical mirror surface 12, 14 providing simultaneously an input mirror surface 12 and an output mirror surface 14 of the beam switch apparatus 100. The input and output mirror surface 12, 14 has a radius of curvature R_{rot} , and it is inclined with an angle of incidence α_{AOI} relative to the rotation axis 17. In other words, a normal direction of the input and output mirror surface 12, 20 14 at the location of the rotation axis 17 deviates from the rotation axis 17, such that a laser beam 1 travelling along the rotation axis 17 is deflected by the rotating mirror 11 with a certain deflection angle to the stationary mirror 21.

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The stationary mirror 21 has a concave spherical mirror surface 22 with a radius of curvature of R_{stat} and a mirror diameter D . The stationary mirror 21 is placed with a mirror surface 22 facing the input and output mirror surface 12, 14 of the rotating mirror 11, wherein the rotating mirror 11 is placed in the center of curvature of the stationary mirror 21. The mirror diameter D is selected in dependency on the angle of incidence α_{AOI} on the rotating mirror 11 and the radius of curvature R_{rot} of the rotating mirror 11 such that,

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for the formation of the deflection beam path 3, the deflected laser beam 1 is incident on the mirror surface 22. Preferably, the focal length of the rotating mirror 11 is equal to the radius of curvature R_{stat} of the stationary mirror 21, i.e. $R_{\text{rot}} = 2 R_{\text{stat}}$. Accordingly, a collimated laser beam 1 is focussed on the mirror surface 22 of the stationary mirror 21 and reflected back to the rotating mirror 11. The input and output mirror surfaces 12, 14 are imaged onto themselves, so that the laser beam 1 is reflected back into the input beam path 2, irrespectively of the rotational angle of the rotating mirror 11.

Figure 1 illustrates the beam switch apparatus 100 with a folding mirror 41 and a hole 23 in the center of the stationary mirror 21, thus providing a folded input and output beam path 2, 4. The illustrated embodiment with the folded input and output beam path 2, 4 has advantages in terms of a compact size of the beam switch apparatus 100 and an integration of the beam switch apparatus 100 in a resonator cavity, wherein the folding mirror 41 provides one of the cavity mirrors (see Figure 5). It is noted that the folding mirror 41 and the hole 23 represent optional features of the beam switch apparatus 100. With alternative embodiments, the folding mirror 41 can be placed in front of the mirror surface 22 of the stationary mirror 21, so that the hole 23 can be omitted, or the folding mirror 41 can be omitted and the input and output beam path 2, 4 can be provided with a non-folded straight course along the rotation axis 17. While Figure 1 shows a plane folding mirror 41 and a curved rotating mirror 11, a curved folding mirror 41 can be provided focussing the laser beam on the stationary mirror 21 in combination with a plane or curved rotating mirror 11.

With the rotation of the rotating mirror 11, the deflecting beam path 3 describes a circle on the mirror surface 22 of the stationary mirror 21. For small angles of incidence α_{AOI} on the rotating mirror 11, the radius of the circle described by the foci of the rotated deflection beam path on the stationary mirror 21 is given by $r = R_{stat} \cdot \tan(2\alpha_{AOI})$. To spatially separate individual laser pulses of the laser beam 1, the focus size $2 \cdot w_0$ in the sagittal plane of the beam switch apparatus 100 should be smaller than the pulse separation, leading to the relation:

$$w_0 \leq r \pi \cdot (f_{rot}/f_{rep}) \quad (1)$$

wherein f_{rot} is the rotation frequency of the rotating mirror 11 and f_{rep} is the repetition frequency of the laser pulses of the laser beam 1.

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The focus size and shape depends on the focal length of the curved mirrors 11, 21 and the features of the input laser beam 1. In an optical cavity, the mode size is dependent on the cavity design and its position in the stability range.

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The surface of the curved rotating mirror 11 can be either spherical or parabolic. Spherical mirrors are astigmatic at non-zero angles of incidence. The sagittal and tangential planes with respect to the rotating mirror 11, and thus the astigmatism, are rotating together with the mirror. In particular in resonators operated close to an edge of the stability range [13], this astigmatism could result in a rotating ellipticity of the cavity mode. Furthermore, the phase and reflectivity of dielectric mirror coatings typically show increasing polarization dependence with a larger angle of incidence and increasing bandwidth of the coating.

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While the setup does not change the polarization geometrically, this effect could cause rotation-angle and wavelength-dependent birefringent effects for larger angles of incidence.

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Both these effects can severely affect passive enhancement cavities. Astigmatism reduces the spatial overlap with the input beam and, thus, the enhancement in cavities operated close to the stability edge, while the birefringence limits the spectral bandwidth. Thus, there is a trade-off between focus size and spectral bandwidth on the one hand, and the angle of incidence, i.e. the footprint of the system, on the other hand. In the case of regenerative amplifiers, both effects are relatively uncritical.

To use this implementation of the beam switch apparatus 100 as an optical switch, at least one output and/or input coupling hole 31 is provided in the stationary mirror 21 for coupling individual pulses 5 in and out of the laser beam, e. g. in a resonator cavity. Since the beam is reflected back into its previous path, this implementation can only be used as an end mirror in linear resonators.

With practical examples, the beam switch apparatus 100 of Figure 1 can be provided with the following preferred dimensions. R_{stat} can be selected in a range from 5 cm to 2 m. The angle of incidence α_{AOI} is selected from a range from 1° to 20° , and $R_{\text{rot}} = 2 R_{\text{stat}}$. Accordingly, the mirror diameter D of the stationary mirror 21 perpendicular to the rotation axis 17 preferably is in a range of 5 cm to 50 cm. The drive unit 16 is preferably adapted for rotating the rotating mirror 11 with a rotation frequency f_{rot} in a range from 1 kHz to 10 kHz. If the drive unit 16 of the first circular embodiment is operated in vacuum, a magnetic bearing of the rotating mirror 11 is provided.

Focussing the laser pulses on the mirror surface 22 of the stationary mirror 21 can have advantages with regard to minimizing the diameter of the coupling hole 31, which can be se-

lected in a range from 50 μm to 2 mm. However, focussing may result in a laser beam intensity damaging the mirror surface 22. For reducing the intensity on the mirror surface 22, line shaped foci can be created on the stationary mirror 21. This can be achieved by using an astigmatically focussed input beam, or the alternative variant of the first circular embodiment of the inventive beam switch apparatus 100 can be provided as illustrated with Figs. 2 and 3.

The tight focus in the coupling hole 31 as shown in Figure 1 allows for a smaller distance of successive pulses and thus for a more compact system, so that it also leads to higher intensities on the mirror surface 22. While the beam profile in the implementation of Figure 1 preferably is round with axis-symmetry, the focus size and shape can be changed by using elliptic and/or astigmatic input beams. For example, the input laser beam 1 in Figure 1 can be focused on the rotating mirror 11 in one plane, while being collimated in the other, so that the beam profile on both the rotating mirror 11 and the stationary mirror 21 is line-shaped. The profiles of successive pulses on the stationary mirror 21 are no longer separated in all phases of the rotation. At rotation angles where the line foci are nearly perpendicular to the direction of movement of the deflection beam path 3, however, they can be separated as well as in the case of round foci, while the intensity on the large mirror is greatly reduced. The same scheme can be applied to the second embodiment (see Figure 5). Alternatively, the creation of a line shaped focus on the stationary mirror is possible for an input beam that is collimated in both light field planes, as illustrated in the following with reference to the variants of Figures 2 and 3.

Figures 2 and 3 illustrate views on the first circular embodiment of the inventive beam switch apparatus 100, which has a

similar structure as shown in Figure 1. The rotating mirror device 10 comprises the single rotating mirror 11, which is rotated with the drive unit 16. The rotating mirror 11 provides the common input and output mirror surfaces 12, 14 of the beam switch apparatus 100. The stationary mirror device 20 comprises the single stationary mirror 21 with a mirror surface 22 and a central hole 23. The stationary mirror 21 includes a coupling hole like in Figure 1 (not shown in Figures 2 and 3). The laser beam 1 travelling along the input beam path 2 is reflected by the rotating mirror 11 on the deflection beam path 3 to the mirror surface 22 and back via the rotating mirror 11 to the output beam path 4. The common input and output beam path 2, 4 is folded with a folding mirror 41, which is arranged on a back side of the stationary mirror 21.

