

HIGH POWER NARROW LINEWIDTH FIBER LASER SYSTEM WITH SINGLE FREQUENCY DEPOLARIZED SOURCE

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The disclosure relates to high power fiber laser systems with a master oscillator power fiber amplifier (MOPFA) architecture including a linearly polarized single mode (SM) single frequency (SF) seed and a power fiber amplifier (PA). In particular, the disclosure relates to the MOPFA with a one-piece fiber depolarizer scrambling the linearly-polarized output of the SF seed so as to suppress the onset of a four wave mixing (FWM) nonlinear effect (NLE) in the PA which outputs substantially a SM beam of at least 2 KW with a linewidth substantially matching the linewidth of light which is coupled into the input of the PA.

2. Background of the Invention

[0002] High-power solid-state/fiber single transverse mode (SM) single-frequency (SF) continuous-wave (CW) lasers with high beam quality and narrow linewidth have attracted growing attention in the fields of basic scientific research, military, nuclear physics, precision measurement, and many others. Yet SMSF lasers were not known for high output powers required by rapidly increasing industrial demands.

[0003] Referring to FIG. 1, the power scalability of SF lasers was improved by the introduction of laser sources having a master oscillator power amplifier (MOPA)/fiber amplifier (MOPFA) architecture 10. In this architecture, a seed module 12 includes a relatively low-power SNSF signal generator or seed 16 outputting a signal at the desired wavelength which is further amplified in a module 14 housing one or several amplifiers. Typically, module 14 includes at least one or more pre-amplifiers 22 and a power fiber amplifier (PA) 24 also known as a booster. Control and stabilization of a SF seed are much simpler at low powers, whereas due to the cavity-free nature of the amplifier, the spectral purity of the seed can be maintained with a slightly broader linewidth at the PA's output.

[0004] As known, for any type of laser, there is a power level that is difficult to exceed without degrading beam quality. The narrow linewidth MOPA sources support this notion mainly because narrow-line fiber amplifiers are susceptible to Brillouin scattering (SBS). The SBS threshold can

be increased by implementing an electro-optical phase modulator (EOM) 18 of FIG. 1 which controllably broadens the linewidth. In addition to the SBS, stimulated Raman scattering (SRS) and transverse mode instability (TMI) also contribute to the undesirable beam degradation.

[0005] The combination of the above-mentioned NLEs detrimentally affects the output power of SM narrow linewidth MOPFA architectures. This limitation has been relaxed by depolarizing the SF seed which, as a rule, is a linearly polarized source. The depolarization technique and numerous devices carrying out this technique are well known. Basic requirement of depolarization of polarized light is a birefringent medium, such as an optical fiber.

[0006] FIG. 2 in combination with FIG. 1 shows a well-known to one of ordinary skill in the laser arts a Lyot depolarizer 20 as disclosed in US provisional application No.: 63/441,603 which is fully incorporated herein by reference. The operational principle of Lyot depolarizer 20 is based on splitting the coupled light and transiting split light portions along different optical paths to the output, where they are recombined with differential time delays between the two orthogonal polarization states. A typical Lyot fiber depolarizer includes two sections of birefringent fibers spliced to one another at a 45° offset angle so as to depolarize a randomly oriented linear polarized SF seed. The downstream output section L_2 is twice as long as an upstream input section L_1 which has the length greater than or equal to the coherence length of SF seed 16 of FIG. 1.

[0007] With all of the above improvements, a continuous wave (CW) narrow linewidth fiber laser depolarized sources operating in a 1 μm wavelength range and outputting 2-4 KW light have been recently reported by, among others, the inventors of the subject matter device. Yet experiments conducted by the inventors convincingly showed that while output powers can indeed reach a 3 – 4 KW range as a result of depolarization, the linewidth at the output of the MOPFA, while still remaining adequate for selected SF applications, is substantially broadened compared to that of the seed. For all practical purposes, the output linewidth of system 10 of FIG. 1 has been measured to be practically twice as broad as that of the seed. This may not meet the requirements of some industrial applications including, for example, beam combining techniques.

