

OPTICAL LIGHT SOURCE AND METHOD OF CONTROLLING THE SAME

Cross-Reference To Related Application

5 **[0001]** This application claims the benefit of priority of Singapore patent application No. 10201502249T, filed 23 March 2015, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

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[0002] Various embodiments relate to an optical light source and a method of controlling an optical light source.

Background

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[0003] High power fiber lasers have been found to be useful laser sources in many applications. In reality, the laser source must be compact, environmentally stable, user friendly, and require minimal power consumption compared with the solid state lasers and CO₂ lasers.

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[0004] The recent advance of high-power pulsed fiber laser technology has further enhanced the capability of fiber laser processing (marking, cutting, cleaning, welding, etc.) for various industry sectors, such as telecommunications, medicine, automotive, aerospace, energy, semiconductor and electronics, spectroscopy, among others. However, many complex-processing applications require only one laser system to have multifunction, which can operate switchable continuous wave (CW) and pulse laser states.

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[0005] Usually, one uses two different laser systems to get the CW fiber lasers and the pulsed lasers, respectively. This makes the cost of the laser system relatively high and also makes the laser system complex and difficult to integrate.

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Summary

[0006] According to an embodiment, an optical light source is provided. The optical light source may include an optical resonator including a gain medium, and an optical pump source optically coupled to the optical resonator, wherein, in a first mode of operation, the optical pump source is configured to supply a continuous wave optical pump signal to the optical resonator, and the optical resonator is configured to generate a continuous wave optical signal in response to the continuous wave optical pump signal, and wherein, in a second mode of operation, the optical pump source is configured to supply a pulsed optical pump signal to the optical resonator, and the optical resonator is configured to generate a pulsed optical signal in response to the pulsed optical pump signal.

[0007] According to an embodiment, a method of controlling an optical light source is provided. The method may include supplying, in a first mode of operation, a continuous wave optical pump signal to an optical resonator including a gain medium to generate a continuous wave optical signal from the optical resonator in response to the continuous wave optical pump signal, and supplying, in a second mode of operation, a pulsed optical pump signal to the optical resonator to generate a pulsed optical signal from the optical resonator in response to the pulsed optical pump signal.

Brief Description of the Drawings

[0008] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0009] FIG. 1A shows a schematic cross-sectional view of an optical light source, according to various embodiments.

[0010] FIG. 1B shows a flow chart illustrating a method of controlling an optical light source, according to various embodiments.

[0011] FIG. 2 shows a schematic diagram of an optical light source, according to various embodiments.

[0012] FIGS. 3A and 3B show results for the continuous wave (CW) fiber laser of various embodiments.

5 [0013] FIGS. 4A and 4B show results for the pulsed fiber laser of various embodiments.

Detailed Description

10 [0014] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as
15 some embodiments can be combined with one or more other embodiments to form new embodiments.

[0015] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

20 [0016] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature
25 in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0017] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

30 [0018] In the context of various embodiments, the term “about” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0019] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0020] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0021] Various embodiments may relate to all-fiber components and lasers, for example, integration of continuous wave (CW) and pulsed laser in one (single) fiber laser system.

[0022] Various embodiments may provide a multifunctional continuous wave (CW) and pulsed fiber laser in one laser system based on electronics modulation and the gain-switched effect. In various embodiments, using only one laser system to generate switchable CW laser and high peak power pulsed laser may make the fiber laser system cost effective and it may potentially be applied in many applications.

[0023] Various embodiments may provide an optical light source (e.g., a laser) including an electrical modulator, an optical pump source, and an optical resonator, wherein, in a first mode of operation, the electrical modulator may be configured to supply a continuous wave (CW) electrical signal to the optical pump source to generate a CW optical pump signal, wherein the optical resonator may be configured to receive the CW optical pump signal and further configured to generate a CW optical signal based on the CW optical pump signal, wherein, in a second mode of operation, the electrical modulator may be configured to supply a pulsed electrical signal to the optical pump source to generate a pulsed optical pump signal, and wherein the optical resonator may be configured to receive the pulsed optical pump signal with microsecond pulse width and further configured to generate a pulsed optical signal with nanosecond pulse width based on the pulsed optical pump signal. The optical signal pulse width may be much narrower than the electrical pulse widths, which thus may increase the peak output power significantly.

[0024] The electrical modulator may be a high-power electrical modulator including a current modulator. The current modulator may include one or more electrical components and an arbitrary waveform generator. The electrical pulse width may be easily controlled by the waveform generator and the electric capacity of the circuit of the current

modulator or current driver (which may be customised) that supplies current to the optical pump source (e.g., laser diode). The waveform generator has the capacity of generating electrical pulses with a pulse width in the nanosecond to microsecond level.