Contrary to Figure 1, the input and output mirror surface 12, 14 of the rotating mirror 11 has a concave, cylindrical shape, which is illustrated with a top view in Figure 2 and a side view in Figure 3 at a rotational angle of e.g. 90°. Furthermore, the mirror surface 22 of the stationary mirror 21 is a conic mirror. The distance between the cylindrical input and output mirror surface 12, 14 of the rotating mirror 11 and the conic mirror surface 22 of the stationary mirror 21 and the apex angle β of the conic mirror surface 22 are selected such that the light field of the laser beam 1 is focussed by the rotating mirror 11 as a line focus on the stationary mirror 21. In particular, the distance is equal to the half radius of curvature R_{rot} of the rotating mirror 11.

As the input and output mirror surface 12, 14 have a cylindrical shape, focussing the laser beam 1 creates the line-shaped focus on the mirror surface 22 of the stationary mirror 21. Accordingly, imaging of the input mirror surface 12

onto itself is obtained in one light field plane only. Advantageously, the line-shaped focus has a reduced intensity and reduced thermal load on the stationary mirror 21. Simultaneously, a slit-shaped coupling hole can be provided in the stationary mirror 21 for out-coupling a temporal laser beam section from the laser beam 1.

With practical examples, the beam switch apparatus 100 of Figures 2 and 3 can be provided with the following preferred dimensions. R_{rot} can be selected cm as mentioned above with reference to Figure 1. The angle of incidence α_{AOI} is selected from a range from 1° to 20° . Note that the apex angle β has a fixed relationship to the angle of incidence α_{AOI} : $\beta = 90^\circ - 2 * \alpha_{\text{AOI}}$. The drive unit 16 is preferably adapted for rotating the rotating mirror 11 with a rotation frequency f_{rot} in a range from 1 kHz to 10 kHz, allowing the separation of single pulses of a pulse train of the laser beam 1 with a repetition frequency in a range from 5 MHz to 50 MHz.

Figure 4 illustrates the first planar embodiment of the inventive beam switch apparatus 100, comprising the rotating mirror device 10 with one single rotating mirror 11 and the stationary mirror device 20 with one single stationary mirror 21. Similar to the first circular embodiment, a common input and output beam path 2, 4 is provided by the current input and output mirror surface 12, 14 of the rotating mirror 11. The common input and output beam path 2, 4 is folded with the folding mirror 41 towards the rotating mirror 11. A laser beam 1 travelling along the input beam path 2 is reflected by the input mirror surface 12 of the rotating mirror 11 towards the mirror surface 22 of the stationary mirror 21 and back to the rotating mirror 11 simultaneously providing the output mirror surface 14, wherein the laser beam is reflected back to the output beam path 4. With this embodiment, the coupling

element comprises the free space 33 adjacent to at least one of the first and second edges of the stationary mirror 21. A coupling hole is not necessary, as input and output coupling is possible in space 33 beyond the at least one of the first and second edges of the stationary mirror 21, respectively. Alternatively or additionally, the stationary mirror 21 can include a coupling hole like in Figure 1 (not shown in Figure 4).

Contrary to the first circular embodiment, the first planar embodiment of the beam switch apparatus 100 is configured with a rotation axis 17 of the rotating mirror 11 being perpendicular to the input and output beam path 2, 4. Advantageously, this embodiment allows the creation of a longer arm of the deflection beam path 3 compared with the embodiment of Figures 1 to 3. The angle of incidence on the rotating mirror 11 is varying in dependency on the rotational angle of the rotating mirror 11.

The embodiment of Figure 4 illustrates a rotating mirror 11 with three facets 18, which have an equal size and shape. Depending on the current rotating angle of the rotating mirror 11, one of the facets 18 facing the input and output beam path 2, 4 provides the input and output mirror surface 12, 14 deflecting the laser beam 1 towards the stationary mirror 21. With the rotation of the rotating mirror 11, the deflection beam path 3 is moved across the mirror surface 22 of the stationary mirror 21, where a dot- or line-shaped focus can be formed in dependency on a spherical or cylindrical shape of the input and output mirror surface 12, 14. The edges of the stationary mirror 21 define limits of the range for reflecting the deflection beam path 3. When the deflection beam path 3 has crossed one of the edges of the stationary mirror 21 (see dotted illustration showing an out-coupled temporal la-

ser beam section 5), the resonator is not closed until the subsequent facet 18 is rotated into the input and output beam path 2, 4 for creating the deflection beam path 3 at the other edge of the stationary mirror 21. The size of the stationary mirror 21 in the plane of rotating the deflection beam path 3 is selected depending on the number of pulses which the resonator should be closed for. With alternative embodiments, the rotating mirror 11 can be provided with one single facet, i.e. as a rotating plate with one mirror surface only, or with more facets, e.g. 2, 4 or even more facets as illustrated with the rotating mirror 11A in the right part of Figure 4.

Figures 5 to 10 illustrate the second embodiment of the inventive beam switch apparatus 100, wherein the rotating mirror device 10 comprises two rotating mirrors 11, 13 and the stationary mirror device 20 comprises two stationary mirrors 21, 24. Although the second embodiment of the invention has a more complex optical set-up compared with the first embodiment of Figures 1 to 4, a substantial advantage is obtained in terms of the imaging of the input mirror surface 12 of the first rotating mirror 11 onto the output mirror surface 14 of the second rotating mirror 13. Contrary to the first embodiment, the light field of the laser beam 1 is not focussed onto the mirror surfaces 22, 25 of the first and second stationary mirrors 21, 24, but at a position, in particular at a half distance, in a symmetry plane between the stationary mirrors 21, 24. Accordingly, at least one output and/or input coupling mirror 32 can be arranged in the deflection beam path 3 between the stationary mirrors 21, 24. The size and shape of the coupling mirror 32 can be reduced to the size and shape of the laser beam focus, e.g. to a dot or line shape. Accordingly, the coupling of single laser pulses without deteriorating the transmission of preceding or subsequent

laser pulses is facilitated. Alternatively, the size and shape of the coupling mirror 32 can be larger than the size and shape of the laser beam focus as blocking multiple pulses can be allowed e. g. for opening a resonator including the inventive beam switch apparatus 100. Furthermore, the light field spots of subsequent laser pulses on the mirror surfaces 22, 25 of the stationary mirrors 21, 24 may have a mutual overlap, resulting in a reduced intensity of the stationary mirrors 21, 24.

The second circular embodiment of the beam switch apparatus 100 as well as embodiments of a regenerative amplifier 200 or an enhancement cavity 300, including the beam switch apparatus 100, are schematically illustrated in Figure 5. The beam switch apparatus 100 comprises the rotating mirror device 10 with a first rotating mirror 11 and a second rotating mirror 13 being supported by motor axes of the drive unit 16, including e.g. one single or two synchronously operated electric motors. The first rotating mirror 11 provides the input mirror surface 12 having a plane shape, and the second rotating mirror 13 provides the output mirror surface 14, having the same size and plane shape like the input mirror surface 12. Fixing the rotating mirrors 11, 13 and their bearings mechanically without blocking the deflection beam path 3 for some rotation angles is possible with sufficiently thin support rods. However, for the applications described below, an eventual local blocking of the deflection beam path 3 is not a problem, since some paths are blocked by output or input coupling mirrors anyway. If the drive unit 16 is operated in vacuum, a magnetic bearing of the first and second rotating mirrors 11, 13 is provided. While the beam switch apparatus 100 is designed to be relatively insensitive to small misalignments to the rotating mirrors 11, 13, the rotor should run as vibration-free as possible.

