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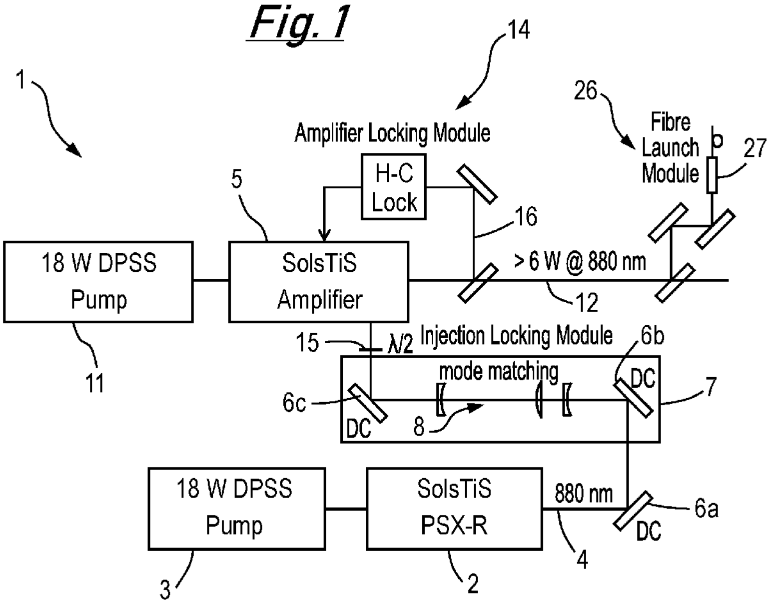
(54) Title: LASER SYSTEM FOR COHERENTLY COMBINING MULTIPLE LASER SOURCES

Fig. 1



(57) **Abstract:** A method and system for combining two or more optical fields is disclosed. A first continuous-wave high powered output field generated by a solid-state master laser is injected into a first solid state optical amplifier to produce a single output field from the laser system that exhibits a high phase-coherence with the output field of the master laser. The power of the output field equals the sum of powers of the master laser and that generated by the first optical amplifier, while exhibiting similar beams characteristics to that produced by the output field of the master laser i.e. it exhibits low noise, in a single transverse and longitudinal mode Gaussian beam, and has a single polarisation. The laser system is highly scalable in that N optical amplifiers may be located in series with the master laser to provide a single low noise, high power output field.

WO 2020/002933 A1

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Laser System for Coherently Combining Multiple Laser Sources

The present invention relates to the field of lasers and, in particular, to a laser system for coherently combining multiple laser sources.

There exist a number of applications that require a higher power laser source, generated within in a single beam, that also exhibits very low noise properties. Such an application is the optical trapping of atoms. Here, an induced dipole force generated by a laser source acts on the atoms located within its output field causing them to be attracted to (repelled from), and trapped at, the maximum (or minimum) in intensity of the output field (a kind of optical tweezer). The higher the power within the output field, the greater the depth of the trap, hence, the desire for a high power laser source. Any perturbation of the generated light field (i.e. mode fluctuations and other residual noise) gives rise to unwanted motion, or heating, of the atoms. It is therefore desirable for the high power laser source to also exhibit low noise. Thus, the combination of high power and low noise is ideal for optical trapping applications. Optical traps may be employed for the emulation of crystalline, solid-state systems since the atoms are trapped in a highly configurable light field. Optical traps are also employed within optical clocks, quantum computing, optical tweezers and quantum optics experiments.

A number of laser systems are known in the art that provide a means for coherently summing the output optical fields produced by two or more independent gain media. For example, US patent number US 4,649,351 discloses a laser system within which a diffraction grating is employed to combine the output optical fields generated by a plurality of lasers. The diffraction grating is configurated to generate, upon illumination, substantially equal intensities of diffraction orders corresponding to the number of lasers while suppressing higher unwanted orders. Phase locking of the plurality of lasers may be accomplished by employing an independent single master laser to generate a reference beam for each laser via the diffraction grating.

US patent number US 4,757,268 discloses a laser system wherein a pulsed output from a master laser source is split by a series of mirrors and reflective prisms to enable the simultaneous driving of a plurality of laser gain elements. A phase conjugate reflector, operatively coupled to the gain elements, reflects the phase conjugate of the amplified radiation back into the gain elements where it is further amplified. An output coupler then couples the amplified radiation from the plurality of gain elements out of the laser system to form as a single coherent output.

An alternative laser system for coherently combining multiple laser devices is disclosed in US patent publication number US 2004/165620. Here, the laser devices comprise optical fibres with laser active regions. Each of the fibres has a reflector disposed at one end and is connected to an optical combiner on the other end. The optical combiner acts to combine the output produced within each of the optical fibres to form a single coherent output.

In US patent publication number US 2009/296751 the laser system comprises a plurality of semiconductor diode lasers that are phase-locked by direct current injection. The optical output of each diode laser is then amplified by fibre amplifiers and thereafter combined by a beam combining module, comprising multiple beam splitter plates, to form a single coherent output beam.

These above described laser systems are not particularly efficient due to the number of optical components involved within the laser systems and thus the powers that can be produced are significantly limited. In addition, the output optical fields generated by these laser systems are known to be of poor mode quality, particularly where multiple outputs are combined in an array rather than in a single beam, and exhibit high noise levels due to the presence of the multiple optical components required to combine the outputs of the individual laser sources. As a result, these laser systems do not lend themselves for use within the above described high power, low noise applications.

Higher power, lower noise laser systems based on injection locking monolithic, unidirectional single-mode Nd:YAG ring lasers (NPRO) are known in the art for use within free space communication, see for example SPIE Proceedings Volume 1417. Free-Space Communication Technologies III (June 1991) entitled "*Injection chaining of diode-pumped single-frequency ring lasers for free-space communication*" in the name of Cheng et al. This paper discloses the injection locking of an NPRO laser (the slave laser) to the continuous-wave single-frequency output generated by a separate NPRO laser (the master laser). The output of the injection locked NPRO laser (the slave laser) may then be employed to injection lock a third NPRO laser. The output power of each NPRO laser is in the range of 300 milliwatts to 350 milliwatts at the normal operating wavelength of 1064nm for Nd:YAG. When arranged in the above described manner, the disclosed laser system provides a single frequency output having a power in the range of 750 milliwattts to 1 Watt at 1064nm. In practice, it is found that such systems are very sensitive and are not particularly stable.

US patent number US 5,027,360 discloses a solution for increasing the stability of the aforementioned Nd:YAG injection locked laser systems. The solution provided by, US patent number US 5,027,360 is to employ an NPRO laser (the master laser), having a power in the range of 30 to 40 milliwatts at 1064nm, to injection lock a traditional Nd:YAG ring cavity laser to produce an output field from the system having a power as high as 13 Watts at 1064nm. The system further comprises a servo-loop control system employed to maintain the injection-locked condition. This is achieved by generating an error signal that is indicative of fluctuations within the slave laser cavity and employing this error signal to adjust the length of the slave laser cavity to maintain the locked condition. In practice, it is found that the power generated by the laser system disclosed in US patent number US 5,027,360 is limited to that which can be produced by the Nd:YAG ring cavity laser since increasing the power of the NPRO laser (the master laser) leads to a decrease in overall stability of the system.

