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(54) Benævnelse: **LASERINDRETNING, ISÆR TIL OFTALMOLOGISK LASERKIRURGI**

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Description

The invention relates to laser apparatuses and in particular to the testing of a scan function of a laser apparatus.

Laser apparatuses which operate using focused laser radiation to process dead or living tissue (for example, human eye tissue) frequently have controllable components which enable a scan function. Using the scan function, the radiation focus can be set precisely to different positions in a plane orthogonal to the radiation propagation direction (transversal scanning) and/or to different positions along the radiation propagation direction (longitudinal scanning). Examples of components which can be used for scanning laser radiation are pivotably arranged mirrors, deformable mirrors, electrooptical crystals, displaceably arranged lenses, lenses having variable refractive power, etc. When scan components are referred to in the scope of this disclosure, this means not only the optical components acting on the laser radiation, but rather the entirety of the components which are required for scanning of the laser radiation and which can be influenced by electrical control signals of an electronic control arrangement. Thus, the scan components in the meaning of the invention in particular also include the actuators possibly required for actuating the optical scan components, which can be controlled by the control signals of the control arrangement. Such actuators can comprise, for example, galvanometer drives, piezo drives, motorized drives, controllable voltage or current sources, etc. It is obvious that the above list of possible optical scan components and actuators is solely by way of example and is not to be understood as restrictive.

The invention proposes a preferred laser apparatus, which is intended and configured for ophthalmological laser surgery, comprising a laser source for providing laser radiation, controllable scan components for setting a focal position of the laser radiation, measuring components for acquiring information representative of an actual position of the radiation focus, and a control arrangement controlling the laser source and the scan components, said control arrangement being configured to effect a test configuration of at least some of the scan components being carried out when the laser source is switched off, according to the stipulation of a predetermined test and pattern, wherein the test scan pattern represents a plurality of discrete intended focal positions to be approached in sequence and the control arrangement is configured to stop the scan movement of the scan components at each intended focal position and establish, assigned to one of the intended focal positions, an actual focal position in each case on the basis of the acquired information from the measuring components. The test operation run is a type of dry run, in which the scan function of the laser apparatus can be checked, without laser radiation simultaneously being emitted from the laser apparatus.

Such a system is known from US2002/0193704. Appearances of aging, a long period of nonuse, or interruptions of the data transfer paths can have the result that an intended setting of the scan components recommended by the control arrangement (corresponding to a certain intended position of the radiation focus) is not precisely implemented and the actually achieved actual setting of the scan components deviates from the intended setting. When the laser source is turned on, the actual position of the radiation focus would then deviate from the intended position. This may still be acceptable in the processing of dead material because the processing can be repeated with a new workpiece if it proves that the first processing was not sufficiently precise. In the case of living tissue, for example, human eye tissue, such a procedure is not acceptable for comprehensible reasons. Carrying out a prior test operation run of the scan components can provide certainty that during the subsequent laser processing, intended and actual are actually located together sufficiently accurately, and/or it can provide clarification about the extent of possible deviations between intended and actual, so that suitable correction measures (for example, replacement of at least a part of the scan components, establishment of correction factors, and adaptation of the intended values on the basis of the correction factors) may still be initiated before the laser processing.

The test scan pattern represents a plurality of discrete intended focal positions to be approached individually, wherein the scan components (in general: the scan system) are controlled by the control arrangement such that the scan movement caused by the scan components stops at each of the intended focal positions, so that the actual focal positions are measured at a standstill. Preferably, a certain time (settling time) is waited in each case with the measurement of the actual focal position, after the scan components have reached an intended focal position. This settling time can be, for example, in the order of magnitude of one or several milliseconds. Because the measurement of the actual focal positions occurs at a standstill, it is possible to use the maximum possible measuring accuracy of the measuring components (measuring apparatus).