Furthermore, the beam switch apparatus 100 comprises the stationary mirror device 20, comprising a first stationary mirror 21 and a second stationary mirror 24, each with a mirror surface 22, 25 and a central hole 23, 26. The first and second stationary mirrors 21, 24 have spherical or parabolic mirror surfaces 22, 25 imaging the input mirror surface 12 onto the output mirror surface 14.

The laser beam 1 travels along the input beam path 2, which is folded with the first folding mirror 41 to the input mirror surface 12, deflecting the laser beam 1 towards the first stationary mirror 21. Due to the rotation of the first rotating mirror 11, each of the subsequent laser pulses of the laser beam 1 travels along a specific, spatially separated deflection beam path 3. The deflection beam path 3 of each laser pulse is spanned from the input mirror surface 12 via the mirror surface 22 of the first stationary mirror 21 and the mirror surface 25 of the second stationary mirror 24 to the output mirror surface 14 of the second rotating mirror 13. Due to the symmetric imaging properties of the first and second stationary mirrors 21, 24, the temporal and spatial characteristic of the laser pulses is reconstructed in the output beam path 4. With the second rotating mirror 3, the original pulse train of the input laser beam 1 is reconstructed with the exception of one single laser pulse, which has been coupled out of the deflection beam path 3 at the position of the schematically shown coupling mirror 32.

The stationary mirrors 21, 24 are arranged with rotation symmetry relative to the common rotation axis of the rotating mirrors 11, 13. The first stationary mirror 21 with the spherical mirror surface 22 is arranged at a distance from the first rotating mirror 11 that is equal to its focal

length f , wherein the focal length is half the radius of curvature of the first stationary mirror 21. The second stationary mirror 24 is arranged at the same distance f from the second rotating mirror 13.

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Between the rotating mirrors 11, 13, some space is needed for the drive unit 16 bearing and propulsing the rotating mirrors, separating them by a distance d . Since the rotating mirrors 11, 13 are located in the focal points of the first and second stationary mirrors 21, 24, the distance L between the stationary mirrors is $2f + d$. For a collimated input beam, the focus along the deflection beam is not positioned halfway between the stationary mirrors, and the output beam 4 is not perfectly collimated. Depending on the relative size of the distances L and d , this effect can be negligible. Optionally, to focus the rotating beam in the symmetry plane, it may be provided that the input laser beam 1 is weakly focused. As shown in Figure 6, the foci 1A of the individual pulses are now located on a ring in the symmetry plane between the first and second stationary mirrors 21, 24 with the radius

$$r = \frac{1}{2} (L - d) \tan(2\alpha_{AOI}). \quad (2)$$

Together with (1), w_0 is obtained:

$$w_0 \leq \frac{\pi}{2} (L - d) \tan(2\alpha_{AOI}) \frac{f_{rot}}{f_{rep}}. \quad (3)$$

Depending on the current rotating angle provided by the drive unit 16, the laser pulses 1A describe a circle, wherein the laser pulse being incident on the coupling mirror 32 is coupled out of the deflection beam path as a temporal laser beam section 5.

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The surface of the curved mirrors of Figure 5 can be either spherical or parabolic. In general, spherical mirrors are

easier to align, and cheaper and easier to manufacture, especially in the case of rather large mirrors needed here. The effects of the angle of incidence on polarization and mode shape are the same as discussed for the embodiment of Figure 1, making small angles of incidence desirable. To use the device as an optical switch, output or input coupling mirrors can be placed in the focal plane. This implementation can be used both in ring resonators and in linear resonators.

As mentioned above, in contrast to the embodiment of Figure 1, the beam is large on all intracavity optics in Figure 5, except for the coupling mirror 32. A relatively low average power is applied to the coupling mirror 32, which is hit only once during every rotation period of the rotating mirror device 10. However, here the beam size is smallest, and on the coupling mirror 32 the pulse has the most energy, making it the element most prone to intensity-induced damage. For a given coupling mirror 32, the maximum possible peak power scales with the squared focus size. A larger focus size, for a fixed number of bounces during one rotation period, can be easily accommodated by increasing the size of the system, which renders the concept inherently power-scalable.

With preferred variants of the invention, the coupling mirror 32 is placed to reflect the pulse under grazing incidence, so that the risk of damages can be reduced. For instance, at an extreme angle of incidence of 89° , the irradiated area would be stretched by a factor of about 57. At this angle, and a wavelength of $1\text{ }\mu\text{m}$, the reflectivity of an uncoated quartz surface for s-polarized light is 94%. By avoiding a coating, which would include materials with a lower damage threshold and which typically comes with small deposition errors and irregularities, the highest possible damage threshold can be achieved. The coupling mirror 32, preferably being a simple

quartz (or sapphire or diamond etc.) plate and independent of any more complex optical or mechanical assembly (i.e. the cavity or the rotor), is the cheapest and most easily replaced element in the system, and thus a suitable bottleneck for intensity-related damage.

Preferably, the following dimensions are provided with the beam switch apparatus 100 of Figure 5. The focal length f is selected in a range from 5 cm to 2 m, and the mirror diameter D of the first and second stationary mirrors 21, 24 is selected in a range from 5 cm to 50 cm. The first and second rotating mirrors 11, 13 are adapted for a rotation frequency in a range from 1 kHz to 10 kHz, allowing the separation of single pulses of a pulse train of the laser beam 1 with a repetition frequency in a range from 5 MHz to 50 MHz. In particular, to achieve a sufficient separation of laser pulses from a MHz pulse sequence in a compact system, the rotation frequency of the rotor needs to be in the order of a few kilohertz. Depending on the desired output repetition rate, over ten kilohertz might be desirable.

With a practical example, the drive unit 16 comprises a magnetic bearing motor, preferably achieving a rotation frequency of 8.33 kHz and having a length of 55 mm (see e. g. magnetic bearing motor CM-AMB-400, www.celeroton.com, [12]). With this motor, the diameter D of the first and second stationary mirrors 21, 24 would need to be 100 mm to achieve a pulse separation of 0.25 mm for a pulse train with a repetition rate of 10 MHz. At an angle of incidence of 2° even broadband highly-reflective mirrors exhibit no birefringent effects. With this angle of incidence, the separator of the double-mirror implementation would have a length L of 1.5 m, and would still fit in large vacuum chambers. For a less conservative choice of the angle of incidence and/or the neces-

sary pulse separation, the setup could be made significantly more compact. Compared to the numbers envisaged for a chopper-wheel output coupler in [5], the achieved output repetition rate is lower by about a factor of two. On the other hand, the proposed chopper wheel covers only 0.1 mm in between two pulses, meaning that the beam must be focused far more tightly, and intensity related damages set in at lower pulse energies. Moreover, the numbers shown for the inventive beam switch apparatus are based on existing technology, while a chopper wheel capable of reaching the parameters outlined in [5] has not been designed yet.

A regenerative amplifier device 200 including the inventive beam switch apparatus 100 comprises a regenerative amplifier resonator 210 (partially shown), including the resonator mirror 211 and the first and second folding mirrors 41, 42 as further resonator mirrors. Furthermore, the regenerative amplifier resonator 210 includes a gain medium 212 as it is known from conventional regenerative amplifier devices. The gain medium 212 is pumped during a predetermined number N of circulations of a laser pulse circulating in the resonator cavity 210. During the circulation, the resonator cavity 210 is closed (see Figure 11). When the circulating laser pulse has reached a predetermined intensity, it is coupled out of the resonator cavity 210 using the coupling mirror 32. Subsequently, the next pulse is coupled in and is amplified during a number N of circulations, as shown in Figure 11. The regenerative amplifier device 200 of Figure 5 has a repetition frequency equal to the rotation frequency of the rotating mirror device 10, while the repetition frequency of the laser beam 1 is determined by the length of the regenerative amplifier cavity 210. As the regenerative amplifier device 200 is operated with the coupling mirror 32 as a reflective switch rather than a transmissive switch (like a Pockels cell), the

average power and pulse energy of the laser pulses amplified within the regenerative amplifier resonator cavity 210 can be substantially increased.