There exist a number of low noise applications that require higher powers than are achievable from the above described Nd:YAG based injection locked laser systems, for example laser system for gravitational wave detectors. An example of such a system is disclosed within Applied Physics B, March 2011, Volume 102, Issue 3, pages 529–538 entitled "*Injection-locked single-frequency laser with an output power of 220 W*" in the name of Winkelmann et al. Here an NPRO laser with 2 W output power is amplified by a four-head Nd:YVO laser amplifier to a power level of 35 Watts. The light from the Nd:YVO laser amplifier then injection locks a Nd:YAG oscillator. The Nd:YAG oscillator consists of four end-pumped Nd:YAG crystals arranged within a single ring resonator resulting in output powers as high as 220 Watts at 1064nm.

Summary of Invention

It is therefore an object of an embodiment of the present invention to obviate or at least mitigate the foregoing disadvantages of the injection-locked laser system known in the art.

It is a further object of an embodiment of the present invention to provide an alternative laser system to those known in the art for generating a high power output field.

A yet further object of an embodiment of the present invention to provide a laser system which generates an output field of increased operating wavelength flexibility when compared with those laser systems known in the art.

According to a first aspect of the present invention there is provided a laser system comprising:

a first laser, the first laser comprising a Ti:sapphire gain medium that generates a first continuous-wave output field having a first frequency (f_1) and a first power (P_1), and

a first optical amplifier, the first optical amplifier comprising a Ti:sapphire gain medium that generates a second continuous-wave output field having a second frequency (f_2) and a second power (P_2),

wherein

the first continuous-wave output field is injected into the first optical amplifier resulting in the second continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the sum of the first (P_1) and the second (P_2) powers.

The above arrangement provides a solid-state laser system having a high power, low noise single output field, namely the second continuous-wave output field that exhibits a single transverse and longitudinal mode, single polarisation and a high phase-coherence with the first continuous-wave output field. Most significantly, the wavelength of the single output field is tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the first laser. This makes the laser system particularly suited for employment within an optical trap.

It is preferable for the second power (P_2) to be similar to the first power (P_1) i.e. in the range $0.5\ P_1 > P_2 < 1.5\ P_1$.

Most preferably, the first power (P_1) is greater than or equal to 1 Watt. Preferably, the first power (P_1) is greater than or equal to 4 Watts.

Preferably the first optical amplifier comprises a ring cavity within an arm of which is located the Ti:sapphire gain medium.

Preferably the laser system further comprises a first injection locking module located within an optical path between the first laser and the first optical amplifier wherein the injection locking module provide a means for ensuring that the mode of the first continuous-wave output field matches that of the first optical amplifier.

Most preferably the laser system further comprises a first optical isolator located within an optical path between the first laser and the first optical amplifier. Optionally the first optical isolator comprises one or more dichroic mirrors.

Most preferably the laser system further comprises a first frequency lock control loop to frequency lock the second continuous-wave output field to the frequency of the first continuous-wave output field.

Optionally, the laser system further comprises a second optical amplifier comprising a Ti:sapphire gain medium that generates a third continuous-wave output field having a third frequency (f_3) and a third power (P_3) wherein the second continuous-wave output field is injected into the second optical amplifier resulting in the third continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1), second (P_2) and third (P_3) powers.

The above arrangement provides a laser system having a single output field, namely the third continuous-wave output field that exhibits a single transverse and longitudinal mode, single polarisation and a high phase-coherence with the first and second continuous-wave output field. The single output field exhibits a power level which is effectively the sum of the powers of the first, second and third continuous-wave output fields. Most significantly, the wavelength of the single output field is again tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the first laser.

Preferably the laser system further comprises a second injection locking module located within an optical path between the first and second optical amplifiers wherein the second injection locking module provides a means for ensuring that the mode of the second continuous-wave output field matches that of the second optical amplifier.

Most preferably the laser system further comprises a second optical isolator located within an optical path between the first and second optical amplifiers. Optionally the second optical isolator comprises one or more dichroic mirrors.

Most preferably the laser system further comprises a second frequency lock control loop to frequency lock the third continuous-wave output field to the frequency of the second continuous-wave output field.

It will be appreciated than the laser system is easily scalable to include N optical amplifiers located in series with the first laser which will generate a single output field having a power which is effectively the sum of the powers of the output fields from the first laser and the N optical amplifiers. The system would therefore preferably comprise an injection locking module and or an optical isolator located within the optical paths between these components. In addition, it is preferable that each optical amplifier comprise a frequency lock control loop to frequency lock the optical amplifiers to the previous optical amplifier in the series.

According to a second aspect of the present invention there is provided a method of combining two or more optical fields the method comprising:
providing a first laser comprising a Ti:sapphire gain medium to generate a first continuous-wave output field having a frequency (f_0) and a first power (P_1);
providing a first optical amplifier comprising a Ti:sapphire gain medium to generates a second continuous-wave output field having a second frequency (f_2) and a second power (P_2); and
injecting the first continuous-wave output field into the first optical amplifier causing the second continuous-wave output field to form a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the sum of the first (P_1) and the second (P_2) powers.

It is preferable for the second power (P_2) to be similar to the first power (P_1) i.e. in the range $0.5\ P_1 > P_2 < 1.5\ P_1$.

Most preferably, the first power (P_1) is greater than or equal to 1 Watt. Preferably, the first power (P_1) is greater than or equal to 4 Watts.

Preferably providing a first optical amplifier comprises providing a ring cavity within an arm of which is located the Ti:sapphire gain medium.

Preferably the method of combining two or more optical fields further comprises matching the mode of the first continuous-wave output field to that of the first optical amplifier.

Most preferably the method of combining two or more optical fields further comprises optically isolating the first solid state laser from the first optical amplifier.

Most preferably the method of combining two or more optical fields further comprises frequency locking the first optical amplifier to the first continuous-wave output field.

Optionally, the method of combining two or more optical fields further comprises providing a second optical amplifier comprising a Ti:sapphire gain medium to generates a third continuous-wave output field having a third frequency (f_3) and a third power (P_3) wherein the second continuous-wave output field is injected into the second optical amplifier resulting in the third continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1), second (P_2) and third (P_3) powers.

Preferably the method of combining two or more optical fields further comprises matching the mode of the second continuous-wave output field to that of the second optical amplifier.

Most preferably the method of combining two or more optical fields further comprises optically isolating the first optical amplifier from the second optical amplifier.

Most preferably the method of combining two or more optical fields further comprises frequency locking the second optical amplifiers to the second continuous-wave output field.

Embodiments of the second aspect of the present invention may comprise features to implement the preferred or optional features of the first aspect of the present invention or vice versa.

According to a third aspect of the present invention there is provided a laser system comprising:

a first laser, the first laser comprising a gain medium that generates a first continuous-wave output field having a first frequency (f_1) and a first power (P_1); and

N optical amplifiers where N is an integer equal to two or more, each of the N optical amplifiers comprising a gain medium that generates a continuous-wave output field having a frequency (f_N) and a power (P_N),

wherein

the continuous-wave output field of the first optical amplifier is injection locked to the first continuous-wave output field and the continuous-wave output field of the Nth optical amplifier is injection locked to the continuous-wave output field of the N-1 optical amplifier resulting in the Nth continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1) to Nth (P_N) powers.