The intended focal positions are preferably distributed so that all regions of the nominally available scan space are covered. A voluminous prior check of the positioning accuracy of the scan function in all approachable regions of the scan space is thus possible. By selecting a number of intended focal positions which is not excessively large, the testing procedure can simultaneously be kept short, which particularly enables the test operation run to be carried out before each planned laser processing, without losing an excessively large amount of time in this case. For example, it can be sufficient to previously establish fewer than 100, better fewer than 50, and still better fewer than 20 intended focal positions, which are to be approached in the scope of the test operation run.

It is obvious that the reference to intended and actual focal positions is only used for theoretical clarification, because in the test operation run, no laser radiation falls on the scan components and accordingly no radiation focus is also present. When the laser source is turned on, the radiation focus then present would certainly assume a position which is given by the actual setting of the scan components.

The range within which the radiation focus can be adjusted is typically delimited by structural, physical, and/or control specifications. The user thus has a predefined maximum scan field available, which establishes the outer boundaries for the scan movements of the radiation focus. In embodiments which enable solely transversal focus movements, the available scan field is accordingly a transversal surface. In embodiments which enable transversal and longitudinal focus movements, in contrast, the available scan field is a three-dimensional space. The available scan field can have a circular outer boundary in the transversal case, for example. In the three-dimensional case, the available scan field can have a circular-cylindrical shape, for example.

At least in some cases, it can be that the available scan field is to be used up to close to its boundaries for an application. Not only then, but particularly then it is important to have certainty that scan components operate precisely in the edge regions of the available scan field and intended/actual deviations of the focal positions only occur in tolerable amounts, if at all. Therefore, in one preferred embodiment, at least a subset of the intended focal positions are advantageously arranged on the edge of a given maximum scan field. It is even possible that all intended focal positions are arranged on the edge of the maximum possible scan field.

The intended focal positions can comprise at least one group of focal positions which are arranged distributed in a transversal plane orthogonal to the radiation propagation direction. In this case, the intended focal positions can comprise at least one group of focal positions which are arranged along a circular line, in particular distributed at regular angular intervals, in the transversal plane. For example, it can be sufficient to only define a few intended focal positions along the circular line, for example, one intended focal position per quadrant.

In the case of longitudinal scan capability of the scan components, at least a part of the intended focal positions can be arranged distributed in the radiation propagation direction. In particular, it is conceivable that the intended focal positions comprise a plurality of groups of focal positions which are arranged distributed in various transversal planes orthogonal to the radiation propagation direction. In this case, for example, a first group of intended focal positions can be located in a first transversal plane which delimits the available scan field longitudinally in a first direction. A second group of intended focal positions can be located in a second transversal plane which delimits the available scan field longitudinally in another direction. If desired, further intended focal positions can be located in one or more transversal intermediate planes which are located between the two terminal transversal planes of the first and the second groups of intended focal positions. Alternatively or additionally, the intended focal positions can comprise a group of focal positions which are arranged along a helical line, the helical axis of which extends in parallel to the radiation propagation direction.

To obtain a measure of the positioning precision of the scan components, the control arrangement can be configured to establish deviations between the intended focal positions and the actual focal positions and to compare the determined deviations to at least one predetermined deviation threshold. In particular if the number of predetermined intended focal positions to be tested by the test scan pattern is comparatively small, for example, in the low two-digit range, the requirement can be that no positioning errors can occur, i.e., all intended/actual deviations have to be located within the boundaries given by the at least one deviation threshold.

In other cases, in contrast, a certain number of positioning errors can be tolerable. In any case, in a preferred embodiment of the invention, a highest number is predetermined for the case in which the determined deviations exceed an associated deviation threshold. This highest number can either be zero or a value different from zero. The control arrangement is preferably configured only to release operation of the laser apparatus with a switched-on laser source if only at most as many determined deviations exceed an associated deviation threshold as are predetermined by the highest number. Otherwise, the control arrangement will block the laser apparatus against operation with a switched-on laser source, so that no laser processing is possible. If the test operation run is carried out unsuccessfully, the control arrangement will accordingly enter a blocking mode, which can be embodied, for example, so that the control arrangement can leave it only after successfully carrying out another test operation run of the scan components.