[0025] In various embodiments, the optical pump source may include a fiber laser diode.

5 [0026] In various embodiments, the pump laser source may include one or more multimode fiber-pigtailed laser diodes. Each of them may have the capacity of generating tens of watts output power or even higher.

[0027] In various embodiments, a plurality of different pump laser sources may be combined by an optical beam combiner to couple the many different lasers with different
10 multimode fibers into one passive large mode area (LMA) double cladding fiber.

[0028] In various embodiments, the optical light source may include a plurality of optical pump sources optically coupled to the optical resonator into one passive large mode area double-cladding fiber. The optical light source may further include an optical combiner to optically couple the plurality of optical pump sources to the optical resonator.

15 [0029] In various embodiments, the optical resonator may include a pair of optical reflectors arranged spaced apart from each other, and an active (gain) fiber arranged in between the pair of optical reflectors. The reflectors may be a pair of fiber Bragg gratings (FBG) with different reflectivities. One FBG may be a high-reflective fiber Bragg grating, while the other FBG may be a low reflective fiber Bragg grating. The passive
20 double-cladding fiber may be connected with the input of the high-reflective FBG of the pair of FBGs, and then the output of the high-reflective FBG may be connected with the active LMA double-cladding fiber with length varying from a few meters to hundreds of meters. The active fiber may then be connected with the input of the low-reflective FBG of the pair of FBGs. The output of the low-reflective FBG may be connected with one
25 core-less glass fiber as a beam expander.

[0030] In various embodiments, the optical light source may be an all-fiber optical light source.

[0031] FIG. 1A shows a schematic cross-sectional view of an optical light source 100, according to various embodiments. The optical light source 100 includes an optical
30 resonator 102 including a gain medium 104, and an optical pump source 106 optically coupled to the optical resonator 102, wherein, in a first mode of operation, the optical

pump source 106 is configured to supply a continuous wave (CW) optical pump signal 110a to the optical resonator 102, and the optical resonator 102 is configured to generate a continuous wave optical signal 112a in response to the continuous wave optical pump signal 110a, and wherein, in a second mode of operation, the optical pump source 106 is configured to supply a pulsed optical pump signal 110b to the optical resonator 102, and the optical resonator 102 is configured to generate a pulsed optical signal 112b in response to the pulsed optical pump signal 110b.

[0032] In other words, an optical light source 100 may be provided, which may include an optical resonator 102 and an optical pump source 106 optically coupled to each other.

The optical resonator 102 may mean an optical cavity or a resonator cavity or a laser cavity. The optical pump source 106 may be arranged at an input side of the optical resonator 102.

[0033] The optical resonator 102 may include a gain medium 104 for optical amplification, meaning that the gain medium 104 may be an active medium or element that may amplify light or optical signal received by the gain medium 104 and passing through the gain medium 104, thereby providing an amplified light or optical signal. The optical resonator 102 or the gain medium 104 may be pumped by the optical pump source 106.

[0034] The optical light source 100 may be operated in two modes of operation. In a first mode of operation, the optical resonator 102 may receive a continuous wave (CW) optical pump signal 110a generated by the optical pump source 106, and thereafter generate a continuous wave optical (output) signal 112a (as an amplified light or optical signal) in response to the continuous wave optical pump signal 110a received. In this way, the first mode of operation may be referred to as the continuous wave (CW) operation mode. The continuous wave optical signal 112a may be coherent light.

[0035] In a second mode of operation (different from the first mode of operation), the optical resonator 102 may receive a pulsed optical pump signal 110b generated by the optical pump source 106, and thereafter generate a pulsed optical (output) signal 112b (as an amplified light or optical signal) in response to the pulsed optical pump signal 110b received. In this way, the second mode of operation may be referred to as the pulsed operation mode. The pulsed optical signal 112b may be coherent light.

[0036] Therefore, in the first mode of operation, the optical pump source 106 may operate as a CW optical pump source 106, while in the second mode of operation, the optical pump source 106 may operate as a pulsed optical pump source 106. Consequently, in the first mode of operation, the optical light source 100 may be a continuous wave (CW) optical light source 100 generating a CW optical signal 112a, while in the second mode of operation, the optical light source 100 may be a pulsed optical light source 100 generating a pulsed optical signal 112b. Accordingly, the optical light source 100 may operate as a CW optical light source 100 in the first mode of operation and may operate as a pulsed optical light source 100 in the second mode of operation by using CW pumping and pulsed pumping respectively. Therefore, the optical light source 100 may be a CW optical light source and a pulsed optical light source, providing continuous wave optical signal 112a and pulsed optical signal 112b as output signals.