Embodiments of the third aspect of the present invention may comprise features to implement the preferred or optional features of the first to second aspects of the present invention or vice versa.

According to a fourth aspect of the present invention there is provided a method of combining three or more optical fields the method comprising:
providing a first laser comprising a gain medium to generate a first continuous-wave output field having a frequency (f_0) and a first power (P_1);
providing N optical amplifiers, where N is an integer equal to two or more, each of the N optical amplifiers comprising a gain medium that generates a continuous-wave output field having a frequency (f_N) and a power (P_N); and
injecting locking the continuous-wave output field of the first optical amplifier to the first continuous-wave output field and injection locking the continuous-wave output field of the Nth optical amplifier to the continuous-wave output field of the N-1 optical amplifier resulting in the Nth continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1) to Nth (P_N) powers

Embodiments of the third aspect of the present invention may comprise features to implement the preferred or optional features of the first to second aspects of the present invention or vice versa.

Brief Description of Drawings

There will now be described, by way of example only, various embodiments of the invention with reference to the drawings, of which:

Figure 1 presents a schematic representation of a laser system in accordance with an embodiment of the present invention;

Figure 2 presents a schematic representation of:
(a) an optical amplifier employed within the laser system of Figure 1 and
(b) an alternative optical amplifier employed within the laser system of Figure 1;

Figure 3 presents a schematic representation of a laser system in accordance with an alternative embodiment of the present invention; and

Figure 4 presents a schematic representation of a laser system in accordance with a further alternative embodiment of the present invention.

In the description which follows, like parts are marked throughout the specification and drawings with the same reference numerals. The drawings are not necessarily to scale and the proportions of certain parts have been exaggerated to better illustrate details and features of embodiments of the invention.

Detailed Description

Details of the laser system will now be described with reference to Figures 1. In particular, Figure 1 presents a schematic representation of a laser system in accordance with a first embodiment of the present invention, as generally depicted by reference numeral 1.

The laser system 1 can be seen to comprise a Ti:sapphire laser 2 employed as the master (or seed) laser within the system 1. The master Ti:sapphire lasers 2 is optically pumped at 532 nm by a dedicated continuous wave diode-pumped solid-state (DPSS) laser source 3 to produce a continuous-wave output field 4. The applicant's proprietary SolsTiS® laser is a suitable example of a Ti:sapphire laser for use as the master laser 2 while the pump laser 3 may comprise a commercially available diode-pumped solid-state (DPSS) laser.

The pump laser 3 has the capability of providing up to ~18 Watts of pump power to the master Ti:sapphire laser 2. In the presently described embodiment, the pump laser 3 is arranged to provide ~18 W of pump power to the master Ti:sapphire laser 2 to provide a tuneable continuous-wave output field 4 (tuneable between 660nm and 1060nm) with a power of around ~4.7 W at 880nm. Due to the presence of a number of intracavity elements (e.g. etalons) and control electronics the generated tuneable continuous-wave output field 4 operates at a single frequency (f_0), as a single transverse and longitudinal mode and exhibits low phase noise. In practice, the quality of the output field 4 can be maintained when the master Ti:sapphire laser 2 is configured to operate at a power as low as 400 milliwatts.

As can be seen from Figure 1, the continuous-wave output field 4 is injected into a first optical amplifier 5 i.e. the continuous-wave output field 4 is employed as a seed optical field for the first optical amplifier 5 resulting in the first optical amplifier 5 being slaved to the master Ti:sapphire laser 2. A first dichroic mirror 6a is employed to redirect the seed optical field 4 into the first optical amplifier 5.

It is preferable for an injection locking module 7 to also be located within the optical path between the master Ti:sapphire laser 2 and the slave optical amplifier 5. The injection locking module can be seen to comprise beam shaping optics 8 located between two dichroic mirrors 6b and 6c. The combined effects of the beam shaping optics 8 provide a means for ensuring that the mode of the seed optical field 4 matches that of the slave optical amplifier 5.

Figure 2(a) presents a schematic representation of the first optical amplifier 5 employed within the laser system 1. The first optical amplifier 5 comprises a ring cavity 9 within an arm of which is located a Ti:sapphire gain medium 10 , the Ti:sapphire gain medium 10 being optically pumped at 532 nm by a dedicated continuous wave DPSS laser source 11 to produce a continuous-wave output field 12. The applicant's proprietary SolsTiS® amplifier is an example of a suitable optical amplifier 5 for use within the laser system 1. Unlike the master Ti:sapphire laser 2, the first optical amplifier 5 comprises no additional intracavity elements. Therefore, in the absence of the seed optical field 4 the first optical amplifier 5 is effectively free running, and thus produces a bi-directional output at 770nm when pumped at 532 nm by the dedicated continuous wave DPSS laser source 11. In the presently described embodiment the pump laser 11 is arranged to provide ~18 W of pump power to the Ti:sapphire laser 5.

The cavity of the first optical amplifier 5 is arranged to be resonant at the frequency (f_0) of seed optical field 4, namely the 880 nm output field 4. As described above, the continuous-wave output field 4 is employed as a seed optical field for the first optical amplifier 5. This is achieved by arranging for the continuous-wave output field 4 to be incident upon the output coupler 13 of the first optical amplifier 5. As a result, a fraction the optical field 4 enters the ring cavity 9 of the first optical amplifier 5 while the remainder is reflected from the output coupler 13 of the first optical amplifier 5.

The fraction of the output field 4 that enters the ring cavity 9 acts as a "seed" for the first optical amplifier 5. This "seed" results in stimulated emission within the first optical amplifier 5 at the same frequency as the output field 4 of the master Ti:sapphire laser 2, as well as causing the first optical amplifier 5 to operate in a unidirectional manner.

The fraction of the seed optical field 4 entering the ring cavity 9, and amplified therein, is also in phase with that reflected from the output coupler 13, thus ensuring temporal phase coherence between the seed optical field 4 and the output field 12 of the first optical amplifier 5.

Spatial phase-coherence between the fraction of the optical field 4 which is reflected from the output coupler 13, and that which is amplified within the ring cavity 9, is ensured by having a high degree of mode-matching between the seed optical field 4 and the output field 12 of the optical amplifier 5. The injection locking module 7 is employed to assist with mode-matching the seed optical field 4 to the output field 12

The output field 12 of the optical amplifier 5 is therefore combined with the output field 4 of the master Ti:sapphire laser 2 such that the laser system 1 provides a single output exhibiting a single transverse and longitudinal mode Gaussian beam, that exhibits a single polarisation and a high phase-coherence with the seed optical field 4 i.e. their frequencies are in phase to << 1 cycle of the waveform. The output field 12 has a power ~9.4 W which is effectively the sum of the powers of the output field 4 of the master Ti:sapphire laser 2 and the output field 12 of the first optical amplifier 5. Most significantly, the wavelength of the output field 12 is tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the master Ti:sapphire laser 2. By comparison the Nd:YAG laser systems of the prior art are only tuneable over a range of around 0.05nm. Thus, unlike the Nd:YAG laser systems of the prior art the present laser system 1 able to be employed within optical traps where it is necessary to be able to tune the laser source to different atomic wavelengths depending on the particular atom required to be trapped e.g. Barium, Beryllium, Caesium, Magnesium, Rubidium, Strontium and Ytterbium.