The invention will be defined by the claims and explained in greater detail hereafter on the basis of the appended drawings. In the figures:
Figure 1 shows a schematic block diagram of elements of a laser apparatus according to one exemplary embodiment, and
Figure 2 shows an example of a test scan pattern, which consists of discrete intended focal positions, for the laser apparatus of Figure 1.

The laser apparatus of Figure 1 - identified in general therein with 10 - is used for the cutting processing of an object, which is shown in the exemplary case as a human eye 12, by means of ultrashort-pulse focused laser radiation. Ultrashort pulse means pulse durations in the range of femtoseconds to at most single digit picoseconds here. The effect used for the cutting processing is so-called laser-induced optical breakthrough, which results in a photodisruption inside the processed material (eye tissue here). By placing a plurality of such photo disruptions adjacent to one another, manifold cut figures can be created in the eye 12 and above all in the cornea therein.

The laser apparatus 10 comprises a femtosecond laser source 14, which provides a laser beam 16, which, after passing through an optical route, along which various elements for beam guiding and shaping are arranged, is incident as a focused laser beam 16‛ on the eye 12. The mentioned elements for beam guiding and shaping comprise a focusing optical unit 18, which is formed, for example, by an F-theta objective, and scan components 20, which are schematically indicated here by a single block.

It is to be emphasized that the illustration of the focusing optical unit 18 and the scan components 20 in Figure 1 as separate blocks is used solely for the purpose of better comprehensibility. It is readily conceivable that a part of the optical components responsible for the focusing of the laser beam 16 can also assume scan functionality. It is thus not precluded, for example, that one or more lenses contained in the focusing optical unit 18 or even the focusing optical unit 18 as a whole are adjustable for the purpose of longitudinal positioning of the beam focus in the beam propagation direction. Similarly, in a preferred embodiment, the optical components used for the scanning of the laser beam 16 are separate from the optical components used for the focusing of the laser beam 16 and as a result thereof are arranged outside the focusing optical unit 18.

For example, the scan components for the transversal scanning of the laser beam 16 can comprise a pair of rotatably arranged deflection mirrors, the rotational axes of which are perpendicular to one another, and an individually controllable galvanometer drive assigned to each of the deflection mirrors. Such galvanometrically actuated deflection mirrors are known per se in the technical world; no more detailed explanation thereof is required at this point.

For the longitudinal scanning of the beam focus, the scan components 20 can use, for example, a lens provided as part of a beam widening optical unit (not shown in greater detail), which is arranged adjustably for the purpose of divergence variation of the laser beam 16 in the beam propagation direction or is adjustable with respect to its refractive force. An associated actuator in the form of a linear drive or a controllable voltage source can then also be part of the scan components 20.

In a minimum equipment of the laser apparatus 10, the scan components 20 are designed in any case for the transversal scanning of the laser beam 16. In one preferred embodiment, the scan components 20 are additionally configured for the longitudinal scanning. Moreover, it is apparent that in addition to the mentioned exemplary embodiments of the scan components, other action principles can be used, which enable transversal and/or longitudinal scanning, for example, a control beam deflection in an electrooptical crystal or a divergence influencing of the laser beam by deformation of an optical mirror arranged in the propagation path of the laser beam 16.

The laser apparatus 10 additionally contains a processor-based control arrangement 22 for controlling the operation of the laser apparatus. The control arrangement 22 is program-controlled; the control program of the control arrangement 22 is stored in a storage arrangement 24.