[0037] As described above, therefore, the optical light source 100 may supply different types of optical signals 112a, 112b in different modes of operations in response to the corresponding type of optical pump signal 110a,110b supplied by the optical pump source 106 to the optical resonator 102. This may mean that the optical resonator 102 may be modulated by the optical pump source 106 to generate the corresponding desired optical signal, i.e., a CW optical signal 112a and a pulsed optical signal 112b. This may also mean that the optical light source 100 may be a switchable optical light source 100, to generate a CW optical signal 112a and a pulsed optical signal 112b in different respective operation modes.

[0038] The optical pump source 106 and the optical resonator 102 are part of one (single) optical light source 100. This may mean that a CW optical signal 112a and a pulsed optical signal 112b may be provided from one (single) optical light source 100 or from one (single) optical resonator 102.

[0039] In various embodiments, the optical pump source 106 may be a fiber-based optical pump source and the optical resonator 102 may be a fiber-based optical resonator. Therefore, the optical light source 100 may be a CW and pulsed fiber optical light source 100. The optical pump source 106 and the optical resonator 102 may collectively be an all-fiber arrangement.

[0040] In various embodiments, the width of the pulsed optical signal 112b may be less than the width of the pulsed optical pump signal 110b.

[0041] In various embodiments, the duration or pulse width of the pulsed optical signal 112b may be about hundreds of nanosecond to several microseconds, and may be
5 narrowed to tens of nanoseconds by optimizing the optical resonator 102.

[0042] In various embodiments, the pulsed optical pump signal 110b may have a microsecond (μ s) pulse width, while the pulsed optical signal 112b may have a nanosecond (ns) pulse width.

[0043] The optical light source 100 may further include an electrical modulator (or
10 electrical driver) 108, wherein, in the first mode of operation, the electrical modulator 108 may be configured to supply a continuous wave (CW) electrical signal 114a to the optical pump source 106 to generate the continuous wave optical pump signal 110a, and wherein, in the second mode of operation, the electrical modulator 108 may be configured to supply a pulsed electrical signal 114b to the optical pump
15 source 106 to generate the pulsed optical pump signal 110b. This may mean that the optical pump source 106 may be modulated by the electrical modulator 108 to generate the corresponding desired optical pump signal, i.e., a CW optical pump signal 110a and a pulsed optical pump signal 110b. Therefore, a CW and pulsed optical light source 100 may be realized based on a modulated optical pump source 106. Further, this may mean
20 that operation in both the CW and pulsed operation modes may be realized by modulating the electrical modulator 108.

[0044] The electrical modulator 108 may be electrically coupled to the optical pump source 106. The electrical modulator 108 may be mounted on the optical pump source 106. In various embodiments, the electrical modulator 108 may be a high power
25 electrical modulator.

[0045] In various embodiments, the electrical modulator 108 may include a current modulator (or current driver source). In this way, the continuous wave electrical signal 114a may be a continuous wave current signal, while the pulsed electrical signal 114b may be a pulsed current signal.

[0046] In various embodiments, switching between the continuous wave optical light source 100 and the pulsed optical light source 100 may be realized by modulating the
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optical pump source 106 based on the electrical modulator 108 or the current modulator. As a non-limiting example, a CW optical light source 100 may be realized by the optical pump source 106 by the electrical modulator 108 or the current modulator without modulation. This may mean that the electrical modulator 108 or the current modulator
5 may be operated in its normal operation, without modulation, to supply a continuous wave electrical signal 114a or continuous wave current signal. By modulating the electrical modulator 108 or the current modulator to supply a pulsed electrical signal 114b or pulsed current signal, a pulsed optical pump source 106 may be realized. The optical resonator 102 may then be pumped by the pulsed optical pump source 106
10 based on the modulated (pulsed) electrical signal 114b or current signal.

[0047] In various embodiments, the current modulator may include an arbitrary waveform generator. The arbitrary waveform generator may generate electrical waveforms, for example, to define or generate the continuous wave electrical (or current) signal 114a and the pulsed electrical (or current) signal 114b. The pulse width of the
15 pulsed electrical (or current) signal 114b may be controlled or tuned by the arbitrary waveform generator. The pulse width of the pulsed electrical (or current) signal 114b may be controlled to be in the nanosecond to microsecond level. In various embodiments, the current modulator may further include one or more other electrical components, for example, one or more resistors and/or one or more capacitors, for example, for the
20 purpose of impedance matching.

[0048] In various embodiments, the optical pump source 106 may include a fiber laser diode. The fiber laser diode may be or may include a multimode laser diode, e.g., a multimode fiber-pigtailed laser diode.