5 With the alternative application of the invention, the beam switch apparatus 100 is included in an enhancement cavity 300, which is correspondingly illustrated in Figure 5. With this embodiment of the invention, the enhancement cavity 300 comprises resonator mirrors 311, 312, 41 and 42, wherein the
10 resonator mirror 311 provides an in-coupling mirror of the enhancement cavity device 300. With the enhancement cavity device 300, a large number of laser pulses is coherently added. A circulating laser pulse is created during N circulations of the laser pulses coupled into the enhancement cavity
15 210. After N circulations, the resulting laser pulse is out-coupled at the coupling mirror 32, as illustrated in Figure 12. Advantageously, the acousto-optical modulator with low damage threshold, nonlinear self-phase modulation and limited efficiency of out-coupling as used in prior art enhancement
20 cavity devices is replaced by the reflecting coupling mirror 32, providing an out-coupling for pulses with higher pulse energies and with improved efficiency.

Figure 7 illustrates an alternative variant of the second
25 circular embodiment of the inventive beam switch apparatus 100 having a non-axis-symmetry, which has advantages for the access to the rotating mirror device 10 without blocking the deflection beam path 3 between the stationary mirrors 21, 24 of the stationary mirror device 20. With this embodiment, the
30 rotation axis 17 of the first and second rotating mirrors 11, 13 is tilted relative to the input beam path 2 and relative to the output beam path 4. The input laser beam 1 impinges on the first rotating mirror 11 with an angle ϕ with respect to the rotation axis 17. The angle of the mirror surface 12 to

the rotation axis 17 is ϑ . The angle of incidence on the mirrors 11, 13 oscillates between $2\phi - \vartheta$ and $2\phi + \vartheta$.

A laser beam 1 travelling along the input beam path 2 is deflected by the first rotating mirror 11 via the first and second stationary mirrors 21, 24 to the second rotating mirror 13. Along the deflection beam path, the laser pulses of the laser beam 1 are spatially separated. Due to the imaging of the input mirror surface 12 of the first rotating mirror 11 onto the output mirror surface 14 of the second rotating mirror 13, foci are created in the symmetry plane between the first and second stationary mirrors 21, 24. The straight and dotted lines in Figure 7 illustrate the deflection beam path 3 with different rotating angles of the rotating mirror device. At a predetermined rotational angle of the rotating mirror device 10, the deflection beam path 3 hits the coupling mirror 32, coupling a single laser pulse or another laser beam section out of the beam switching apparatus 100. The practical dimensions of the embodiment of Figure 7 can be selected as mentioned above with reference to the embodiments of Figures 1 to 5.

While the embodiments of Figures 5 and 7 illustrate the creation of dot-shaped foci of the laser pulses, an alternative variant of the second circular embodiment of the beam switch apparatus 100 is adapted for creating line-shaped foci of the laser pulses between the first and second stationary mirrors 21, 24 as illustrated in Figures 8 and 9. With this embodiment, the first and second rotating mirrors 11, 13 comprise flat mirrors, while the mirror surfaces 22, 25 of the first and second stationary mirrors 21, 24 are conic mirrors. Line-shaped foci are created as described above with reference to Figures 2 and 3. The practical dimensions of the embodiment

of Figures 8 and 9 can be selected as mentioned above with reference to the embodiments of Figures 1 to 5.

Figure 10 schematically illustrates the second planar embodiment of the inventive beam switch apparatus 100, comprising the rotating mirror device 10 with a first rotating mirror 11 and a second rotating mirror 13 being formed by opposite surfaces of a plane plate 15, and further comprising the stationary mirror device 20 with a first stationary mirror 21 and a second stationary mirror 24. With this embodiment of the invention, the rotation axis 17 of the rotating mirror device 10 is perpendicular to the plane spanned by the input beam path 2, the deflection beam path 3 and the output beam path 4. The straight and dotted lines illustrate different spatial courses of the deflection beam path 3 with varying rotational angles of the rotating mirror device 10. At a predetermined azimuthal position in the symmetry plane between the first and second stationary mirrors 21, 24, a coupling mirror 32 is arranged for out-coupling single laser pulses or other temporal laser beam sections 5 through the central hole 25 of the second stationary mirror 24. With the illustrated embodiment, the first and second rotating mirrors 11, 13 have a plane input mirror surface 12 and a plane output mirror surface 14, while the stationary mirrors 21, 24 have spherical or cylindrical mirror surfaces 22, 25. The practical dimensions of the embodiment of Figure 10 can be selected as mentioned above with reference to the embodiments of Figures 1 to 5.

The features of the invention disclosed in the above description, the drawings and the claims can be of significance both individually as well as in combination or sub-combination for the realization of the invention in its various embodiments.

Claims

- 5 1. Beam switch apparatus (100), being configured for deflecting a laser beam (1) from an input beam path (2) along a deflection beam path (3) to an output beam path (4), comprising
- 10 - a rotating mirror device (10) having at least one rotating mirror (11, 13) which can be rotated in a range of rotational angles, wherein the rotating mirror device (10) defines an input mirror surface (12) and an output mirror surface (14) of the beam switch apparatus (100), and
 - a stationary mirror device (20) having at least one stationary mirror (21, 24), wherein
 - 15 - the deflection beam path (3) is spanned from the input mirror surface (12) of the rotating mirror device (10) via the at least one stationary mirror (21, 24) to the output mirror surface (14) of the rotating mirror device (10), and
 - 20 - the deflection beam path (3) has a variable spatial course determined by the current rotational angle of the at least one rotating mirror (11, 13),
- characterized in that**
- 25 - the at least one rotating mirror (11, 13) and the at least one stationary mirror (21, 24) are configured such that the input mirror surface (12) is imaged in at least one plane onto the output mirror surface (14), and
 - at least one coupling element (31, 32, 33) is arranged in the deflection beam path (3) for coupling at least one temporal laser beam section (5) into and/or from the deflection beam path (3) per rotation of the at least one rotating mirror (11, 13).
 - 30

2. Beam switch apparatus according to claim 1, wherein
- the at least one stationary mirror (21, 24) is configured
for guiding the laser beam (1) along the deflection beam path
5 (3) for a continuous range of rotational angles of the at
least one rotating mirror (11, 13).

3. Beam switch apparatus according to one of the forego-
ing claims, wherein

10 - the at least one stationary mirror (21, 24) is a curved
concave, in particular spherical or parabolic or conical,
mirror.

4. Beam switch apparatus according to one of the forego-
15 ing claims, wherein

- the coupling element (30) comprises a coupling hole (31)
arranged in the at least one stationary mirror (21, 24).

5. Beam switch apparatus according to one of the forego-
20 ing claims, wherein

- the coupling element (30) comprises a coupling mirror (32)
arranged in the deflection beam path (3), in particular under
grazing incidence.

25 6. Beam switch apparatus according to one of the forego-
ing claims, wherein

- the rotating mirror device (10) has one single rotating
mirror (11) providing both of the input mirror surface (12)
and the output mirror surface (14),

30 - the stationary mirror device has one single stationary mir-
ror (21), and

- the input beam path (2) and the output beam path (4) coin-
cide as a common input and output beam path.

7. Beam switch apparatus according to claim 6, wherein
- the rotating mirror (11) is a plane mirror or a curved concave, in particular cylindrical, spherical or parabolic, mirror focussing the laser beam (1) onto the stationary mirror (21).

8. Beam switch apparatus according to one of the claims 6 to 7, wherein

- the rotating mirror (11) has a rotation axis (17) being parallel or tilted relative to the common input and output beam path, and

- the rotating mirror (11) has one single mirror facet being tilted relative to the rotation axis (17) thereof.

9. Beam switch apparatus according to claim 8, wherein
- the single mirror facet has an angle of inclination below 20° relative to mirror rotation axis.

10. Beam switch apparatus according to one of the claims 6 to 7, wherein

- the rotating mirror (11) has a rotation axis perpendicular to the common input and output beam path (2, 4), and

- the rotating mirror (11) has at least one facet being arranged parallel or inclined relative to the rotation axis

(17) of the rotating mirror (11), wherein

- the at least one facet provides both of the input mirror surface (12) and the output mirror surface (14) at a continuous range of rotational angles of the rotating mirror device (10).