Although the control arrangement 22 is shown in Figure 1 by a single block, it is apparent that its control functions can be allocated to various control modules, which can be installed on separate control circuit boards in different structural modules. Thus, the control arrangement 22 can comprise, for example, a scan control module shown by dashed lines at 22a, which is responsible for the control of the scan components 20 and is integrated together with them – or together with at least a part of the scan components 20 – in a scanner preinstalled as a separate component. The remaining control functions of the control arrangement 22 can be combined, for example, in a central control module 22b (also indicated by dashed lines), which is structurally located outside the scanner and which is responsible, *inter alia*, for the synchronization of the operation of the laser source 14 and the operation of the scan components 20 and can accordingly send control commands to the scan control module 22a to start a scan procedure. The specific positioning operations for setting the scan components 20 are then controlled by the scan control module 22a according to the stipulation of suitable scan data, which were previously loaded into the scan control module and define a scan pattern to be executed.

Corresponding to the possible allocation of the control arrangement 22 into separate control modules, the storage arrangement 24 can also be allocated into separate storage modules and also the mentioned control program can be allocated into separate program modules, which can in turn be stored in various storage modules. For example, one storage module can be integrated jointly with the scan control module 22 in the mentioned scanner, and can store those program parts which are necessary for the control of the scan components 20. One or more further storage modules, in contrast, can be assigned to the central control module 22b and can store the remaining program parts of the control program.

Furthermore, an output unit 26 in the form of a monitor is connected to the control arrangement 22, on which test results, to be explained hereafter, can be output, which are obtained in the scope of a test operation run of the laser apparatus 10. Although it is not shown in greater detail in Figure 1, alternatively or additionally to the monitor 26, a printer can be connected to the control arrangement 22, to output the mentioned test results in printed form.

Figure 1 additionally shows a three-axis coordinate cross, which spans, according to routine notation, an X-Y transversal plane orthogonal to the radiation propagation direction of the laser beam 16, while the Z axis defines the longitudinal direction of the beam propagation.

The control arrangement 22 is configured to carry out a test operation run with a switched-off laser source 14, in which the scan components 20 or at least a part thereof are controlled according to the stipulation of a predetermined test scan pattern. This dry run, in which no laser radiation is emitted by the laser source 14, is to enable a position check, by which it is to be ensured that the entire range in which the beam focus can be nominally set in the X, Y, and optionally Z directions can be approached with the best possible precision. In particular, the position check is to enable checking of possible intended/actual deviations of the focal position in the entire scan range. The maximum scan range, which is a three-dimensional space in the present case under the assumption of both transversal and also longitudinal scan capability, is also referred to here as the available scan field.

Measuring components 30, which are schematically indicated as a single block, are provided to acquire the actual setting state of at least a part of the scan components 20 metrologically and to supply corresponding measured values to the control arrangement 22. This control arrangement can calculate values for the actual position of the beam focus from the supplied measured values. For example, to acquire the actual position of a rotatable deflection mirror contained in the scan components 20, the measuring components 30 comprise a position detector, as shown and described in EP 1 295 090 B1.

The control arrangement 22 can store the calculated actual focal positions in the storage arrangement 24 in assignment to associated intended focal positions. During cutting processing of the eye 12, the intended focal positions are predetermined in tabular form, for example, by indicating the respective X, Y, and Z values. After completion of the cutting processing of the eye 12, the control arrangement 22 can compare the actual values of the focal position determined in the meantime to the associated intended values and can output corresponding information via the monitor 26 or a connected printer. The operator or an automatically operating analysis program can determine on the basis of the results of the intended/actual comparisons whether the scan system operates with the required high precision in the entire available scan space.

The above-mentioned test operation run is advantageous above all (but not only) if measured values for the actual focal position can be recorded and stored during the scan operation of the laser apparatus 10 by means of the measuring components 30, but the laser apparatus 10 is not configured to analyze the actual focal positions during the scan operation with respect to deviations from the associated intended focal positions and to engage correctively if needed, if impermissibly large deviations occur. Such conditions can exist, for example, if the intended and actual data of the focal positions during a scan procedure cannot be transmitted from the scan control module 22a to the central control module 22b, but rather the central control module 22b only receives access to these data after completion of the scan procedure. The test operation run thus enables a previous check of the positioning quality of the scan components 20. Depending on the results of the test operation run, it can be shown that the scan precision in the available scan field is sufficiently high to carry out planned eye processing, or measures such as a replacement of at least a part of the scan components can be necessary, if the scan accuracy should prove to be inadequate.