[0049] In various embodiments, the optical light source 100 may include a plurality of
25 optical pump sources optically coupled to the optical resonator 102, for example, two, three, four, five or any higher number of optical pump sources. Each optical pump source of the plurality of optical pump sources may be as described in the context of the optical pump source 106. Each optical pump source may supply an optical pump signal, i.e., a continuous wave (CW) optical pump signal (e.g., 110a) in the first mode of operation and
30 a pulsed optical pump signal (e.g., 110b) in the second mode of operation, to the optical resonator 102. Each optical pump source may include a fiber laser diode, for example, a

multimode laser diode such as a multimode fiber-pigtailed laser diode. Each fiber laser diode (e.g., multimode fiber-pigtailed laser diode) may be capable of generating tens of watts output power or even higher.

5 **[0050]** Accordingly, in various embodiments, one or more fiber laser diodes, e.g., one or more multimode fiber-pigtailed laser diodes, may be employed to pump the optical resonator 102. There may be two, three, four, five or any higher number of fiber laser diodes in the optical light source 100.

10 **[0051]** In various embodiments, the optical light source 100 may further include an optical (beam) combiner to optically couple the plurality of optical pump sources to the optical resonator 102. The optical combiner may be arranged in between the plurality of optical pump sources and the optical resonator 102. For example, the optical combiner may combine the output signals (optical pump signals) of the plurality of optical pump sources into one (single) optical pump signal to be supplied as the continuous wave (CW) optical pump signal 110a to the optical resonator 102 in the first mode of operation, and
15 as the pulsed optical pump signal 110b to the optical resonator 102 in the second mode of operation. This may mean that the optical combiner may have inputs respectively optically coupled to the plurality of optical pump sources and an output optically coupled to the optical resonator 102. The optical combiner may be a (optical) fiber-based optical combiner.

20 **[0052]** In various embodiments, the plurality of optical pump sources, the optical resonator 102 and the optical combiner may collectively be an all-fiber arrangement.

[0053] In various embodiments, the optical light source 100 may further include a passive double cladding (optical) fiber (e.g., a passive large mode area (LMA) double cladding fiber) to optically couple the optical combiner to the optical resonator 102. The
25 passive double cladding fiber may be arranged in between the optical resonator 102 and the optical combiner. This may mean that an output of the optical combiner may be optically coupled to the passive double cladding fiber. Therefore, the optical combiner may optically couple the plurality of optical pump sources to the passive double-cladding fiber to combine the optical pump signals of the plurality of optical pump sources into the
30 (one) passive double-cladding fiber. The term “passive” as used herein may mean absence of a gain medium. In other words, the passive double cladding fiber acts as a

waveguiding fiber to propagate light or optical signal without subjecting the light or optical signal to optical amplification in the passive double cladding fiber.

[0054] In various embodiments, the optical light source 100 may further include a plurality of electrical modulators, wherein a respective electrical modulator of the plurality of electrical modulators may be configured, in the first mode of operation, to supply a respective continuous wave electrical signal to a respective optical pump source of the plurality of optical pump sources to generate a respective continuous wave optical pump signal, and, in the second mode of operation, to supply a respective pulsed electrical signal to the respective optical pump source to generate a respective pulsed optical pump signal. Each electrical modulator of the plurality of electrical modulators may be as described in the context of the electrical modulator 108. Each electrical modulator may include a current modulator.

[0055] In various embodiments, the optical resonator 102 may include a (optical) fiber arrangement and the gain medium 104 may be comprised in the fiber arrangement, the gain medium 104 including a rare-earth doped (active) fiber. Therefore, the optical resonator 102 may be or may include an active fiber arrangement. The rare-earth doped fiber may be a double cladding fiber, e.g., an active large area mode (LMA) double cladding fiber (DCF). The term “active” as used herein may mean inclusion or presence of a gain medium. In other words, the rare-earth doped fiber, apart from propagating light or optical signal, also acts as a gain medium to subject the light or optical signal to optical amplification in the rare-earth doped fiber. In the context of various embodiments, the rare-earth material may include but not limited to ytterbium (Yb), erbium (Er), thulium (Tm), and holmium (Ho), which may emit light in different wavelength regimes. For example, ytterbium may emit light in a wavelength range of about 900 - 1100 nm, erbium may emit light in a wavelength range of about 1530 - 1570 nm, thulium may emit light in a wavelength range of about 1800 - 2200 nm, while holmium may emit light in a wavelength range of about 2000 - 3950 nm.