[0008] The beam combining techniques, such as spectral beam combining (SBC), require the excellent beam quality of each individual beam. As known, the beams each diverge as it propagates which leads to the increased spot diameter in the focal plane and, as a consequence, decreased beam quality which is often represented by an M^2 factor. The closer each of the combinable beams

to a diffraction-limited beam, the smaller the divergence angle among combinable beams relative to one another, the higher the beam quality of the combined beam. Thus, as the linewidth of each individual SF laser broadens, the divergence of individual beams relative to one another increases which leads to the deteriorated quality of the combined beam. In practical terms, the increased divergence limits the number of channels or laser sources that can be combined together without prohibitively low quality of the combined beam.

[0009] The broadening of the line of the subject matter system has been attributed to and proved to be another well-known NLE – the FWM which is rather inconsequential in MOPFA 10 of FIG. 1 at the output powers of up to 2 KW. At higher powers, at least one of the factors contributing to the onset of FWM has been identified to be two-piece Lyot depolarizer 20 of FIG. 2.

[0010] Based on the foregoing, there is a need for a narrow linewidth MOPFA with the suppressed onset of FWM at the output powers exceeding 2 KW.

SUMMARY OF THE DISCLOSURE

[0011] This need is met by incorporating a one-piece fiber depolarizer into the MOPFA scheme of FIG. 1. Similarly to a two-piece fiber depolarizer, the one-piece depolarizer is used to depolarize the output of a SF seed which leads to the increased power threshold in the booster at which FWM becomes problematic. As with the 2-piece depolarizer, the inventive MOPFA scheme of FIG. 1 with the one-piece depolarizer is capable of outputting a 3-4 KW power signal. In contrast to the know art, the use of the one-piece depolarizer does not cause substantial broadening of the linewidth at the output of the booster.

[0012] The depolarization of the linearly polarized seed output introduces additional spectral components. Intuitively, it is easy to realize that a single piece of depolarizing fiber introduces fewer additional spectral components than the two-piece depolarizer. The FWM is a well-known nonlinear phenomenon, whereby interactions between three spectral components produce a 4th spectral component. The FWM between different spectral components or longitudinal modes is the main line-broadening mechanism. Accordingly, the number of spectral components obtained in the single-piece depolarizer is smaller than that associated with a two-piece scrambler. Consequently, the line broadening in the disclosed MOPFA structure with a one-piece depolarizer is limited by comparison with the same structure incorporating a standard 2-piece scrambler.

[0013] The above and disclosed features are discussed in detail below. Moreover, it is to be understood that both the foregoing information and the following detailed description are merely illustrative examples of various aspects and embodiments, and are intended to provide an overview or framework for understanding the nature and character of the claimed method and apparatus.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. The figures are included to provide an illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification, but are not intended as a definition of the limits of any particular embodiment. The drawings, together with the remainder of the specification, serve to explain principles and operations of the described and claimed aspects and embodiments. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. In the figures:

[0015] FIG. 1 is a diagrammatic schematic of the known high power narrow linewidth fiber laser source having a MOPFA configuration;

[0016] FIG. 2 is an optical schematic of the known two-piece fiber Lyot depolarizer;

[0017] FIG. 3 is an optical schematic of the disclosed MOPFA;

[0018] FIG. 4 is the disclosed one-piece fiber depolarizer of the source of FIG. 3; and

[0019] FIG. 5 illustrates linewidth/output power relationships obtained with the two-piece depolarizer of FIG. 2 and disclosed one-piece depolarizer of FIG. 4, respectively.

SPECIFIC DESCRIPTION

[0020] The disclosed high power narrow linewidth laser source with a MOPFA architecture incorporating a one-piece depolarizer improves the known, similarly configured laser sources with a standard two-piece scrambler by not only outputting a high quality beam of up to four (4) KW, but also by substantially preserving the linewidth of a SMSF seed signal during its amplification. The one-piece fiber depolarizer increases the threshold of the FWM because, by comparison with the laser source having a standard 2-piece Lyot scrambler, there are fewer

spectral components obtained during the depolarization of the linearly polarized SF seed. The lower the number of spectral component, the higher the FWM threshold.

[0021] FIG. 3 illustrates the disclosed narrow linewidth all fiber source 25 having a MOPFA architecture which is configured with a seed module 30 and amplifier module 40. The seed module 30 functions as a generator of SM narrow line signal at the desired wavelength. Guided along a path via a fiber train, the generated signal is coupled into amplifier module 40 providing the signal with gain. Thereafter, the amplified signal is guided via an output fiber 50 having an end cap or collimator or connector between output fiber 50 and a laser head (not shown here.)