The test operation run can be carried out by the control arrangement 22, for example, in reaction to a start command input by a user to carry out laser processing (for example, to create a flap incision in the scope of a LASIK operation of the eye 12), wherein the control arrangement only begins the laser processing when the test operation run has successfully been carried out beforehand. Otherwise, for example, it can output a suitable warning message on the monitor 26, which notifies the operator that the test operation run was unsuccessful and therefore the planned laser processing cannot be carried out.

Reference is now additionally made to Figure 2 for the explanation of the test scan pattern executed in the scope of the test operation run. The test scan pattern is composed of a plurality of discrete intended focal positions 32, the X, Y, and Z coordinate values of which were previously loaded into the control arrangement 22 and in particular into the scan control module 22a therein. In the scope of the test operation run, the scan components 20 are set so that the predetermined intended focal positions are approached in rapid succession. The scan components 20 are continuously controlled in this case until an intended focal position is reached. The control of the scan components 20 then stops for a short time, before the scan components 20 are adjusted again to approach the next intended focal position. The adjustment procedure of the scan components 20 is thus a step-by-step process, in contrast to continuously traveling down a predefined path.

In the example shown in Figure 2, the intended focal positions 32 are allocated to a plurality (three here) of groups which are each assigned to an X-Y transversal plane. The intended focal positions 32 of the relevant group are arranged distributed along an imaginary circular line 34 at regular angular intervals in each transversal plane. The imaginary circular lines 34 are indicated by dashed lines in Figure 2. In the example of Figure 2, a total of four intended focal positions 32 are predetermined per circular line 34, i.e., one intended focal position per quadrant. It is apparent that the number of the intended focal positions 32 per transversal plane can deviate therefrom, in particular can also be greater. It is also apparent that notwithstanding the example shown, where the number of the intended focal positions 32 in each transversal plane is equal, this number can be different for various transversal planes.

The intended focal positions 32 are located longitudinally one over another in the various transversal planes in the example of Figure 2, i.e., they are congruent with one another in the Z direction. This is also not a requirement; it is readily conceivable to select an arrangement picture of the intended focal positions 32 which is angularly offset in relation to one another from transversal plane to transversal plane.

The chronological sequence in which the intended focal positions 32 are approached can be selected arbitrarily per se. It is advantageous if firstly all intended focal positions are approached in one transversal plane, before changing to the next transversal plane. Within one transversal plane, the intended focal positions can be approached individually in succession along the relevant circular line 34, for example.

Under the assumption of a circular-cylindrical available scan field (i.e., a scan field, the transversal outer boundary of which is circular), the circular lines 34 can extend on the outer boundary of this available scan field, for example, so that the intended focal positions 32 are used above all to test the scan precision at the outer boundaries of the available scan field. It is similarly conceivable to arrange the intended focal positions 32 within the available scan field at a distance from its outer boundaries, if a position check of the inner regions of the available scan field is desired.

As soon one of the intended focal positions 32 has been approached and a short-term control stop of the scan components 20 takes place, the actual focal position is acquired by means of the measuring components 30 and stored in assignment to the relevant intended focal position 32. The measurement thus takes place at a standstill of the scan system, i.e., during a stop of the scan movement. To eliminate settling procedures in the measurement result, after reaching an intended focal position, a certain time is preferably also waited before the measurement is carried out, for example, several milliseconds.

The scan movement is then continued and the next intended focal position is approached. This is repeated successively for all intended focal positions 32. It can be sufficient to only consider and store one or two coordinates instead of all three coordinates of the X-Y-Z coordinate system for the intended focal positions 32 and/or the actual focal positions. For example, it can be sufficient for the intended focal positions 32 of the test scan pattern according to Figure 2 to only represent the intended focal positions and/or the actual focal positions by the Z coordinate value and a transversal coordinate value, such as the X coordinate value. If the laser apparatus 10 enables it, however, it can be desirable to register all three coordinate values for all intended focal positions 32 and associated actual focal positions.