Since the first optical amplifier 5 is a resonant device, and as explained above, injection locking occurs when the seed optical field 4 is in resonance with the ring cavity 9 of the optical amplifier 5, it is beneficial for the stable operation of the laser system 1 to frequency lock the resonance condition of the first optical amplifier 5 to the seed optical field 4.

In the embodiment presented in Figure 2(a) a preferred frequency lock control loop 14 based on the Hänsch–Couillaud technique is employed to achieve the desired frequency locking. This technique was first described in Optics Communication Volume 35, Issue 3, pages 441 to 444 (1980) and exploits the fact that the Ti:sapphire gain medium 10 of the first optical amplifier 5 is Brewster cut crystal. As a result, there exists an asymmetry in the two orthogonal polarisation components of the resonance frequency. To exploit this fact, a half-wave plate 15 is employed to introduce an offset to the polarisation of the fraction of the the seed optical field 4 that enters the ring cavity 9 to introduce a component of polarisation orthogonal to the plane of incidence to the Brewster-cut Ti:sapphire gain medium 10. A component 16 of the output field 12 is then directed towards a polarisation analyser 17 employed to detect dispersion shaped resonances which can provide an error signal generated by locking electronics 18 for electronic frequency stabilisation via a piezo-mounted cavity mirror 19.

In an alternative embodiment presented in Figure 2(b) a frequency lock control loop 20 based on the Pound–Drever–Hall technique is employed to achieve the desired frequency locking. This technique is described in Applied Physics. B, Volume 31, Pages 97 to 105 (1983). In this technique a frequency modulator 21 applies a frequency-modulation to the seed optical field 4 that is detected within a component 22 of the output field 12 by a photodiode 23. This frequency modulated signal is then demodulated by via a frequency mixer 24 to generate an error signal. Frequency locking electronics 25 then provide a correction signal for electronic frequency stabilisation via the piezo-mounted cavity mirror 19.

It should be noted that the above described frequency locking techniques of the optical amplifiers 5 do not themselves provide for phase-coherence between the seed optical field 4 and the output field 12. Instead, phase coherence is a direct result of the amplification process within the first optical amplifier 5. The frequency locking techniques merely ensures that the frequency of the resonance of the first optical amplifier 5 remains coincident with the frequency of the seed optical field 4.

In order to confirm that the output field 12 comprises the combined output of the master laser 2 and the first optical amplifier 5 a fibre launch module 26 was employed to analyse the output field 12. As can be seen from Figure 1, a fraction of the output field 12 (~ 2%) is picked-off by employing a glass substrate before being coupled into a single mode fibre 27. A coupling efficiency of >80% through single mode fibre 27 served to demonstrate that the output field 12 occupies a single transverse spatial mode. In an independent measurement of beam quality, the M^2 value was found to be $\lesssim 1.1$ which, again, demonstrates that the output field 12 occupies a single transverse spatial mode.

As discussed above, before injection locking has been achieved, the first optical amplifier 5, not containing any internal elements to force unidirectional operation, will operate bi-directionally, with half of its output power being directed back towards the master laser 2. However, the presence of the dichroic mirrors 6a, 6b and 6c prevent the backward going oscillation of the free running optical amplifier 5 at 770nm from returning to the master laser 2. Preferably the optical isolation provided by the dichroic mirrors 6a, 6b and 6c is capable of providing optical isolation of < -50 dB. This method of optically isolating the master laser 2 from the first optical amplifier 5 is particularly suited for laser systems where the wavelength of the output field of the free running optical amplifier 5 is significantly different (i.e. greater than 10 nm different) from the operating wavelength the master laser 2.

It will be appreciated by the skilled reader that an alternative form of optical isolation may be located between the master laser 2 and the optical amplifier 5. By way of example, Figure 3 presents an alternative laser system in accordance with a second embodiment of the present invention, as generally depicted by reference numeral 28. The laser system 28 presented in Figure 3 is similar to the laser system 1 described above, and presented in Figures 1 and 2, with the exception that the dichroic mirrors 6 are replaced by standard mirrors 29 and an optical isolator 30 is located within the optical path between the master laser 2 and the optical amplifier 5. This embodiment does not require there to be a difference between the wavelength of the output field of the free running optical amplifier 5 and the operating wavelength the master laser 2.

The above described laser systems 1 and 28 can provide a high power output field 12 (~9.4 W) which is greater than that which can be achieved by the independent operation of either the master laser 2 or the first optical amplifier 5. Most significantly, the wavelength of the output field 12 is tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the master Ti:sapphire laser 2. This is around two orders of magnitude greater that the Nd:YAG laser systems known in the prior art e.g. those disclosed within US patent number US 5,027,360. This is achieved even though the power of output field 4 generated by the master laser 2 is at least one order of magnitude greater than those employed within the laser systems of US patent number US 5,027,360. The applicants have found that the decreased stability of employing a higher power master laser, although not acceptable within free space communication systems and gravitational wave detectors, is an acceptable trade off for an optical trap laser system where increased tuneability of the operating wavelength of the generated output field is highly beneficial.

A further significant advantage of the laser systems 1 and 28 presented within Figure 1 to 3 is the fact that they are readily scalable through the inclusion of additional optical amplifiers 5. By way of example, Figure 4 presents an alternative laser system in accordance with an embodiment of the present invention, as generally depicted by reference numeral 31.

As can be seen from Figure 4, the continuous-wave output field 12 is now employed as a seed optical field for a second optical amplifier 5b i.e. the continuous-wave output field 12 is employed as a seed optical field for the second optical amplifier 5b resulting in the second optical amplifier 5b also being slaved to the master Ti:sapphire laser 2. A fourth dichroic mirror 6d is employed to redirect the optical field 12 into the second optical amplifier 5b.

It is again preferable for a second injection locking module 7b to also be located within the optical path between the first and second slave optical amplifiers 5 and 5b to ensure that the mode of the seed optical field 12 matches that of the second optical amplifier 5b. It is also beneficial for the stable operation of the laser system 31 to frequency lock the resonance condition of the second optical amplifier 5b to the seed optical field 12, in a similar manner to that described above.

The output field 32 of the second optical amplifier 5b is therefore combined with the output field 12 of the first optical amplifier 5b, and hence the output of the master Ti:sapphire laser 2, such that the laser system 31 provides a single output exhibiting a single transverse and longitudinal mode, single polarisation and a high phase-coherence with the first 4 and second 12 seed optical fields. Most significantly is the fact that the output field 32 has a power ~14 W which is effectively the sum of the powers of the output field 4 of the master Ti:sapphire laser 2, the output field 12 of the first optical amplifier 5 and the output field of the second optical amplifier 5b. Significantly, the wavelength of the output field 32 is again tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the master Ti:sapphire laser 2.