[0022] Focusing specifically on seed module 30, it houses a SMSF linearly polarized seed 32, such as pigtailed diodes or fiber lasers generating a low-power signal. As an example, seed 32 is a distributed feedback diode generating about a 10 mW SMSF output which has a narrow spectral linewidth ranging in a 0.1–10 MHz range. As known, the SMSF signal with such a narrow linewidth cannot be amplified to the desired KW levels primarily due to a very low threshold of SBS in a power amplifier of amplifier module 40.

[0023] To increase the SBS threshold, the spectral line should be broadened which can be accomplished by different techniques carried out by a line-broadening system 34. This technique may include a temporal modulation which is accomplished by a current modulator of the current supplied to SF seed 32. Alternatively, broadening system 34 may be represented by a phase modulator coupled to the output of SF seed 32 and configured to modulate a phase thereof. Regardless of the selected means for spectral broadening in the exemplary schematic 25, the spectral line at the output of line broadening system 34 is expanded to about 30-40 GHz and, if necessary further up to 100 GHz.

[0024] Speaking of the desired power level at the output of amplifier module 40, clearly the “desired” level is a very relative term, and what is considered to be a high power for one industrial application can be grossly inadequate for a different application. Still the goal of the majority of high power laser applications is to squeeze out the last possible iota of the power from any given system without compromising the modality of light. Based on this premise, one of ordinary skill in the laser arts readily realizes that in addition to the broadened spectral line, the SMSF signal from seed 32 should be depolarized, provided that the goal is the highest possible power level, which is what source 25 tries to achieve.

[0025] Referring to FIG. 4 in addition to FIG. 3, the depolarization in the disclosed source 25 is carried out by a fiber depolarizer 36 configured as a one-piece fiber, such as Panda type fiber, which is spliced to seed 32 with a 45° offset. Dimensioned to have substantially the same length as the second section L2 of prior art depolarizer 20 of FIG. 2, one-piece depolarizer 36 introduces fewer additional spectral components than the two-piece depolarizer which, in turn, leads to raising the threshold of the FWM. Once the effect of FWM is weakened, the spectral line at the output of amplifier module 40 remains substantially the same, i.e., 30-40 GHz at full width half maximum (FWHM), at the output powers of source 25 reaching a 3-4 KW range. As powers continue to grow, the line is expected to be broadened. The combination of the depolarized output of SF seed 32 along with the 30-40 GHz broadened linewidth not only allows the signal to reach the above-mentioned high power beam as it is guided through one or more preamplifiers 38 and booster 42, but also it provides the output beam with an excellent M^2 factor of 1.05 – 1.1.

[0026] The amplifier module 40 may be further configured with isolator 44 preventing high power backreflection radiation from being guided in a counter signal-propagating direction. A combination of photodetectors 46 measuring forward- and backward-propagating radiation is disclosed in greater detail in US Provisional Application 63470566 filed concurrently with and fully incorporated in this application by reference. The booster 42 is configured with a multimode (MM) doped fiber advantageously configured with a cylindrical axial cross-section. Advantageously the active fiber has a double bottleneck axial cross-section which has a large diameter middle core region bridging smaller core diameter end regions. The examples of such active fibers are disclosed in USP 7,848,368, 8,655,121 respectively which are fully incorporated herein by reference. The dopants are selected from a group of rare-earth metals to output narrow linewidth light at the desired wavelength. A pump assembly for energizing booster 42 includes a one-directional or two-directional pumping scheme configured with a plurality of MM diodes. The exemplary source 25 has been tested at 1055, 1062 and 1070 nm corresponding to the emission range of ytterbium (Yb) ions. The upstream stretch of the fiber train including all components of seed module 30 is based on fibers selected from PANDA type, bowtie type or any other specialty fiber with strong built-in birefringence. The downstream stretch of the fiber train after the depolarizer does not require specialty fibers.