11. Beam switch apparatus according to one of the claims 1 to 5, wherein

- the rotating mirror device (10) has a first rotating mirror (11) providing the input mirror surface (12) and a second ro-

tating mirror (13) providing the output mirror surface (14), wherein the first and second rotating mirrors (11, 13) have a common rotation axis (17), and

- the stationary mirror device (20) has a first stationary mirror (21) facing to the first rotating mirror (11) and a second stationary mirror (24) facing to the second rotating mirror (13).

12. Beam switch apparatus according to claim 11, wherein
- both of the first and second rotating mirrors (11, 13) are arranged for rotating with the same frequency and fixed mutual phase.

13. Beam switch apparatus according to one of the claims 11 to 12, wherein
- each of the first and second rotating mirrors (11, 13) comprises a plane mirror.

14. Beam switch apparatus according to one of the claims 11 to 13, wherein
- the rotation axis of the first and second rotating mirrors (11, 13) is parallel to the input and output beam paths (2, 4),
- the first rotating mirror (11) is inclined relative to the input beam path (2), and
- the second rotating mirror (13) is inclined relative to the output beam path (4).

15. Beam switch apparatus according to one of the claims 11 to 13, wherein
- the rotation axis of the first and second rotating mirrors (11, 13) is tilted relative to the input and output beam paths (2, 4),

- the first rotating mirror (11) is inclined relative to the rotation axis (17) thereof , and
- the second rotating mirror (13) is inclined relative to the rotation axis (17) thereof.

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16. Beam switch apparatus according to one of the claims 11 to 13, wherein

- the rotation axis of the first and second rotating mirrors (11, 13) is perpendicular to the input and output beam paths (2, 4), and
- the rotating mirror device (10) comprises a rotating plate (15), wherein opposite surfaces of the rotating plate (15) provide the first and second rotating mirrors (11, 13), resp., being arranged perpendicular relative to the input and output beam paths (2, 4).

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17. Regenerative amplifier device (200), comprising

- a regenerative amplifier resonator (210) being arranged for amplifying laser pulses, and
- a beam switch apparatus (100) according to one of the foregoing claims.

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18. Enhancement cavity device (300), comprising

- an enhancement cavity (310) being arranged for coherently adding laser pulses, and
- a beam switch apparatus (100) according to one of the claims 1 to 16.

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19. Beam switching method for deflecting a laser beam (1)

- from an input beam path (2) along a deflection beam path (3) to an output beam path (4), wherein a rotating mirror device (10) having at least one rotating mirror (11, 13) and a stationary mirror device (20) having at least one stationary mirror (21, 24) are used, in particular using a beam switch

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apparatus (100) according to one of the claims 1 to 16, comprising the steps of

- directing the laser beam (1) along the deflection beam path (3) spanned from an input mirror surface (12) of the rotating mirror device (10) via the at least one stationary mirror (21, 24) to an output mirror surface (14) of the rotating mirror device (10), and

- rotating the at least one rotating mirror (11, 13), so that the deflection beam path (3) has a variable spatial course determined by the current rotational angle of the at least one rotating mirror (11, 13),

characterized in that

- the input mirror surface (12) is imaged by the at least one rotating mirror (11, 13) and the at least one stationary mirror (21, 24) in at least one plane onto the output mirror surface (14), and

- at least one temporal laser beam section (5) is or coupled into and/or from the laser beam (1) per rotation of the rotating mirror device (10) by at least one coupling element (31, 32, 33) being arranged in the deflection beam path (3).

20. Beam switching method according to claim 19, wherein the step of coupling the at least one temporal laser beam section (5) comprises at least one of

- passing the temporal laser beam section (5) through a coupling hole (31) arranged in the at least one stationary mirror (21, 24), and

- reflecting the temporal laser beam section (5) with a coupling mirror (32), in particular under grazing incidence, into or out of the deflection beam path (3).

21. Beam switching method according to one of the claims
19 to 20, wherein

- the deflection beam path (3) is spanned from a common input
and output beam path (2, 4) via one single rotating mirror
5 (11) to one single stationary mirror (21) and back to the
single rotating mirror (11) providing both of the input mir-
ror surface (12) and the output mirror surface (14).

22. Beam switching method according to one of the claims
10 19 to 20, wherein

- the deflection beam path (3) is spanned from the input beam
path (2) via a first rotating mirror (11) providing the input
mirror surface (12), a first stationary mirror (21) along the
deflection beam path (3), a second stationary mirror (24) and
15 a second rotating mirror (13) providing the output mirror
surface (14) to the output beam path (2).