It is envisaged that the above described laser system 1 could in fact be scaled up by to provide an output field having a power equal to the sum of the power of the output field 4 of the master laser 2 and N additional optical amplifiers 5.

A number of phase locked injection-locked laser system have also been disclosed. These systems have the advantage that they provide a single output exhibiting a single transverse and longitudinal mode, a single polarisation and a high phase-coherence with the respective seed optical fields. An advantage of the disclosed laser systems is the fact that the output field of the injection-locked laser system is highly scalable thus providing a means for increasing the power of the generated output field.

A further advantage of the disclosed laser system resides in the fact that the generated output field is tuneable over a 400 nm wavelength range (around 660 nm to 1060nm) as controlled by the operating wavelength of the master laser 2. This is a result of the fact that Ti;Sapphire gain media are employed within the master laser 2 and the one or more optical amplifiers 5 located in series with the master laser 2. By comparison Nd:YAG laser systems of the prior art are only tuneable over a range of around 0.05nm. Thus, unlike the Nd:YAG laser systems of the prior art the present laser system able to be employed within optical traps where it is necessary to be able to tune the laser source to different atomic wavelengths depending on the particular atom required to be trapped.

A method and system for combining two or more optical fields is disclosed. A first continuous-wave high powered output field generated by a solid-state master laser is injected into a first solid state optical amplifier to produce a single output field from the laser system that exhibits a high phase-coherence with the output field of the master laser. The power of the output field equals the sum of powers of the master laser and that generated by the first optical amplifier, while exhibiting similar beams characteristics to that produced by the output field of the master laser i.e. it exhibits low noise, in a single transverse and longitudinal mode Gaussian beam, and has a single polarisation. The laser system is highly scalable in that N optical amplifiers may be located in series with the master laser to provide a single low noise, high power output field.

Throughout the specification, unless the context demands otherwise, the term “comprise” or “include”, or variations such as “comprises” or “comprising”, “includes” or “including” will be understood to imply the inclusion of a stated integer or group of integers, but not the exclusion of any other integer or group of integers.

Furthermore, reference to any prior art in the description should not be taken as an indication that the prior art forms part of the common general knowledge.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. The described embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilise the invention in various embodiments and with various modifications as are suited to the particular use contemplated. Therefore, further modifications or improvements may be incorporated without departing from the scope of the invention as defined by the appended claims.

Claims

1) A laser system comprising:
a first laser, the first laser comprising a Ti:sapphire gain medium that generates a first continuous-wave output field having a first frequency (f_1) and a first power (P_1), and
a first optical amplifier, the first optical amplifier comprising a Ti:sapphire gain medium that generates a second continuous-wave output field having a second frequency (f_2) and a second power (P_2),
wherein
the first continuous-wave output field is injected into the first optical amplifier resulting in the second continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the sum of the first (P_1) and the second (P_2) powers.

2) A laser system as claimed in claim 1 wherein the second power (P_2) is in the range $0.5\ P_1 > P2 < 1.5\ P_1$.

3) A laser system as claimed in either of claims 1 or 2 wherein the first power (P_1) is greater than or equal to 1 Watt.

4) A laser system as claimed in any of the preceding claims wherein the first power (P_1) is greater than or equal to 4 Watts.

5) A laser system as claimed in any of the preceding claims wherein the first optical amplifier comprises a ring cavity within an arm of which is located the Ti:sapphire gain medium.

6) A laser system as claimed in any of the preceding claims wherein the laser system further comprises a first injection locking module located within an optical path between the first laser and the first optical amplifier wherein the injection locking module provide a means for ensuring that the mode of the first continuous-wave output field matches that of the first optical amplifier.

7) A laser system as claimed in any of the preceding claims wherein the laser system further comprises a first optical isolator located within an optical path between the first laser and the first optical amplifier.

8) A laser system as claimed in claim 7 wherein the first optical isolator comprises one or more dichroic mirrors.

9) A laser system as claimed in any of the preceding claims wherein the laser system further comprises a first frequency lock control loop to frequency lock the second continuous-wave output field to the frequency of the first continuous-wave output field.

10) A laser system as claimed in any of the preceding claims wherein the laser system further comprises a second optical amplifier comprising a Ti:sapphire gain medium that generates a third continuous-wave output field having a third frequency (f_3) and a third power (P_3) wherein the second continuous-wave output field is injected into the second optical amplifier resulting in the third continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1), second (P_2) and third (P_3) powers.

11) A laser system as claimed in claim 10 wherein the laser system further comprises a second injection locking module located within an optical path between the first and second optical amplifiers wherein the second injection locking module provide a means for ensuring that the mode of the second continuous-wave output field matches that of the second optical amplifier.

12) A laser system as claimed in either of claims 10 or 11 wherein the laser system further comprises a second optical isolator located within an optical path between the first and second optical amplifiers.

13) A laser system as claimed in claim 12 wherein the second optical isolator comprises one or more dichroic mirrors.

14) A laser system as claimed in any of claims 10 to 13 wherein the laser system further comprises a second frequency lock control loop to frequency lock the third continuous-wave output field to the frequency of the second continuous-wave output field.

15) A method of combining two or more optical fields the method comprising:
providing a first laser comprising a Ti:sapphire gain medium to generate a first continuous-wave output field having a frequency (f_0) and a first power (P_1);
providing a first optical amplifier comprising a Ti:sapphire gain medium to generates a second continuous-wave output field having a second frequency (f_2) and a second power (P_2); and
injecting the first continuous-wave output field into the first optical amplifier causing the second continuous-wave output field to form a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the sum of the first (P_1) and the second (P_2) powers.

16) A method of combining two or more optical fields as claimed in claim 15 wherein the second power (P_2) is in the range $0.5\ P_1 > P_2 < 1.5\ P_1$.

17) A method of combining two or more optical fields as claimed in either of claims 15 or 16 wherein the first power (P_1) is greater than or equal to 1 Watt or greater than or equal to 4 Watts.

18) A method of combining two or more optical fields as claimed in any of claims 15 to 17 wherein providing a first optical amplifier comprises providing a ring cavity within an arm of which is located the Ti:sapphire gain medium.

19) A method of combining two or more optical fields as claimed in any of claims 15 to 18 wherein the method further comprises matching the mode of the first continuous-wave output field to that of the first optical amplifier.

20) A method of combining two or more optical fields as claimed in any of claims 15 to 19 wherein the method further comprises optically isolating the first solid state laser from the first optical amplifier.

21) A method of combining two or more optical fields as claimed in any of claims 15 to 20 wherein the method further comprises frequency locking the first optical amplifier to the first continuous-wave output field.

22) A method of combining two or more optical fields as claimed in any of claims 15 to 21 wherein the method further comprises providing a second optical amplifier comprising a Ti:sapphire gain medium to generates a third continuous-wave output field having a third frequency (f_3) and a third power (P_3) wherein the second continuous-wave output field is injected into the second optical amplifier resulting in the third continuous-wave output field forming a single output field for the laser system at the first frequency (f_1) and a power (P_{out}) substantially equal to the summation of the first (P_1), second (P_2) and third (P_3) powers.

23) A method of combining two or more optical fields as claimed in claim 22 wherein the method further comprises matching the mode of the second continuous-wave output field to that of the second optical amplifier.