[0056] In various embodiments, the optical light source 100 may further include a pair of fiber Bragg gratings (FBGs) defined in the fiber arrangement, wherein the rare-earth doped fiber may be arranged in between the pair of fiber Bragg gratings. Therefore, the pair of fiber Bragg gratings may be arranged spaced apart from each other with the rare-

earth doped fiber arranged therebetween. The pair of fiber Bragg gratings and the rare-earth doped fiber may define the optical resonator 102.

[0057] The pair of fiber Bragg gratings may have different reflectivity values, wherein the fiber Bragg grating having the higher reflectivity value (or high-reflectivity fiber Bragg grating) may be arranged at an input side of the rare-earth doped fiber, and wherein the fiber Bragg grating having the lower reflectivity value (or low-reflectivity fiber Bragg grating) may be arranged at an output side of the rare-earth doped fiber. The input side of the rare-earth doped fiber may mean the side that first receives the continuous wave (CW) optical pump signal 110a and the pulsed optical pump signal 110b. The output side of the rare-earth doped fiber may mean the side from which the continuous wave (CW) optical signal 112a and the pulsed optical signal 112b may be outputted. This may mean that the fiber Bragg grating having the higher reflectivity value may be arranged proximal to the optical pump source 106 and/or the optical combiner and/or the passive double cladding fiber.

[0058] In various embodiments, the optical light source 100 may further include an optical beam expander optically coupled to the optical resonator 102 to receive the continuous wave optical signal 112a in the first mode of operation and the pulsed optical signal 112b in the second mode of operation. This may mean that the optical beam expander may be arranged at an output side of the optical resonator 102. The optical beam expander may expand the beam received by the optical beam expander so as to propagate an expanded beam from an output side of the optical beam expander.

[0059] The optical beam expander may be a fiber-based optical beam expander. As a non-limiting example, in various embodiments, the optical beam expander may include or may be a core-less (glass) optical fiber. The fiber-based optical beam expander may be arranged at the output side of the rare-earth doped fiber, for example, with the fiber Bragg grating having the lower reflectivity value arranged in between the rare-earth doped fiber and the fiber-based optical beam expander.

[0060] In the context of various embodiments, the plurality of optical pump sources, the optical resonator 102, the optical combiner and the optical beam expander may collectively be an all-fiber arrangement.

[0061] In the context of various embodiments, the optical light source 100 may be a laser. Therefore, the optical light source 100 may be a continuous wave (CW) and pulsed laser, e.g., a CW and pulsed fiber laser in one fiber laser system. The optical light source 100 may be a high-power CW and high peak power pulsed laser.

5 [0062] FIG. 1B shows a flow chart 140 illustrating a method of controlling an optical light source, according to various embodiments.

[0063] At 142, a continuous wave optical pump signal (e.g., 110a) is supplied, in a first mode of operation, to an optical resonator including a gain medium to generate a continuous wave optical signal (e.g., 112a) from the optical resonator in response to the
10 continuous wave optical pump signal (e.g., 110a).

[0064] At 144, a pulsed optical pump signal (e.g., 110b) is supplied, in a second mode of operation, to the optical resonator to generate a pulsed optical signal (e.g., 112b) from the optical resonator in response to the pulsed optical pump signal (e.g., 110b).

[0065] In various embodiments, at 144, the pulsed optical pump signal may have a pulse
15 width in the microsecond level or range such that the pulsed optical signal generated may have a pulse width in the nanosecond level or range.

[0066] In various embodiments, at 144, the pulsed optical pump signal supplied in the second mode of operation to the optical resonator may have a pulse width in the nanosecond range of between about 50 ns and about 900 ns, depending on the design of
20 the optical light source, for example, between about 50 ns and about 500 ns, between about 50 ns and about 200 ns, between about 200 ns and about 900 ns, between about 500 ns and about 900 ns, or between about 300 ns and about 500 ns. As a result, the pulsed optical signal generated may have a pulse width of between about 10 ns and about 500 ns, such as, for example, between about 10 ns and about 300 ns, between about 10 ns
25 and about 100 ns, between about 10 ns and about 50 ns, between about 100 ns and about 500 ns, between about 300 ns and about 500 ns, or between about 100 ns and about 200 ns.

[0067] In various embodiments, the method may further include supplying, in the first mode of operation, a continuous wave electrical signal (e.g., 114a) to an optical pump
30 source optically coupled to the optical resonator to generate the continuous wave optical pump signal (e.g., 110a) from the optical pump source, and supplying, in the second

mode of operation, a pulsed electrical signal (e.g., 114b) to the optical pump source to generate the pulsed optical pump signal (e.g., 110b) from the optical pump source.

