



US 20190165543A1

(19) **United States**

(12) **Patent Application Publication**
KRIJN et al.

(10) **Pub. No.: US 2019/0165543 A1**

(43) **Pub. Date: May 30, 2019**

(54) **EYE-SAFE LASER-BASED LIGHTING**

F21K 9/64 (2006.01)

H01S 5/00 (2006.01)

F21V 23/04 (2006.01)

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(52) **U.S. Cl.**

CPC *H01S 5/0683* (2013.01); *H01S 5/06808*
(2013.01); *H01S 5/06825* (2013.01); *F21Y*
2115/30 (2016.08); *H01S 5/005* (2013.01);
F21V 23/0457 (2013.01); *F21K 9/64*
(2016.08)

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(21) Appl. No.: **16/263,698**

(57)

ABSTRACT

(22) Filed: **Jan. 31, 2019**

Related U.S. Application Data

(62) Division of application No. 14/848,306, filed on Sep. 8, 2015, which is a division of application No. 13/001,858, filed on Dec. 29, 2010, now abandoned, filed as application No. PCT/IB2009/052837 on Jun. 30, 2009.

Foreign Application Priority Data

Jul. 7, 2008 (EP) 08104656.7

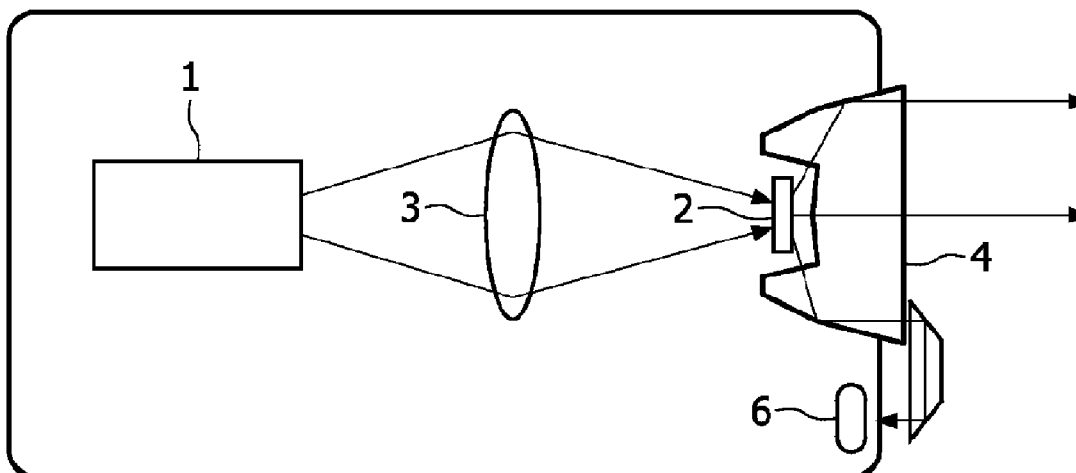
Publication Classification

(51) **Int. Cl.**

H01S 5/0683 (2006.01)

H01S 5/068 (2006.01)

A laser-based light source includes a laser device configured to generate laser light of a predetermined laser wavelength and emit this laser light as a laser beam. A light-conversion device is configured to convert at least part of the laser light into converted light and a laser-output sensor is configured to determine a laser-output signal proportional to the output of laser light emitted by the laser device. Further, a converted-light sensor is configured to determine a converted-light signal proportional to the output of converted light emitted by the light-conversion device. A controller is configured to receive the laser-output signal and the converted-light signal, to determine a safe-to-operate parameter, based on the laser-output signal and the converted-light signal, and to control the operation of the laser-based light source based on a comparison of the safe-to-operate parameter with a at least one predefined threshold.