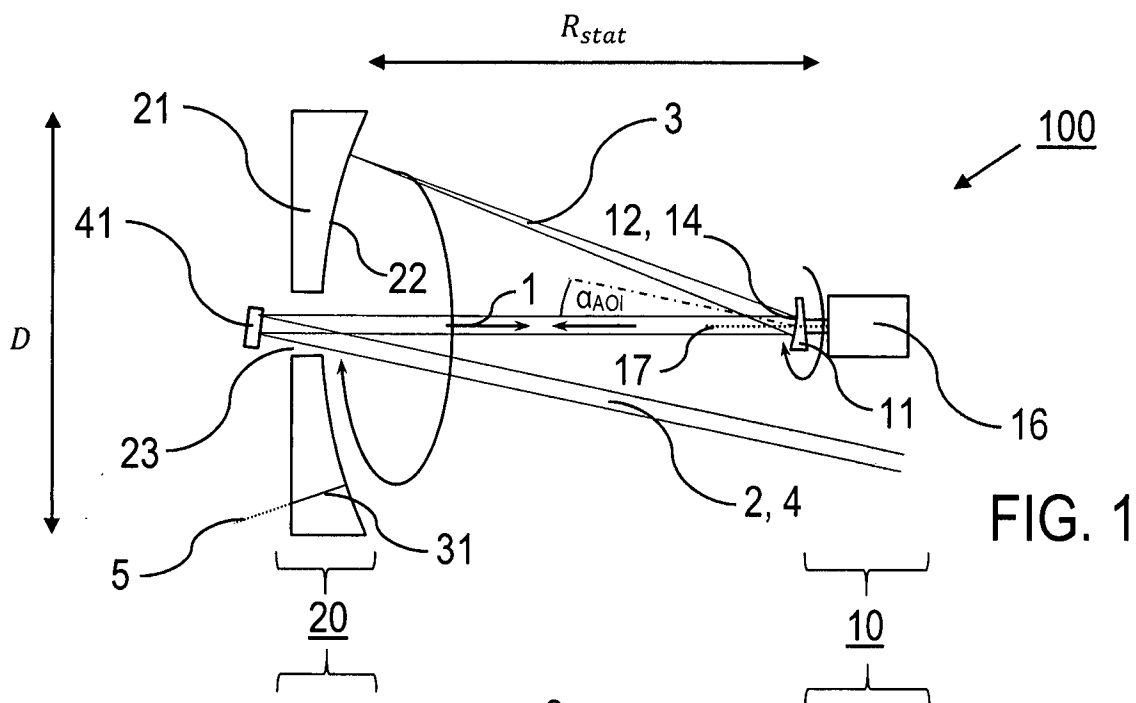


FIG. 1

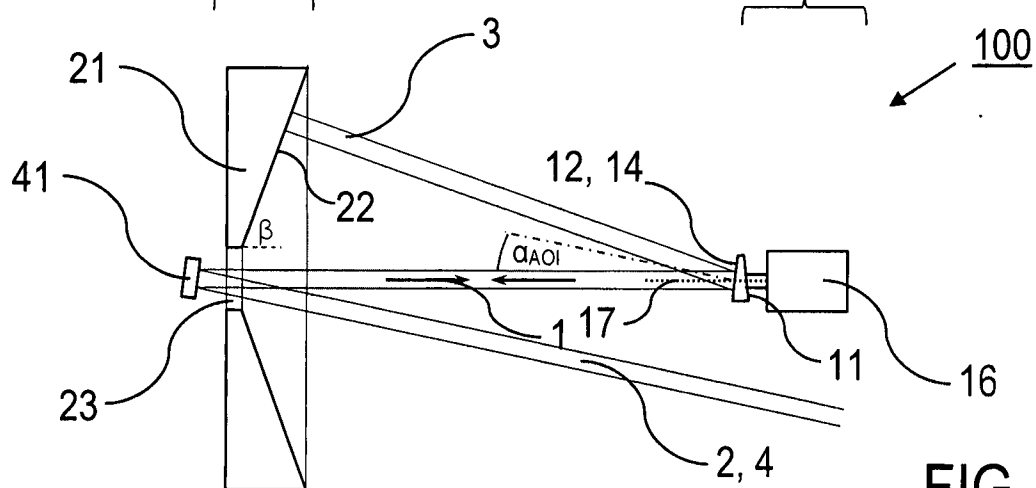


FIG. 2

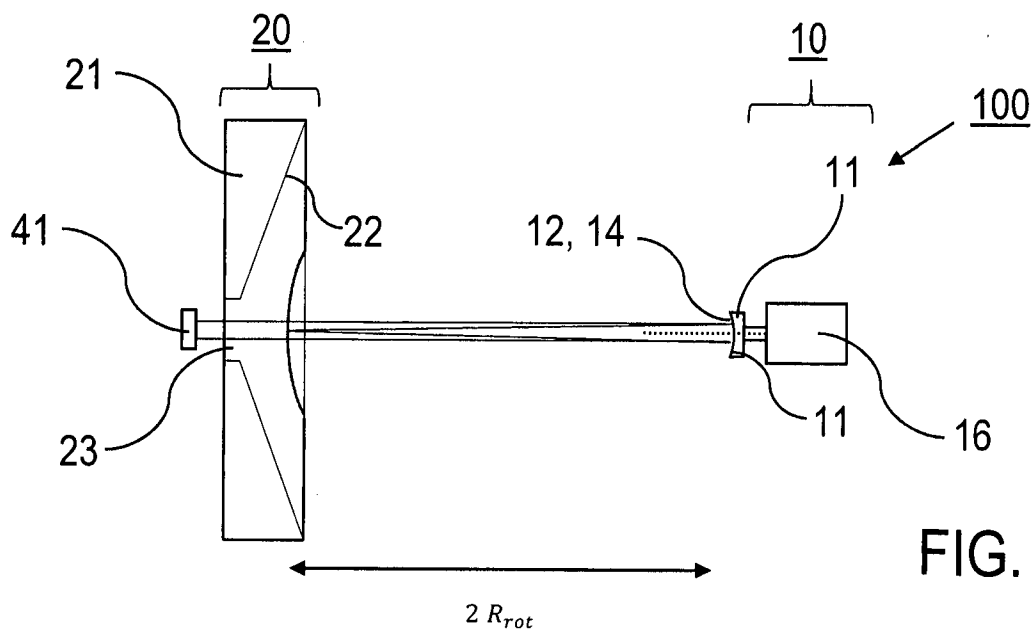