[0068] In various embodiments, the method may further include controlling, in the second mode of operation, at least one of a repetition rate or a pulse width of the pulsed
5 electrical signal to control an output (peak) power of the optical light source.

[0069] In various embodiments, the pulsed electrical signal may have a pulse width in the nanosecond to microsecond level or range. The pulsed electrical signal supplied in the second mode of operation to the optical pump source may have a pulse width of between about 900 ns and about 10 μ s (10000 ns), for example, between about 900 ns and about
10 5 μ s, between about 900 ns and about 2 μ s, between about 2 μ s and about 10 μ s, between about 5 μ s and about 10 μ s, or between about 1 μ s and about 3 μ s.

[0070] In various embodiments, the pulse width of the pulsed optical signal (e.g., 112b) may be far narrower than the pulse width of the pulsed electrical signal (e.g., 114b), thus ‘compressing’ the optical pulses of the pulsed optical signal into narrower pulses and
15 increasing the peak output power of the optical light source.

[0071] It should be appreciated that descriptions in the context of the optical light source 100 may correspondingly be applicable in relation to the method of controlling an optical light source, and vice versa.

[0072] FIG. 2 shows a schematic diagram of an optical light source 200, according to
20 various embodiments, illustrating a switchable continuous wave (CW) and pulsed fiber laser. The optical light source 200 (e.g., a switchable CW and pulsed high-power fiber laser system) may include one or more high-current driver sources (not shown) which may be modulated, one or more multimode laser diodes (three of which are represented by 206a, 206b, 206c) as optical pump sources, a (19*1, or 19-to-1) optical combiner or
25 fiber combiner 220, a high-reflectivity fiber Bragg grating (HR FBG) 222, an active double cladding fiber 204 as a gain medium, a low-reflectivity fiber Bragg grating (LR FBG) 224, and a beam expander 226. The beam expander 226 may be optically coupled to the low-reflectivity fiber Bragg grating (LR FBG) 224 via another optical fiber 228. Each of the multimode laser diodes 206a, 206b, 206c may be a 915 nm laser diode.

[0073] The high-reflectivity fiber Bragg grating (HR FBG) 222, the active double cladding fiber 204, and the low-reflectivity fiber Bragg grating (LR FBG) 224 may define an optical resonator 202.

[0074] The current drivers (or current modulators) (not shown), which may be mounted on the pump laser diodes 206a, 206b, 206c, may generate switchable CW and pulsed currents. The multimode laser diodes 206a, 206b, 206c may receive unmodulated (or CW) current and modulated (or pulsed) current from the current drivers. The high-power CW and high-peak-power pulsed laser 200 may be realized based on the modulated laser diodes 206a, 206b, 206c as the pump sources. The fiber laser may be based on a high power CW fiber laser scheme. However, it may be operated in high powers in both CW and pulsed operation modes by modulating the current driver.

[0075] The approach of various embodiments may address issues related to the conventional approach, which uses two laser systems (one CW fiber laser and one pulsed fiber laser), separately. The approach of various embodiments only uses one system to realize the switchable high-power CW and pulsed fiber laser.

[0076] The peak power of the pulsed fiber laser 200 may be very high, which may address issues related to the conventional method of modulating the output CW laser.

[0077] The high power switchable CW and pulsed fiber laser 200 may have one or more advantages of all-fiber structure (except for the electrical or current modulator which is an electrical circuit), easy to control, compactness and long operation stability. The multifunctional high-power fiber laser of various embodiments may be potentially applied in complex material processing, which often requires the fiber laser system to have the capacity of CW and pulse outputs.

[0078] As non-limiting examples, the duration of the pulsed laser may be about hundreds of nanosecond to several microseconds. Nevertheless, it should be appreciated that the pulse width may be narrowed to tens of nanoseconds by optimizing the fiber laser cavity or resonator 202.

[0079] As described above, the optical light source 200 may be a switchable high power CW and pulsed fiber laser. In order to achieve a high power output, a suitable heat sink may be used in the fiber laser system 200 to obtain good thermal management. For example, the heat sink may be thermally coupled to the optical resonator 202.

[0080] The high power CW fiber laser of various embodiments may be obtained by the laser system pump source by the current driver without modulation. FIG. 3A shows a plot 350a of output spectra of the high power CW fiber laser of various embodiments with different output powers, while FIG. 3B shows a plot 350b of the output power versus the pump power. In FIG. 3A, output spectra 352a and 352b correspond respectively to an output power of 51 W and 87 W.