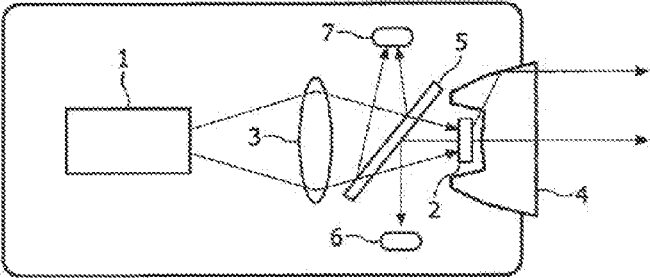


FIG. 1

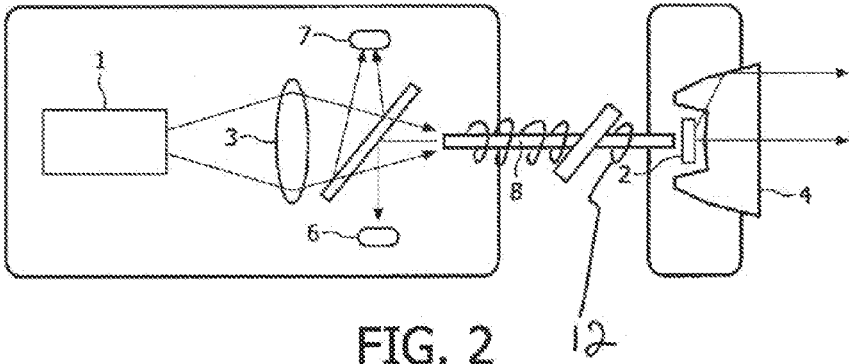


FIG. 2

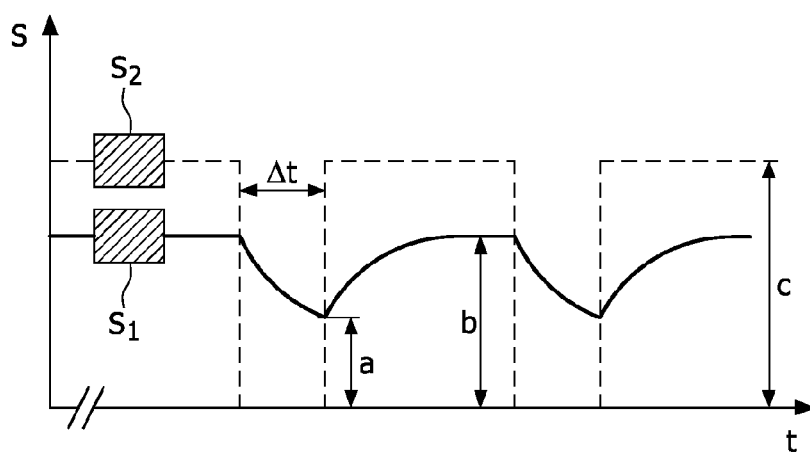


FIG. 3

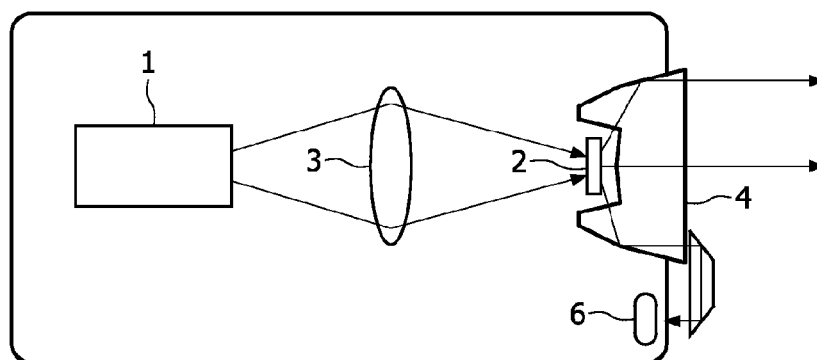


FIG. 4

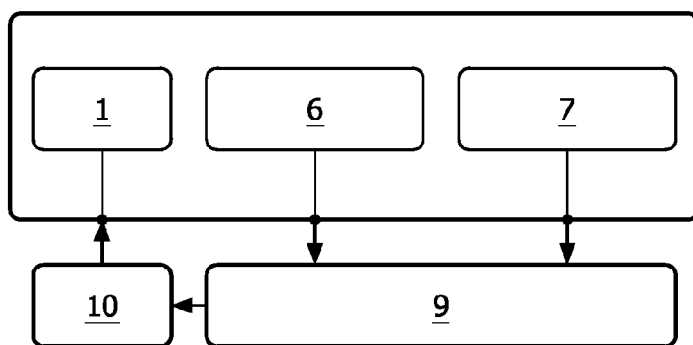


FIG. 5

EYE-SAFE LASER-BASED LIGHTING**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This application is a divisional of pending U.S. patent application Ser. No. 14/848,306, filed Sep. 8, 2015, which is a divisional of prior U.S. patent application Ser. No. 13/001,858, filed Dec. 29, 2010, which is a national application of PCT Application No. PCT/IB2009/052837, filed Jun. 30, 2009 and claims the benefit of European Patent Application No. 08104656.7, filed Jul. 7, 2008, the entire contents of each of which are incorporated herein by reference thereto.