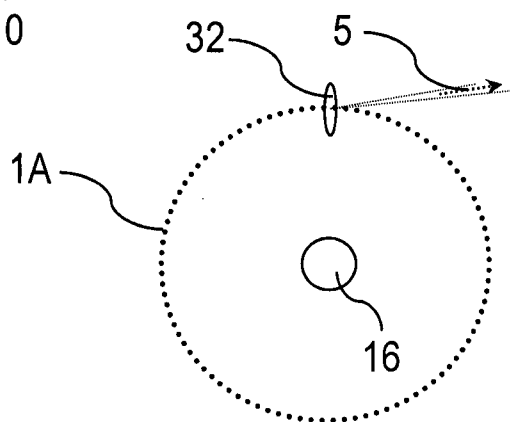
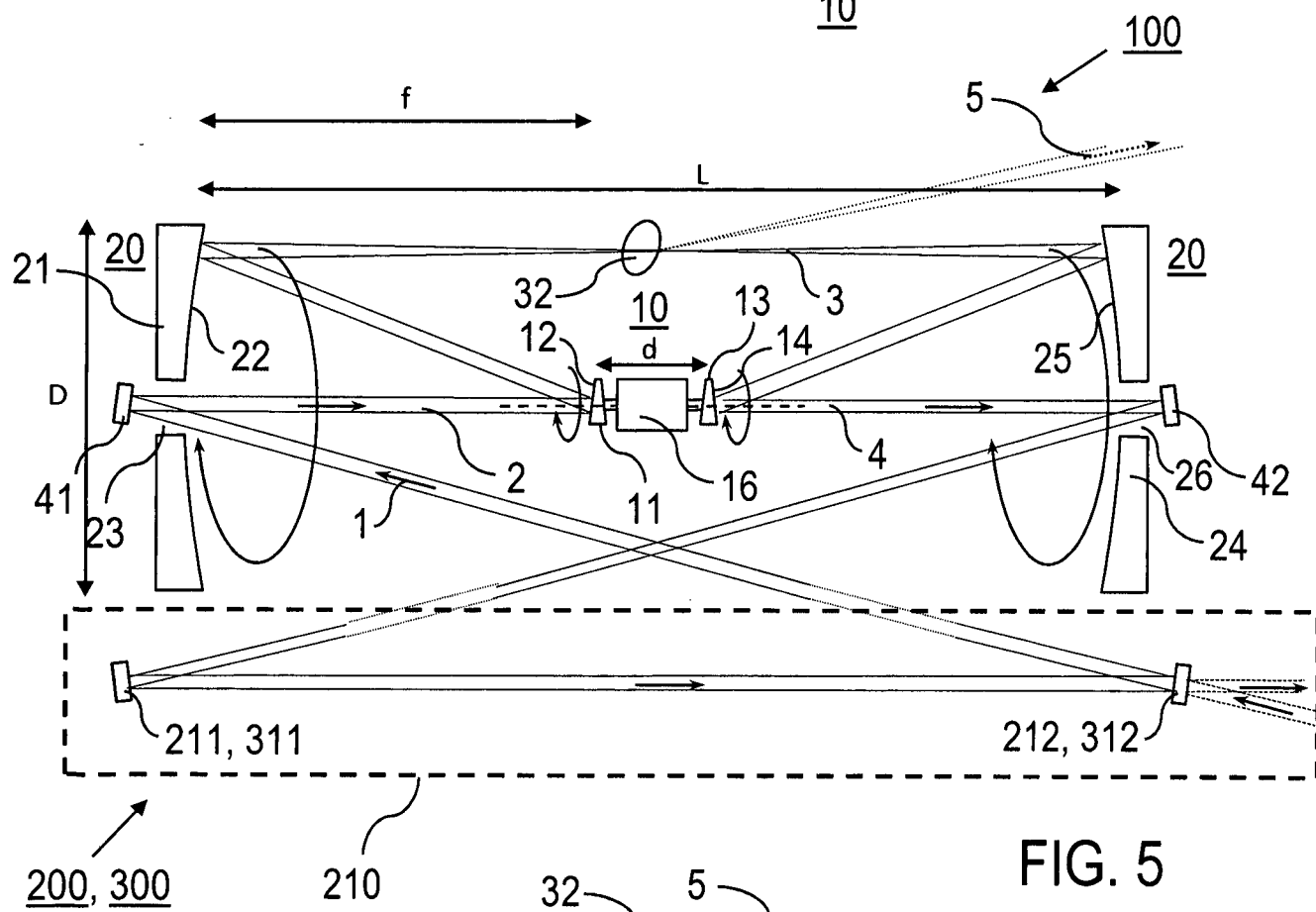
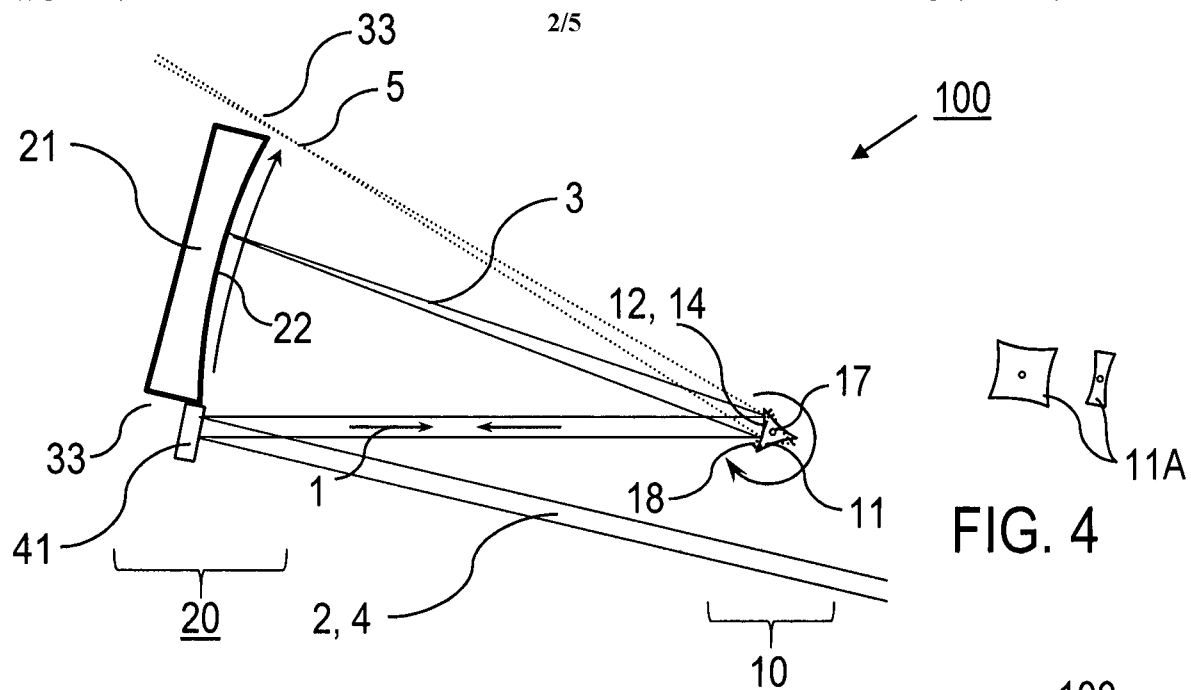