24) A method of combining two or more optical fields as claimed in either of claims 22 or 23 wherein the method further comprises optically isolating the first optical amplifier from the second optical amplifier.

25) A method of combining two or more optical fields as claimed in any of claims 22 to 24 wherein the method further comprises frequency locking the second optical amplifiers to the second continuous-wave output field.

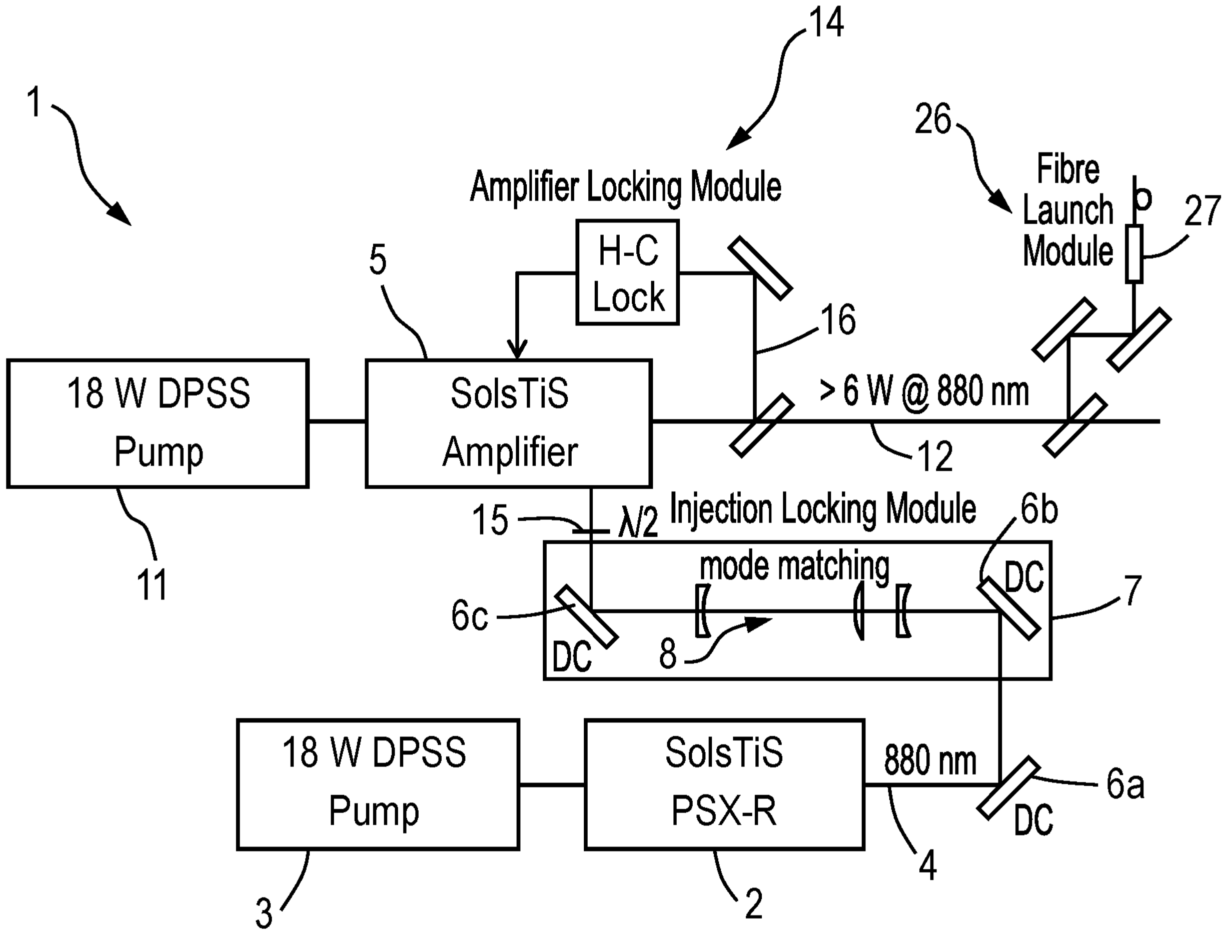
1
14
Amplifier Locking Module
H-C Lock
26
Fibre Launch Module
27
5
16
18 W DPSS Pump
SolsTiS Amplifier
> 6 W @ 880 nm
12
11
15
λ/2
Injection Locking Module
6b
mode matching
DC
7
6c
DC
8
18 W DPSS Pump
SolsTiS PSX-R
880 nm
6a
DC
3
2
4

Fig. 1

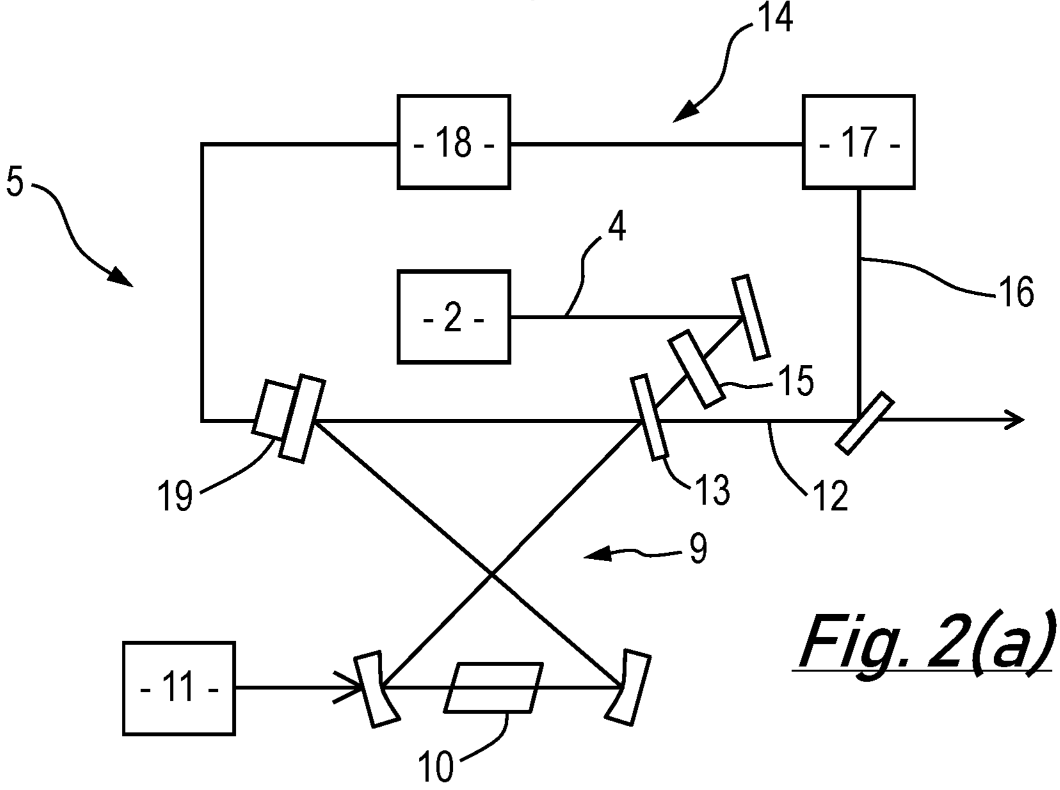

Fig. 2(a)