FIELD OF THE INVENTION

[0002] The invention relates to the field of a laser-based light source and a method of operating the same, and especially to eye-safe laser-based lighting.

BACKGROUND OF THE INVENTION

[0003] During the last decades, thanks to the advances of semiconductor technology, LEDs (Light Emitting Diodes) have become more and more important in lighting applications. Technological breakthroughs in high-power LEDs have opened the door to new lighting concepts driven by miniaturization, lifetime, efficiency and sustainability.

[0004] Compared to LEDs, the advantage of lasers is their much higher brightness. Semiconductor lasers have started to become available in output powers of several Watts, thus enabling a high lumen output. Laser light by itself will not be of much use for illumination since the laser beam is too bright to be eye-safe, too monochromatic for faithful colour reproduction and will result in annoying speckle due to its coherence. A convenient way to resolve these issues is to produce a light source by converting part of the laser light into broadband light via phosphor conversion.

[0005] In nearly all white-light emitting LEDs, a blue emitter is combined with a yellow-light emitting phosphor. By pumping the yellow phosphor with blue light, part of the blue light is converted into broadband yellow light. This yellow light in combination with the remaining blue light renders white light. The colour temperature can be tuned by tuning the phosphor composition and by tuning the ratio of phosphor converted light and remaining blue pump light.

[0006] In the same manner, a blue light emitting laser diode can be used to pump a yellow phosphor to generate white light. Alternatively, a near-UV diode laser can be used to pump a phosphor that emits white light or light of a specific colour. Yet another alternative is to use a red or near-IR laser diode in combination with an upconversion phosphor to generate white light or light of a specific colour.

[0007] Such laser-based light sources relying on phosphor conversion have the advantage that they can be much brighter than the brightness achievable with LEDs: with a laser one can achieve a much higher optical power density at the phosphor than with LEDs. Such light sources are ideal for automotive headlamps and spot-lights. However, one critical issue with laser-based lighting is the fact that the light source should adhere to strict legislation and be eye-safe under all circumstances, even when tampered with.

SUMMARY OF THE INVENTION

[0008] It is an object of the invention to provide a laser-based light source and a method of operating the same, which enable reliable eye-safety to be achieved in an easy way.

[0009] This object is achieved by a laser-based light source, comprising

[0010] a laser device adapted for generating laser light of a predetermined laser wavelength and emitting this laser light as a laser beam;

[0011] a light-conversion device for converting at least part of the laser light into converted light;

[0012] a laser-output sensor for determining a laser-output signal being correlated with the output of laser light emitted by the laser device;

[0013] a converted-light sensor for determining a converted-light signal being correlated with the output of converted light emitted by the light-conversion device; and

[0014] a controller which is adapted for receiving the laser-output signal and the converted-light signal, for determining a safe-to-operate parameter based on the laser-output signal and the converted-light signal, and for controlling the operation of the laser-based light source based on a comparison between the safe-to-operate parameter and at least one predefined threshold.

[0015] The invention is applicable for different types of light-conversion devices. Especially, as light-conversion devices, phosphors as described above, but also up-conversion materials, are preferred, i.e. devices which convert the light to light of another wavelength. But also materials that do not alter the wavelength but the beam properties, e.g. scattering devices, are preferred. Especially the use of a scattering device is advantageous, since this allows reducing the coherence of the beam and, thus, reduces speckle.

[0016] Accordingly, the invention is based on monitoring a signal being correlated with the laser output and a signal being correlated with the amount of converted light. The correlation between the signals and the laser output and/or the amount of converted light may be linear, exponential, logarithmic or the like. In case it is detected on the basis of these signals that a predefined safe-to-operate parameter falls below or exceeds a predefined threshold, the operation of the laser-based light source is automatically adapted accordingly. Situations in which the laser-based light source would be unsafe to operate are when the package of the light source is opened, when an optical component of the light source is removed, when phosphor degradation or phosphor removal occurs, when the position of any component or light-conversion device has moved beyond a predefined tolerance value, or when a light-guiding part, e.g. an optical fiber, is cut or damaged etc.