[0081] By modulating the current driver, a pulsed laser diode pump source may be obtained. FIGS. 4A and 4B show results for the pulsed fiber laser of various embodiments. Single pulse output may be obtained by adjusting the suitable modulation current pulse. FIG. 4A shows a plot 450a of output spectrum of the pulsed fiber laser, while FIG. 4B shows a plot 450b of the corresponding output optical pulse train (solid line 452b) and the pumped current pulse train (dashed line 454b). As may be observed, when the current pulse width is about 120 μ s, a single optical output pulse of about 5 μ s may be obtained. The output power is about 0.5 W. By further optimization of the system, a high power pulsed fiber laser may be obtained.

[0082] The switching between the continuous wave lasers and pulsed lasers may be realized by modulating the pump laser diode based on the current modulator.

[0083] As described above, various embodiments may provide a fiber laser system to generate switchable pulsed and CW laser based (only) on fiber lasers system. The output is laser. The peak power of the pulse may reach very high level, which may be due to the fiber laser being pumped by the pulsed laser diodes based on the modulated current. The peak power of the pulse laser may be far larger than the power of the CW laser. The peak power of the fiber laser system may be further increased by controlling the repetition rate of the current pulse and/or the duration of the current pulse, and/or by optimizing the cavity length of the active large area mode (LMA) double cladding fiber (DCF).

[0084] As also described, various embodiments may be related to a switchable CW and pulsed fiber laser source. The pump laser diode may be modulated based on a current modulator. Therefore, the high-power fiber laser system of various embodiments may work in CW and pulse by using CW pumping and pulsed pumping.

[0085] The duration of the pulsed laser (typically in μs level, but may be narrowed to ns level by optimizing the fiber laser systems) is quite narrower than the duration of the modulated current pulse (several hundreds of μs).

[0086] Further, various embodiments may be based on a high-power fiber laser system without using amplifying systems.

[0087] Various embodiments may achieve high power in both CW and pulsed operations, for example, for versatile material processing, such as welding, marking and cutting. The laser system of various embodiments may have one or more of the following features listed in Table 1 below.

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Table 1

	Type	Various embodiments
Fiber laser system configuration	Master oscillator power amplifier (MOPA)?	No
	Whether single fiber laser cavity?	Yes, only one fiber laser resonator with LMA all-fiber structure
	Method to generate the optical pulse	Current modulation fully utilizes the gain of active optical fiber.
	Method to generate CW laser	Using system same fiber laser by CW pumping, without changing the fiber cavity.
	Gain medium	Rare-earth doped fiber
	Life time of the gain medium	Around 5 ms
Output performance	Pulse width	The pulse width is far narrower than electric pulse width thus 'compressing' the optical pulses into narrower pulses and increasing the peak power.
	Output power for CW laser	In more than hundred watt level
	Peak power for the pulse laser	Very high, the peak power can reach kW level without using any external optical amplifier

[0088] In the high power fiber laser of various embodiments, in order to protect the fiber laser system in case of burning at high power, different large area fibers may be designed and used as output.

[0089] Various embodiments may include fiber based fiber combiners. The input fibers may be 105/125 (core/clad diameter in μm) multimode fibers to let the pump laser signals propagate. There may be, for example, 19 input fibers although any number of input

fibers may be employed. Based on different power levels and applications, the input fiber type and the number of the fibers may be designed differently. The 19 multimode fibers may be fused and spliced with a (passive) double-cladding LMA fiber. The LMA fiber may be, for example, 13/250 (core/clad diameter in μm). However, it should be appreciated that the output fiber may be designed differently in order to apply it to many different applications. Various embodiments may be an all-fiber configuration.

[0090] The combiner in various embodiments may be used to combine many pump lasers into one fiber to pump the gain fiber. There may be a need to consider the mode conversion of the different input fibers and the LMA fiber.

[0091] As described above, various embodiments may provide integration of continuous wave (CW) and pulsed fiber laser in one fiber laser system.

[0092] The high power switchable CW and pulsed fiber laser of various embodiments have great potential applications in versatile industrial material processing (such as welding, cutting, micromachining, marking and engraving, surface modification, etc), remote sensing (e.g., with RADAR), medical applications (e.g., surgery), fundamental science (e.g., particle acceleration), and even laser-induced nuclear fusion.