After execution of the test scan pattern, the control arrangement 22 performs an analysis of the acquired actual focal positions with regard to deviations from the intended focal positions. For this purpose, it compares the deviations found to at least one predetermined threshold. For example, the control arrangement 22 can individually ascertain the deviations between the intended focal positions and the actual focal positions separately for each coordinate axis and compare them to an assigned deviation threshold. The deviation threshold to be applied can be equal for the coordinate axes or can be different for different coordinate axes. If desired, the control arrangement 22 can additionally ascertain a total deviation from the deviations found along the individual coordinate axes, for example, like the Euclidean distance. It can also compare the total deviation thus found to an assigned deviation threshold. It is apparent that each deviation threshold can either be fixedly predetermined or can be selectable by the user via an input unit (not shown in greater detail), which is connected to the control arrangement 22.

In the best case, all actual focal positions are located within the given deviation limits. As soon at least one actual focal position deviates by an impermissibly large amount from the assigned intended focal position 32, the control arrangement 22 causes the output of a warning message on the monitor 26. The warning message communicates to the user that the scanning precision is inadequate. As a further reaction, the control arrangement 22 can enter a blocking mode, which prevents operation of the laser apparatus 10 with switched-on laser source 14. The control arrangement 22 only leaves the blocking mode again and enables the operation of the laser apparatus 10 with switched-on laser source 14 after successfully carrying out a further test operation run, in which all acquired actual focal positions have remained within the given deviation limits.

Alternatively or additionally, the control arrangement 22 can be configured to output the acquired actual focal positions together with the intended focal positions and/or the ascertained intended/actual deviations without further analysis on the monitor 26 or in another form. In this case, the evaluation of the test result can be left to the user.

The test operation run thus explained is used for checking the static behavior of the scan system, in particular the precision of the position finding, and additionally to check whether all signal paths still operate correctly, for example, an analog signal line from a driver circuit board to a scanner servo and a return channel from an encoder (part of the measuring components 30) to the control arrangement 22.

Patentkrav

1. Laserindretning, især til oftalmologisk laserkirurgi, der omfatter
- en laserkilde (14) til tilvejebringelse af laserstråling,
- styrbare scanningskomponenter (20) til at indstille en position for fokus af laserstrålingen,
- målekomponenter (30) til at opsamle information, der er repræsentativ for en aktuel position for fokus af laserstrålingen,
- en styreindretning (22), der styrer laserkilden (14) og scanningskomponenterne (20), hvilken styreindretning er konfigureret til at forårsage en prøvekørsel af mindst nogle af scanningskomponenterne, der udføres, når laserkilden er slukket, ifølge bestemmelsen for et forudbestemt afprøvningsscanningsmønster,
hvori afprøvningsscanningsmønsteret repræsenterer et antal diskrete beregnede positioner for fokus (32), der skal tilnærmes sekventielt, og styreindretningen (22) er konfigureret til at stoppe scanningsbevægelsen af scanningskomponenterne (20) ved hver beregnet position for fokus og etablere, tildelt til hvert af de beregnede positioner for fokus, en faktisk position for fokus i hvert tilfælde på grundlag af den indsamlede information fra målekomponenterne (30), hvor styreindretningen (22) er konfigureret til at etablere afvigelser mellem de beregnede positioner for fokus (32) og de faktiske positioner for fokus,
kendetegnet ved, at styreindretningen endvidere er konfigureret
til at sammenligne de etablerede afvigelser med tærskelværdien for mindst en forudbestemt afvigelse og kun at frigive kørsel af laserindretningen med en tændt laserkilde (14), hvis ikke mere end et forudbestemt maksimalt antal af de etablerede afvigelser overstiger en tærskelværdi for en tilknyttet afvigelse.