[0017] In general, different types of sensors can be used as laser-output sensor or converted-light sensor. However, according to a preferred embodiment of the invention, the laser-output sensor is formed by a laser-light photodiode adapted for receiving at least a part of the laser light. With respect to this, it is preferred to use a beam splitter in order to direct a part of the laser light emitted by the laser device to the laser-light photodiode. In this way, a direct measurement of the laser output can be achieved. Additionally or alternatively, the laser-output sensor is preferably formed by a laser driving current monitor adapted for monitoring the laser driving current. With respect to this, it is especially

preferred to monitor the laser driving current, which is typically proportional to a laser output, apart from a threshold current.

[0018] Further, it is preferred that the converted-light sensor is adapted to receive at least a part of the converted light. The converted light sensor may be a photodiode or the like. For that reason, preferably light emitted by the light-conversion device in a direction back to the laser is used. Further, it is preferred to use a beam splitter, preferably the same beam splitter as used for the laser light, in order to direct part of the light emitted by the light-conversion device to the converted-light sensor.

[0019] Generally, the laser light can be directly coupled into the light-conversion device. However, according to a preferred embodiment of the invention, at least one optical fiber is provided which is adapted for guiding the laser light to the light-conversion device. This makes it possible to place the light-conversion device at a greater distance from the laser device. Further, it is preferred that an optical fiber is provided which is adapted for guiding at least part of the converted light in a direction back from the light-conversion device to the converted-light sensor. Especially, the same optical fiber can be used for guiding the light to the light-conversion device and back, or a separate return fiber can be used for the way back. Furthermore, a single fiber or a plurality of fibers can be used to form a fiber.

[0020] The converted-light sensor can be arranged at different positions. According to a preferred embodiment of the invention, the converted-light sensor is arranged at the end of the fiber which is remote from the light-conversion device. Alternatively, according to a preferred embodiment of the invention, the converted-light sensor is arranged at a position along the fiber, and an outcoupling device is provided for coupling the converted light out of the fiber and into the converted-light sensor. Furthermore, it is preferred to tap laser light at at least one point along the fiber and guide this light to a remote light-conversion device.

[0021] Moreover, when an optical fiber is used, according to a preferred embodiment of the invention, the optical fiber is provided with electrical wiring for detecting damage of the optical fiber. With respect to this, it is especially preferred that conducting wires are wound around the optical fiber, and when a wire is cut or when the capacity changes, it is detected that the fiber might be broken. In this case, a warning can be given and/or the laser device and, thus, the complete light source are preferably shut down.

[0022] Finally, it should be emphasized that according to a preferred embodiment of the invention, the light source is enclosed to prevent tampering and to preclude as much as possible that external stray light, e.g. daylight or artificial light, enters and influences the output signals of the laser-output sensor and the converted-light sensor.

[0023] The above-mentioned object is further addressed by a method of operating a laser-based light source, comprising the following steps:

[0024] generating laser light of a predetermined laser wavelength and emitting this laser light as a laser beam;

[0025] converting at least part of the laser light into converted light;

[0026] determining a laser-output signal being correlated with the output of emitted laser light;

[0027] determining a converted-light signal being correlated with the output of converted light; and

[0028] determining a safe-to-operate parameter based on the laser output signal and the converted light signal;

[0029] comparing the safe-to-operate parameter with at least one predefined threshold; and

[0030] controlling the operation of the laser-based light source, based on the comparison of the safe-to-operate parameter with the predefined threshold.

[0031] According to a preferred embodiment of the invention, the converted light is light of another wavelength or/and light with other beam characteristics.

[0032] According to a preferred embodiment of the invention, this method further comprises the step of comparing the safe-to-operate parameter with a second predefined threshold. In other words, according to this preferred embodiment of the invention, it is checked whether the safe-to-operate parameter lies within or outside a predefined range.

[0033] Further, it is preferred that the method comprises the step of determining the safe-to-operate parameter, based on a ratio between the laser-output signal and the converted-light signal. Furthermore, it is preferred that the step of determining the safe-to-operate parameter is based on the derivative with respect to time of the ratio between the laser-output signal and the converted-light signal. With these ratios it can be ascertained in an easy and reliable way whether the light source is safe to operate.

[0034] In general, the laser light can be emitted in a constant and continuous way. However, according to a preferred embodiment of the invention, the method comprises the steps of modulating the emitted laser light in time, and determining the safe-to-operate parameter based on a ratio of the laser-output signal and the converted-light signal at different points in time.