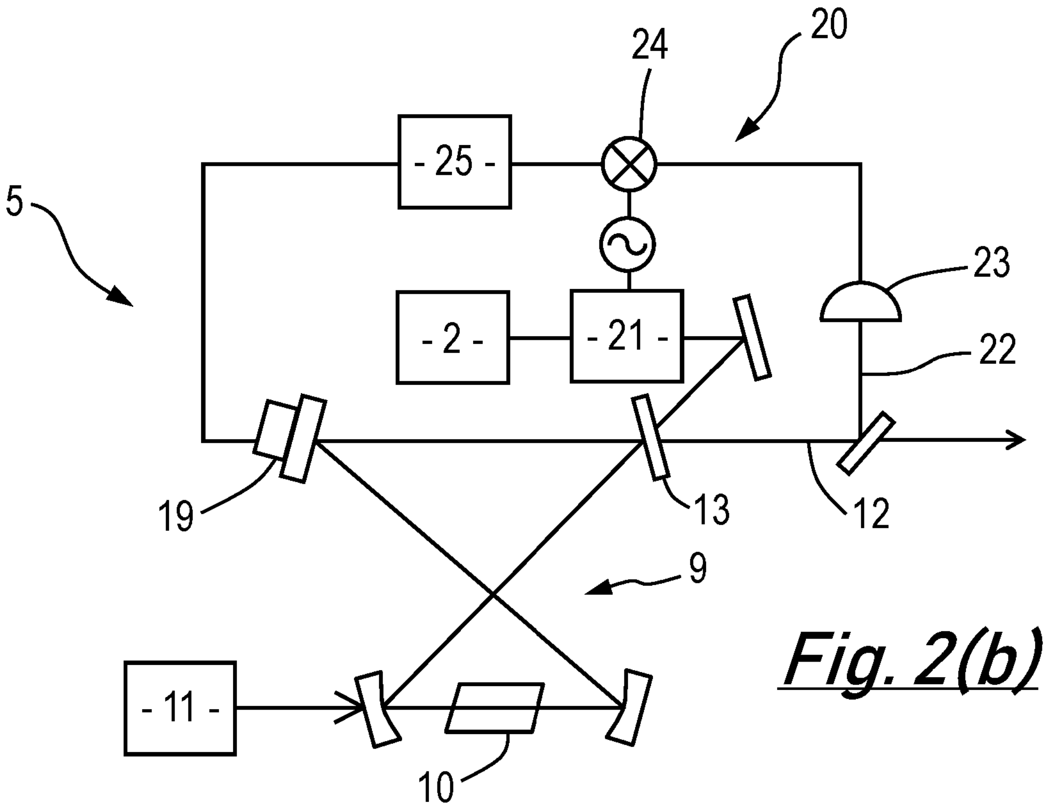

Fig. 2(b)

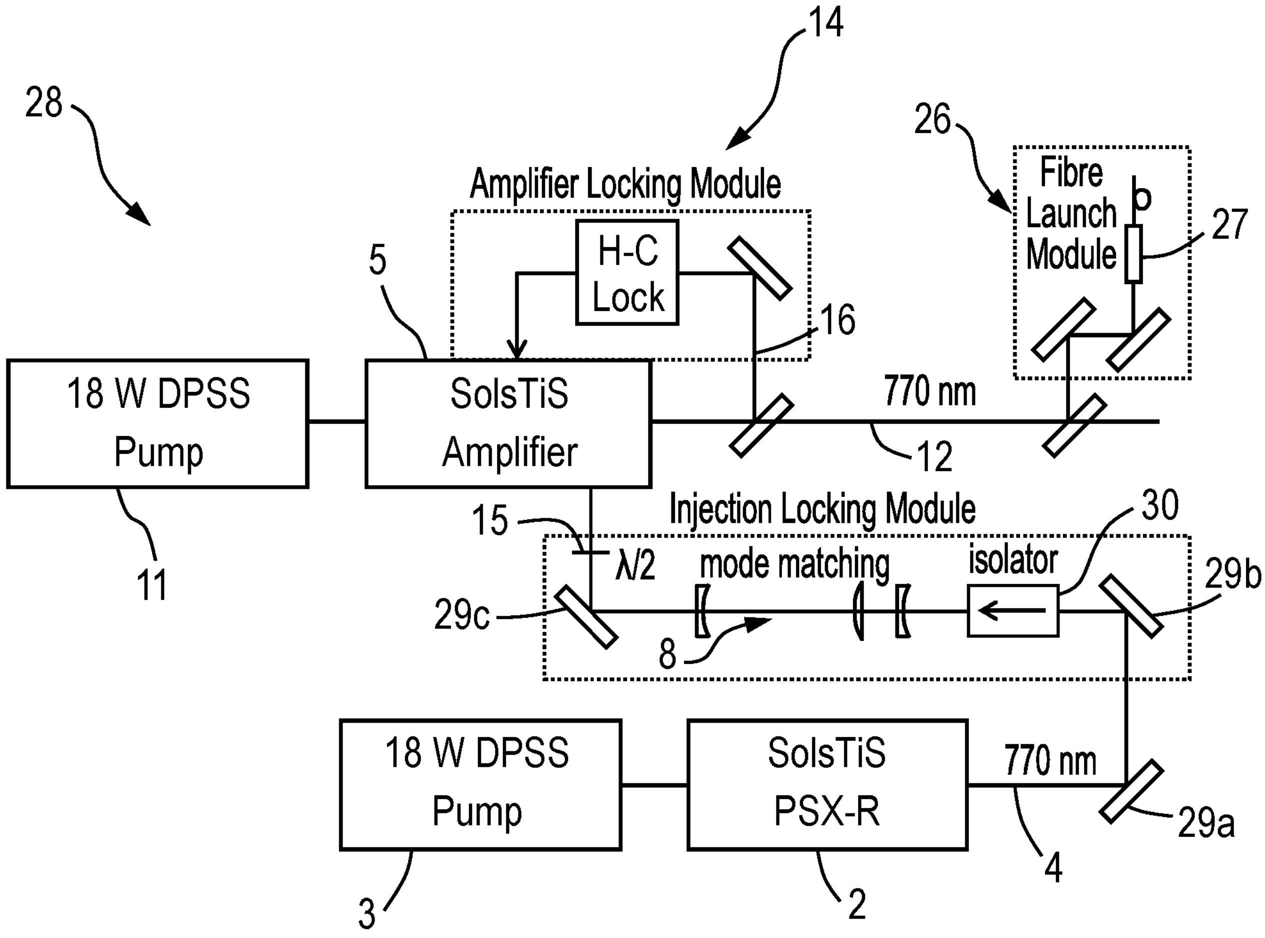
28
14
Amplifier Locking Module
H-C Lock
5
16
26
Fibre Launch Module
27
18 W DPSS Pump
SolsTiS Amplifier
770 nm
12
11
15
Injection Locking Module
30
λ/2
mode matching
isolator
29b
29c
8
18 W DPSS Pump
SolsTiS PSX-R
770 nm
29a
3
2
4