[0027] The utilization of one-piece depolarizer 36 has several advantages over the standard 2-piece Lyot polarization scrambler. One of these advantages is illustrated in FIG. 5. In particular, the linewidth 50 in the inventive source remains practically unchanged during the amplification of the seed signal up to about 4 KW in booster 42. In contrast, the linewidth 60 is broadened more than twice when source 25 of FIG. 3 incorporates the standard 2-piece Lyot depolarizer of FIG. 2. Still another advantage relates to the cost. The source 25 has been tested with a 100-m long standard 2-piece Lyot depolarizer. Using 50-m long one-piece depolarizer 36 in source 25 of FIG. 3 results in the degree of depolarization similar to that observed in source 25 with the 2-piece depolarizer, but the cost of the specialty fiber needed for inventive depolarizer 36 is practically half the cost of the 2-piece scrambler. Considering that 1 meter of Panda costs slightly more than \$6, the savings may be substantial.

[0028] The features disclosed herein in accordance with the present invention, are not limited in their application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. These features are capable of assuming other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. In particular, acts, components, elements, and features discussed in connection with any one or more embodiments are not intended to be excluded from a similar role in any other embodiments.

[0029] Having thus described several aspects of at least one example, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. For instance, examples disclosed herein may also be used in other contexts. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the scope of the following claims. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is:

CLAIMS

1. A high power narrow linewidth laser system having a master oscillator power fiber amplifier architecture, comprising:
 - a single mode single frequency (SMSF) linearly polarized seed outputting a linearly polarized signal at a desired wavelength,
 - a one-piece fiber depolarizer spaced downstream from the seed and configured to depolarize the linearly polarized signal, and
 - a fiber booster amplifying the depolarized signal which suppresses an onset of a four-wave mixing nonlinear effect during amplification in the fiber booster so that the fiber booster outputs the amplified depolarized signal at an output power in excess of 2 KW with a spectral linewidth which matches that of the linearly polarized signal at an input of the one-piece fiber depolarizer.
2. The laser system of claim 1 further comprising a linewidth-broadening unit coupled between an output of the seed and the input of the one-piece fiber depolarizer and configured to broaden a spectral linewidth of the linearly polarized signal at the output of the seed to the spectral linewidth of the linearly polarized signal at the input of the one-piece fiber depolarizer.
3. The laser system of claim 2, wherein the linearly polarized signal at the output of the seed has the linewidth in a 0.1-10 MHz range, and the linewidth at the input of the one-piece fiber depolarizer is in a 30-40 GHz at the output power ranging between 2 KW and 4 KW.
4. The laser system of claim 2, wherein the linewidth broadening unit includes an acousto-optic phase modulator or electro-optical modulator.
5. The laser system of claim 1, wherein the fiber booster is configured with
 - a multimode (MM) active fiber doped with one or more rare-earth ions and having a double bottle-neck-shaped cross-section, and
 - a pair of single mode passive fibers spliced with respective opposite ends of the active fiber, wherein the MM active fiber supports substantially only a fundamental mode having a mode field diameter (MFD) which matches that one of the SM passive fibers.
6. The laser system of claim 5, wherein the fiber booster is energized by a pump including a plurality of multimode diode lasers which are arranged in a uni-directional pumping scheme or two-directional pumping scheme.

7. The laser system of claim 3, wherein the fiber booster is configured to output the amplified depolarized signal.
8. The laser system of claim 2, wherein the SMSF seed, line-broadening unit and one-piece fiber depolarizer are spliced together to define an upstream stretch of a system fiber train, the upstream stretch having specialty fibers with a strong built-in birefringence.
9. The laser system of claim further comprising one or more fiber preamplifiers upstream from the fiber booster, wherein the preamplifiers and fiber booster are housed in an amplifier module.
10. A method of generating a narrow linewidth light signal in a high power laser system having a maser oscillator power fiber amplifier architecture, comprising:
 - generating a single mode single frequency (SMSF) linearly polarized signal;
 - broadening a linewidth of the SMSF linearly polarized signal to a narrow linewidth;
 - guiding the SM linearly polarized narrow linewidth signal through a one-piece fiber depolarizer thereby obtaining a depolarized SM signal with the narrow linewidth;
 - amplifying the depolarized SM signal in a fiber amplifier, wherein the amplified depolarized SM signal is output at an output power in a 2-4 KW diapason and the narrow linewidth unchanged during the amplification.