[0035] According to another preferred embodiment of the invention, the step of controlling the operation of the laser-based light source, based on the comparison of the safe-to-operate parameter with the predefined threshold, comprises shutting down laser emission or/and generating a warning. In this way, a user of the light source is at least warned that handling the damaged light source might be dangerous, and if laser emission is shut down, there is no longer a risk of eye-injury due to the laser beam. Since, according to the invention, the laser-output signal and the converted-light signal are determined, it is especially preferred that the light output of the laser-based light source is stabilized on the basis of the determined laser-output signal or/and the determined converted-light signal. This can especially be done using a closed control loop for controlling the laser-output in dependence on the determined laser-output signal or/and the determined converted-light signal, i. e. the conversion rate.

[0036] Finally, it should be mentioned that it is especially preferred that the laser device is a diode laser. Furthermore, since many diode lasers have a built-in photodiode to monitor the laser output, this built-in photodiode is preferably used as the laser-output sensor, which means that no additional sensor is necessary for this purpose.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

[0038] In the drawings:

[0039] FIG. 1 schematically depicts an embodiment according to the invention;

[0040] FIG. 2 schematically depicts another embodiment of the invention;

[0041] FIG. 3 depicts modulation of the laser output and the corresponding converted light according to another embodiment of the invention;

[0042] FIG. 4 schematically depicts another embodiment of the invention; and

[0043] FIG. 5 schematically depicts a block diagram according to another embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0044] A first embodiment according to the invention is schematically depicted in FIG. 1. Laser light is generated by a laser device 1, i.e. a diode laser, e.g. in an edge-emitting geometry or a vertical-cavity surface-emitting geometry (VCSEL). This laser light is directed via optics 3 to a volume of phosphorous material of a light-conversion device 2 which is in a powdered or crystalline, preferably polycrystalline, state. The laser device 1 emits blue light, preferably around 445 nm. The light-conversion device 2 converts the blue laser light into broadband yellow light. The combination of this yellow light and the remainder of the blue light results in white light. The white light generated in this way is shaped into a beam by means of collimating optics 4.

[0045] Some of the light generated by the light-conversion device 2 as well as some of the laser light is redirected towards the laser device 1. A beam splitter 5 at an angle of 45° is used to direct a fraction of this light towards a converted-light sensor 6 which is formed by a photodiode. A small fraction of the blue laser light is directed towards a laser-output sensor 7 which is formed by another photodiode. The beam splitter 5 may be a simple thin piece of glass or a dichroic filter reflecting the yellow light generated by the light-conversion device 2 and transmitting the blue light of the laser device 1. Also the photodiodes may be equipped with colour filters in order to enhance the selectivity for either the laser-converted light or the phosphor-converted light.

[0046] By monitoring the signal generated by converted-light sensor 6 and laser-output sensor 7, preferably after further filtering and amplifying, it is determined whether the light-source is safe to operate or not. For example, as long as the ratio of the phosphor output and the laser output lies within a lower and an upper predefined threshold, respectively, the laser device 1 can be considered to be safe to operate. Similarly, when the modulus of the derivative in time of the ratio of the phosphor output and the laser output exceeds a predefined threshold, the laser device 1 might be considered to be unsafe to operate and is switched off.

[0047] Another embodiment according to the invention is schematically depicted in FIG. 2. In this case, the location of laser light generation is decoupled from the location of light conversion. An optical fiber 8 is used to transport the laser light towards the remote light-conversion device 2. Part of the light generated by the remote light-conversion device 2 is sent back through the fiber towards converted-light sensor 6. Alternatively, a separate return fiber (not shown) can be used. As shown in FIG. 2, the optical fiber is provided with electrical wiring 12 for detecting damage of the optical fiber. With respect to this, it is especially preferred that conducting wires 12 are wound around the optical fiber, and when a wire is cut or when the capacity changes, it is detected that the

fiber might be broken. In this case, a warning can be given and/or the laser device and, thus, the complete light source are preferably shut down.

[0048] The principle of operation of a still other embodiment is explained in the following with reference to FIG. 3. The light output from the laser device 1 as measured by laser-output sensor 7 is modulated in time, which is shown by the dotted line (signal Sz in FIG. 3). The signal measured by the phosphor-output detector looks like the solid line (signal Si) in FIG. 3 since a phosphor has a finite response time, given by a decay time. The detected phosphor output is proportional to the phosphor-converted yellow light generated and might contain a fraction of the blue laser light. By monitoring for example the signal strengths a and b of the detected phosphor output at different points in time, relative to the strength c of the laser output, as depicted in FIG. 3, it can be ascertained whether the light source is safe to operate.