2. Laserindretning ifølge krav 1, hvor de beregnede positioner for fokus (32) omfatter mindst én gruppe af

positioner for fokus, der er arrangeret fordelt i et tværplan vinkelret på strålingens udbredelsesretning.

3. Laserindretning ifølge krav 2, hvor de beregnede positioner for fokus (32) omfatter mindst én gruppe af positioner for fokus, der er arrangeret langs en cirkulær linje (34) i tværplanet, fortrinsvis fordelt med regelmæssige vinkelintervaller.

4. Laserindretning ifølge et af kravene 1 til 3, hvor mindst nogle af de beregnede positioner for fokus (32) er arrangeret fordelt i strålingens udbredelsesretning.

5. Laserindretning ifølge krav 4, hvor de beregnede positioner for fokus (32) omfatter et antal grupper af positioner for fokus, der er arrangeret fordelt i forskellige tværplaner, som er ortogonale til strålingens udbredelsesretning.

6. Laserindretning ifølge et af kravene 1 til 5, hvor mindst en delmængde af de beregnede positioner for fokus (32), hvis det ønskes alle de beregnede positioner for fokus, er arrangeret på kanten af et givet maksimalt scanningsfelt.

7. Laserindretning ifølge et af de foregående krav, hvor styreindretningen (22) er konfigureret til kun at frigive kørsel af laserindretningen med en tændt laserkilde (14), hvis ingen af de etablerede afvigelser overstiger tærskelværdien af den tilknyttede afvigelse.

FIG 1

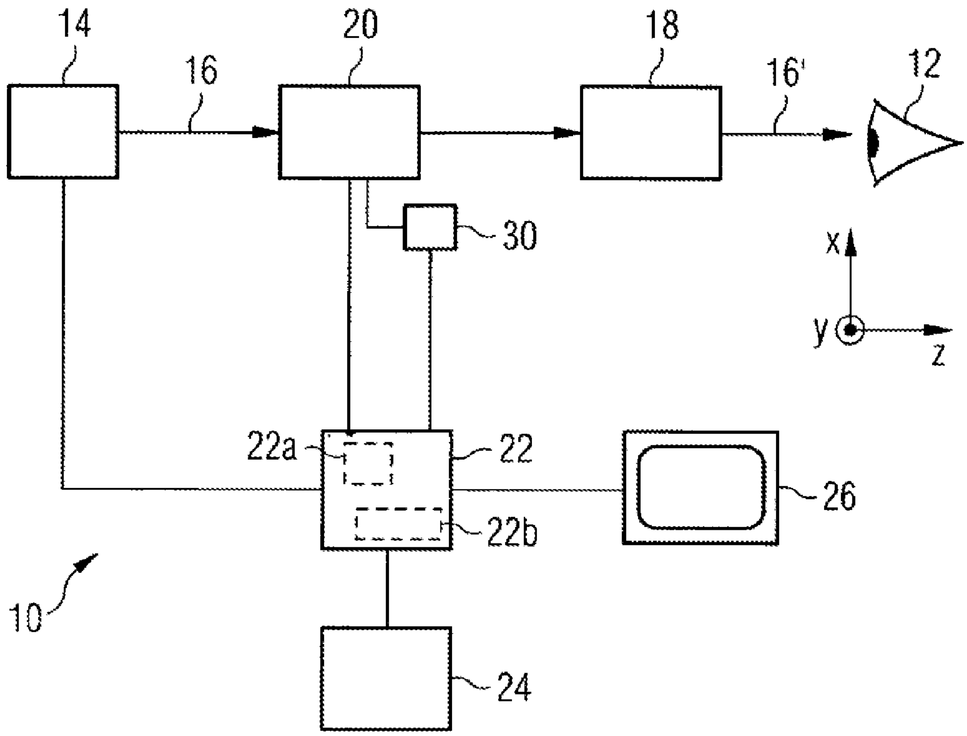

FIG 2