Fig. 3

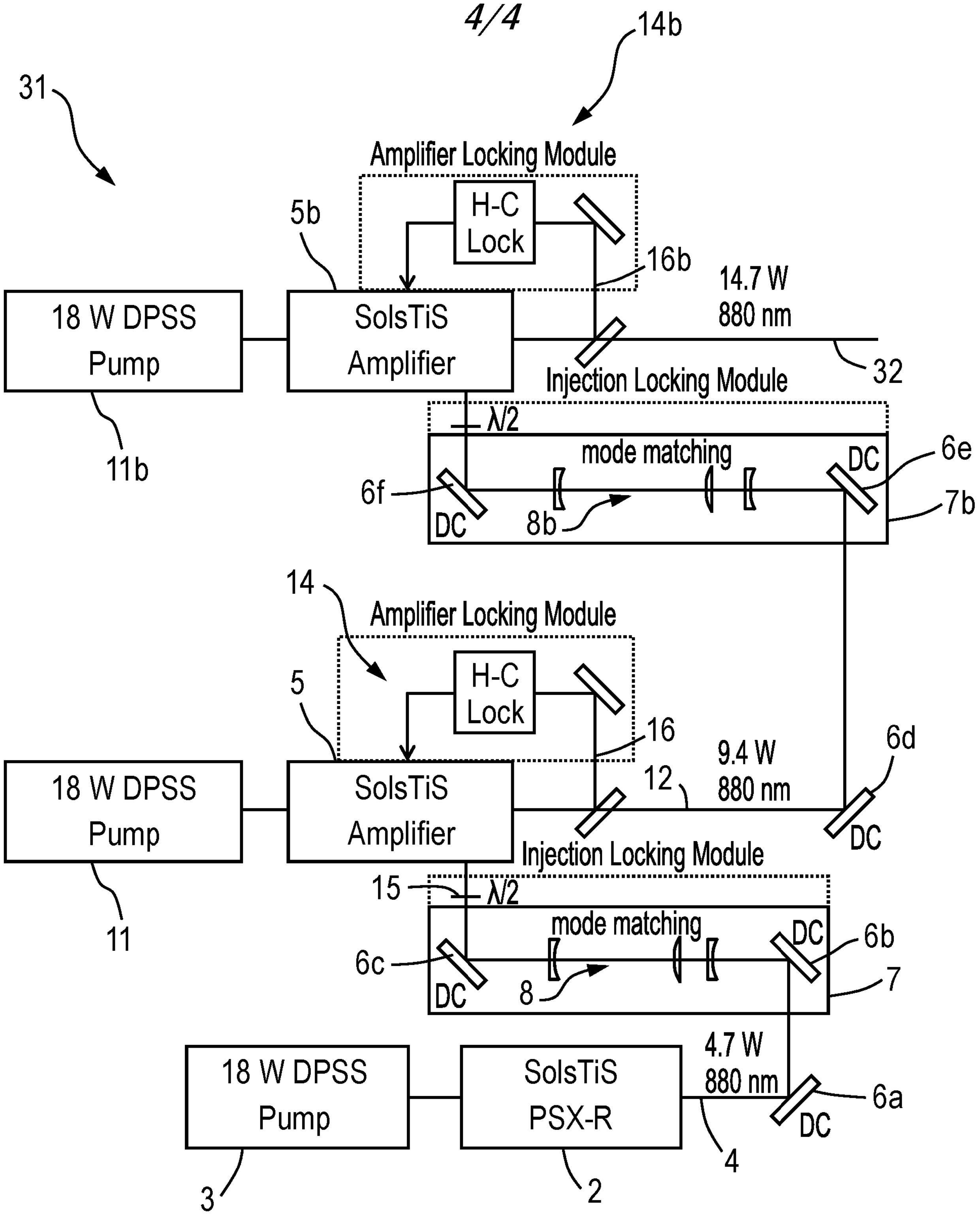
31
14b
Amplifier Locking Module
H-C Lock
5b
16b
14.7 W
880 nm
18 W DPSS Pump
SolsTiS Amplifier
32
Injection Locking Module
11b
λ/2
mode matching
DC
6e
6f
7b
DC
8b
14
Amplifier Locking Module
H-C Lock
5
16
9.4 W
880 nm
6d
12
18 W DPSS Pump
SolsTiS Amplifier
DC
Injection Locking Module
11
15
λ/2
mode matching
DC
6b
6c
7
DC
8
4.7 W
880 nm
18 W DPSS Pump
SolsTiS PSX-R
6a
DC
3
2
4

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2019/051831

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S3/16 H01S3/23 H01S3/10
ADD. H01S3/00 H01S3/0941 H01S3/13 H01S3/08 H01S3/083
H01S3/094

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HOLGER MUELLER ET AL: "Phase-Locked, Low-Noise, Frequency Agile Titanium: Sapphire Lasers for Simultaneous Atom Interferometers", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 27 July 2005 (2005-07-27), XP080202710, DOI: 10.1364/OL.31.000202 pages 1-2 -----	1-3,5,9, 15-18,21
X	US 2017/244215 A1 (WATANABE SHUNTARO [JP] ET AL) 24 August 2017 (2017-08-24) columns 209-213; claims 16-20; figures 2,6,15,16,19 ----- -/--	1,7-14, 20-25

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search 19 November 2019	Date of mailing of the international search report 29/11/2019
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Moskowitz, Pamela

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 027 360 A (NABORS C DAVID [US] ET AL) 25 June 1991 (1991-06-25) cited in the application column 2, lines 27-29; figure 1 column 3, lines 35-36 column 4, line 14 - column 6 -----	1,5-7,9, 15,18-21
X	WINKELMANN L ET AL: "Injection-locked single-frequency laser with an output power of 220 W", APPLIED PHYSICS B ; LASERS AND OPTICS, SPRINGER, BERLIN, DE, vol. 102, no. 3, 11 February 2011 (2011-02-11), pages 529-538, XP019886481, ISSN: 1432-0649, DOI: 10.1007/S00340-011-4411-9 cited in the application abstract; figures 1,4,8 Section 2.4 -----	1,3-5,7, 9,15,20, 21
X	VASA N J ET AL: "COMPARATIVE STUDY OF SPECTRAL NARROWING OF A PULSED TI:SAPPHIRE LASER USING PULSED AND CW INJECTION SEEDING", APPLIED PHYSICS B: LASERS AND OPTICS, SPRINGER INTERNATIONAL, BERLIN, DE, vol. B62, no. 1, January 1996 (1996-01), pages 51-57, XP000551456, ISSN: 0946-2171, DOI: 10.1007/BF01081247 page 1, column 2; figures 1,5 -----	1,5-8, 15,18-20
E	WO 2019/150097 A1 (M SQUARED LASERS LTD [GB]) 8 August 2019 (2019-08-08) the whole document -----	1,5-7,9, 15,18-21

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2019/051831

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		US 2017244215 A1	24-08-2017
		WO 2016103483 A1	30-06-2016
US 5027360 A	25-06-1991	NONE	
WO 2019150097 A1	08-08-2019	GB 2570519 A	31-07-2019
		WO 2019150097 A1	08-08-2019