[0049] Alternatively, the laser output can be modulated in a periodic fashion. Due to the finite response time of the phosphor, the signal measured by the converted-light sensor 6 is delayed in phase relative to the signal measured by the laser-output sensor 7. Monitoring the modulation depth of the detected signals as well as the phase delay between them provides sufficient information to ascertain whether the light source is safe to operate.

[0050] Still another embodiment according to the invention is shown in FIG. 4. In this embodiment, only one photodiode is provided which forms the converted-light sensor 6. The role of the other photodiode in the embodiments described above is taken over by monitoring the driving current of the laser device 1. This current is proportional to the laser output, apart from a threshold current.

[0051] Finally, a general schematic block diagram of the laser-based light source according to an embodiment of the invention is shown in FIG. 5. Part of the light emitted by the laser device 1 and part of the light converted by the light-conversion device 2 is detected by a laser-output sensor 7 and a converted-light sensor 6, respectively, as has been described above. These signals are read by a controller 9, which controls a laser driver 10. The laser driver 10 sets the laser power and can switch the beam on and off, or can switch it to an eye-safe intermediate state. As shown in FIG. 5, the controller is directly connected to the converted-light sensor 6 and the laser-output sensor 7.

[0052] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

[0053] Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

1. A laser-based light source, comprising:
 - a laser device configured to generate laser light of a predetermined laser wavelength and emit the laser light as a laser beam;
 - a phosphor light-conversion device configured to convert at least part of the laser light into phosphor converted light;
 - a laser-output sensor configured to determine a laser-output signal being correlated with an output of the laser light emitted by the laser device;
 - a phosphor converted-light sensor configured to determine a converted-light signal being correlated with an output of the phosphor converted light emitted by the phosphor light-conversion device; and
 - a controller configured to receive the laser-output signal and the phosphor converted-light signal and determine a safe-to-operate parameter of the laser device based on a ratio of the laser-output signal and the phosphor converted-light signal or based on phase delay between the laser-output signal and the phosphor converted-light signal, and control operation of the laser-based light source based on a comparison between the safe-to-operate parameter and at least one predefined eye-safety threshold or legislation.
2. The laser-based light source of claim 1, wherein the laser-output sensor is formed by a laser driving current monitor configured to monitor the laser driving current.
3. The laser-based light source of claim 1, further comprising at least one optical fiber configured to guide the laser light to the light-conversion device.
4. The laser-based light source of claim 3, wherein the phosphor converted-light sensor is arranged at an end of the optical fiber which is remote from the phosphor light-conversion device.
5. The laser-based light source of claim 3, wherein the phosphor converted-light sensor is arranged at a position along the optical fiber, and further comprising a decoupling device configured to couple the phosphor converted light out of the optical fiber and into the phosphor converted-light sensor.
6. The laser-based light source of claim 3, wherein the optical fiber is provided with an electrical wiring for detecting damage to the optical fiber.

7. A method of operating a laser-based light source, comprising acts of:
 - generating laser light of a predetermined laser wavelength and emitting this laser light as a laser beam;
 - converting at least part of the laser light into converted light;
 - determining a laser-output signal being correlated with the output of emitted laser light;
 - determining a converted-light signal being correlated with the output of converted light; and
 - determining a safe-to-operate parameter based on the laser output signal and the converted light signal;
 - comparing the safe-to-operate parameter with a at least one predefined threshold; and
 - controlling the operation of the laser-based light source based on the comparison of the safe-to-operate parameter with the predefined threshold.
8. The method according to claim 7, comprising an act of comparing the safe-to-operate parameter with a second predefined threshold.
9. The method according to claim 7, comprising an act of determining the safe-to-operate parameter based on a ratio between the laser-output signal and the converted-light signal.
10. The method according to claim 7, comprising an act of determining the safe-to-operate parameter based on the derivative with respect to time of the ratio between the laser-output signal and the converted-light signal.
11. The method according to claim 7, comprising acts of modulating the emitted laser light in time; and determining the safe-to-operate parameter based on a ratio between the laser-output signal and the converted-light signal at different points in time.
13. The method according to claim 7, wherein the act of controlling the operation of the laser-based light source based on the comparison of the safe-to-operate parameter with the predefined threshold comprises shutting down laser emission or switching it to a safe intermediate level or/and generating a warning.
13. The laser-based light source of claim 1, wherein the safe-to-operate parameter of the laser device is further based signal strengths of the converted-light signal at different points in time, relative to a strength of the laser output.

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