FIG. 3



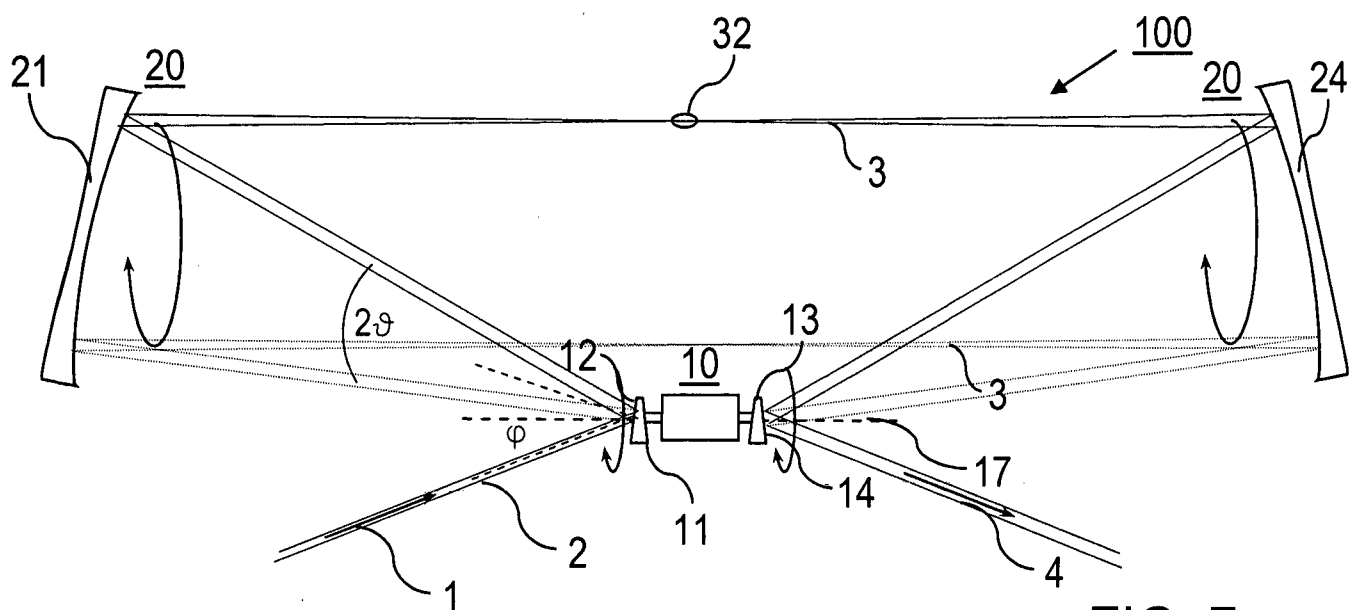


FIG. 7

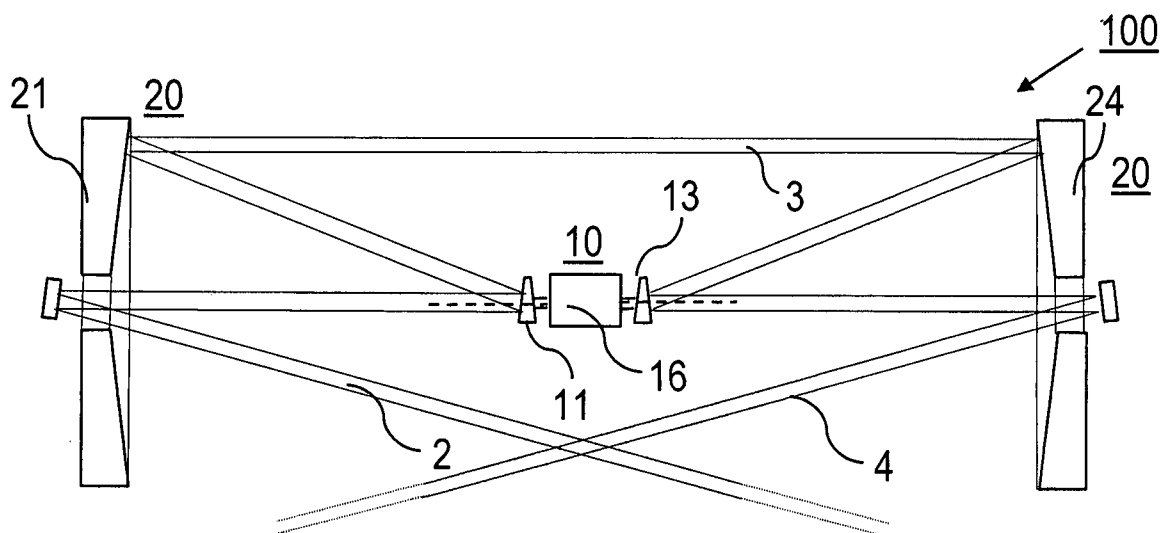


FIG. 8

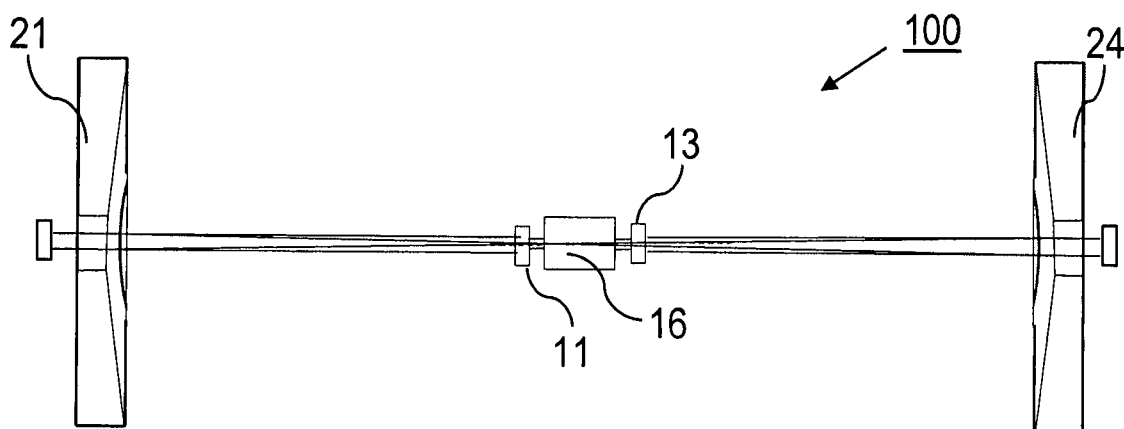


FIG. 9

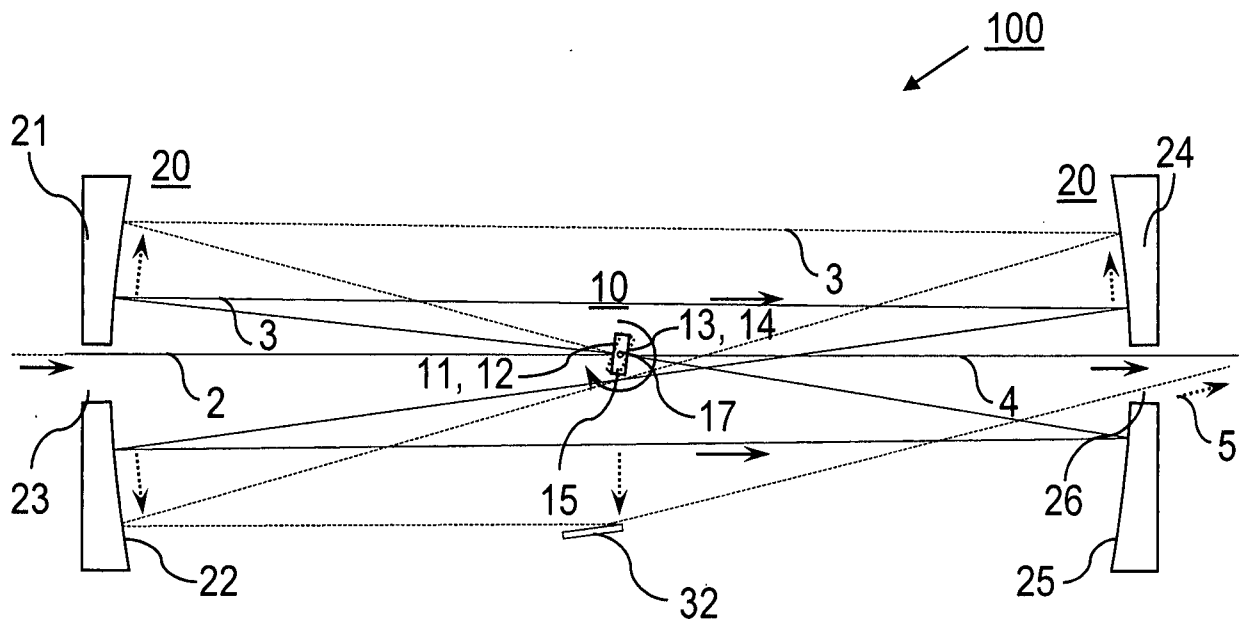


FIG. 10

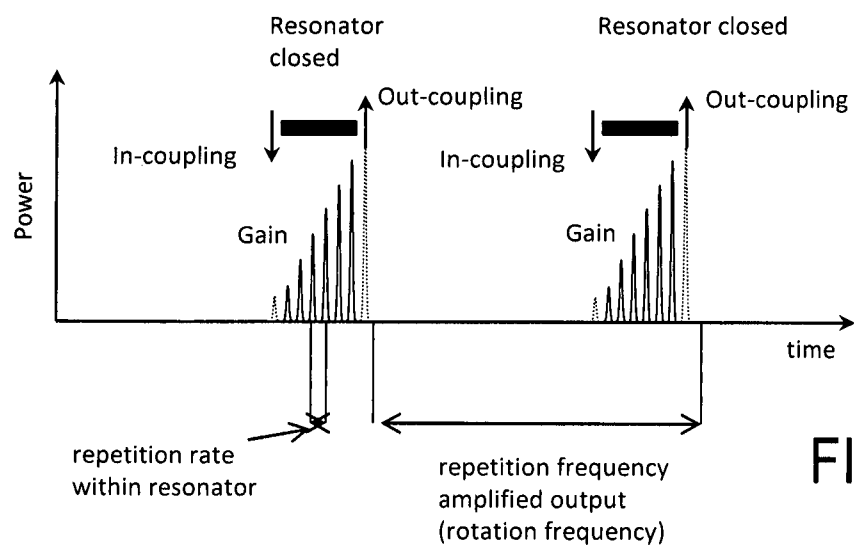


FIG. 11

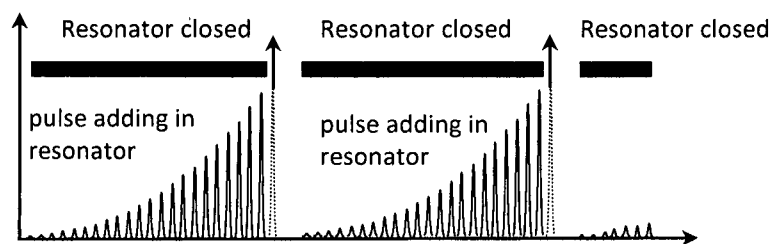
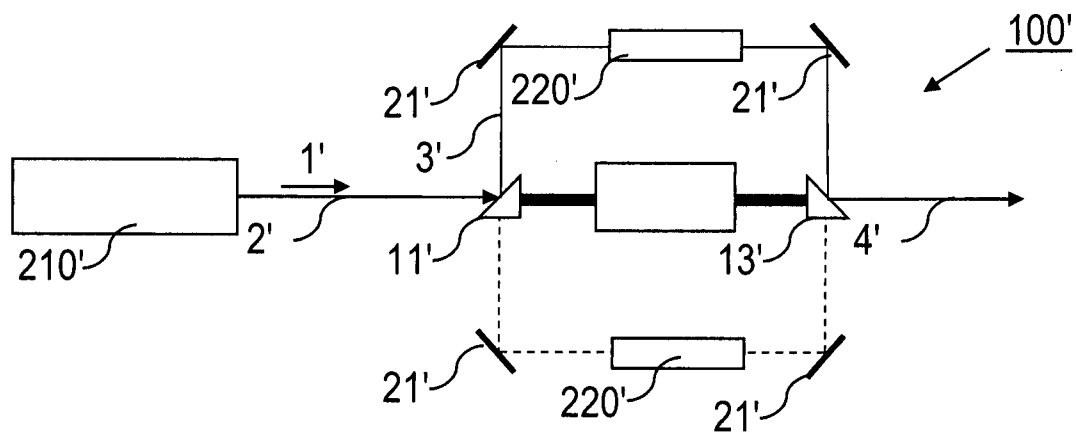


FIG. 12

FIG. 13
(Prior art)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/000966

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S3/00 H01S3/105
ADD. H01S3/08 H01S3/10 H01S3/123 H01S3/23

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 H05G

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, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2007 002888 A1 (FRAUNHOFER GES FORSCHUNG [DE]) 24 April 2008 (2008-04-24)	1-3, 5-17,19, 21,22
Y	paragraphs [0031] - [0036], [0046] - [0050]; figures 1A,4B,4D	4,18,20
Y	US 3 365 671 A (KOGELNIK HERWIG W) 23 January 1968 (1968-01-23) column 2, line 27 - column 4, line 35; figures 1,2	4,20
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Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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"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

2 February 2017

Date of mailing of the international search report

10/02/2017

Name and mailing address of the ISA/

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Authorized officer

Laenen, Robert

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2016/000966

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/000966

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