[0093] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An optical light source comprising:

an optical resonator comprising a gain medium;

5 a fiber laser diode optically coupled to the optical resonator; and

an electrical modulator electrically coupled to the fiber laser diode, the electrical modulator configured to switch the optical light source between a first mode of operation in which the optical light source is a continuous wave optical light source, and a second mode of operation in which the optical light source is a pulsed optical light source;

10 wherein, in the first mode of operation, the fiber laser diode is configured to supply a continuous wave optical pump signal to the optical resonator, and the optical resonator is configured to generate a continuous wave optical signal in response to the continuous wave optical pump signal,

wherein, in the second mode of operation, the fiber laser diode is configured to
15 supply a pulsed optical pump signal to the optical resonator, and the optical resonator is configured to generate a pulsed optical signal in response to the pulsed optical pump signal;

wherein, in the first mode of operation, the electrical modulator is configured to supply a continuous wave electrical signal to the fiber laser diode to generate the continuous wave optical pump signal,

20 wherein, in the second mode of operation, the electrical modulator is configured to supply a pulsed electrical signal to the fiber laser diode to generate the pulsed optical pump signal; and

wherein a width of the pulsed optical signal is less than a width of the pulsed optical pump signal.

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2. The optical light source as claimed in claim 1, wherein the electrical modulator comprises a current modulator.

3. The optical light source as claimed in claim 2, wherein the current modulator
30 comprises an arbitrary waveform generator.

4. The optical light source as claimed in any one of claims 1 to 3, comprising a plurality of fiber laser diodes optically coupled to the optical resonator.

5. The optical light source as claimed in claim 4, further comprising an optical combiner to optically couple the plurality of fiber laser diodes to the optical resonator.

6. The optical light source as claimed in claim 5, wherein the plurality of fiber laser diodes, the optical resonator and the optical combiner are collectively an all-fiber arrangement.

7. The optical light source as claimed in claim 5 or 6, further comprising a passive double cladding fiber to optically couple the optical combiner to the optical resonator.

8. The optical light source as claimed in any one of claims 4 to 7, comprising a plurality of electrical modulators,

wherein a respective electrical modulator of the plurality of electrical modulators is configured, in the first mode of operation, to supply a respective continuous wave electrical signal to a respective fiber laser diode of the plurality of fiber laser diodes to generate a respective continuous wave optical pump signal, and, in the second mode of operation, to supply a respective pulsed electrical signal to the respective fiber laser source to generate a respective pulsed optical pump signal.

9. The optical light source as claimed in any one of claims 1 to 8, wherein the optical resonator comprises a fiber arrangement and the gain medium is comprised in the fiber arrangement, the gain medium comprising a rare-earth doped fiber.

10. The optical light source as claimed in claim 9, further comprising a pair of fiber Bragg gratings defined in the fiber arrangement,

wherein the rare-earth doped fiber is arranged in between the pair of fiber Bragg gratings.

11. The optical light source as claimed in claim 10, wherein the pair of fiber Bragg gratings have different reflectivity values, wherein the fiber Bragg grating having the higher reflectivity value is arranged at an input side of the rare-earth doped fiber, and
5 wherein the fiber Bragg grating having the lower reflectivity value is arranged at an output side of the rare-earth doped fiber.

12. The optical light source as claimed in any one of claims 1 to 11, further comprising an optical beam expander optically coupled to the optical resonator to receive the
10 continuous wave optical signal in the first mode of operation and the pulsed optical signal in the second mode of operation.

13. The optical light source as claimed in claim 12, wherein the optical beam expander comprises a core-less fiber.

14. A method of controlling an optical light source, the method comprising:
switching an electrical modulator so that the optical light source is in a first mode
of operation, wherein the electrical modulator supplies a continuous wave electrical signal
to a fiber laser diode to generate a continuous wave optical pump signal from the fiber laser
20 diode;

supplying, in the first mode of operation, the continuous wave optical pump signal
to an optical resonator comprising a gain medium to generate a continuous wave optical
signal from the optical resonator in response to the continuous wave optical pump signal;

switching the electrical modulator so that the optical light source is in a second
25 mode of operation, wherein the electrical modulator supplies a pulsed electrical signal to
the fiber laser diode to generate a pulsed optical pump signal from the fiber laser diode;
and

supplying, in the second mode of operation, the pulsed optical pump signal to the
optical resonator to generate a pulsed optical signal from the optical resonator in response
30 to the pulsed optical pump signal;

wherein a width of the pulsed optical signal is less than a width of the pulsed optical pump signal.

15. The method as claimed in claim 14, wherein the pulsed optical pump signal
5 supplied in the second mode of operation to the optical resonator has a pulse width of between 50 ns and 900 ns.

16. The method as claimed in claim 14, further comprising controlling, in the second
mode of operation, at least one of a repetition rate or a pulse width of the pulsed electrical
10 signal to control an output power of the optical light source.

17. The method as claimed in any one of claims 14 to 16, wherein the pulsed electrical
signal supplied in the second mode of operation to the fiber laser diode has a pulse width
of between 900 ns and 10 μ s.

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