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(54) Title: RAMAN AMPLIFIERS

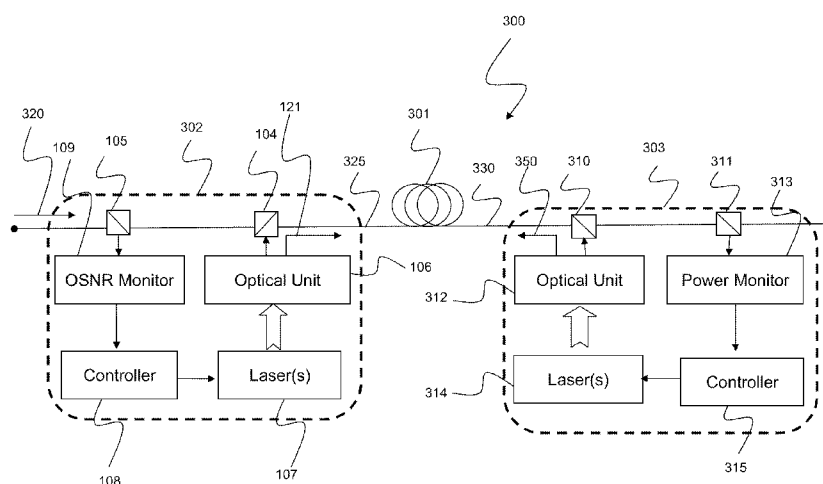


Fig. 3

(57) **Abstract:** An optical amplifier system is disclosed, comprising an optical fibre (301) for carrying an optical signal and a light source (107, 314) for emitting light into the fibre to induce Raman gain of the optical signal passing along the fibre. An optical signal to noise ratio (OSNR) monitor (109) is coupled to the fibre for measuring OSNR of the optical signal. A controller (108) is coupled to the light source (107) and the OSNR monitor for controlling the Raman gain by setting the power of the light source based on the measured OSNR. In order to improve the OSNR, co- and counter - propagating pump light is provided for the Raman amplification in the fibre (301).

Raman Amplifiers**Field of the Invention**

- 5 The present invention relates to Raman amplifiers and, more particularly to control of pump lasers for such amplifiers.

Background of the Invention

- 10 In this specification the term “light” will be used in the sense that it is used in optical systems to mean not just visible light, but also electromagnetic radiation having a wavelength outside that of the visible range.

- Amplifiers are needed in telecommunications systems to overcome losses such as
15 fibre loss, component loss and splice loss. There are many different types of amplifier including erbium doped fibre amplifiers (EDFAs), semiconductor optical amplifiers (SOAs) and Raman amplifiers. Raman amplifiers are of interest, particularly distributed Raman amplifiers (DRA), to 100G system designers since DRA can improve optical signal to noise ratio (OSNR) performance compared to systems having only
20 conventional EDFAs . The OSNR performance is particularly important for higher bit rate communication.

- There are other advantages of Raman amplifiers, including any wavelength operation, wide gain bandwidth and relatively flat gain. The optical fibre Raman amplification
25 process involves the injection of a large amount of pump energy into an optical fibre. Energy is released at a different frequency through inelastic scattering by optical phonons. Stimulated gain can occur if signal light is within the Raman frequency gain band. In a Raman amplifier the amount of stimulated gain is generally controlled through correct setting of the pump power, giving rise to the problem of how to
30 determine the correct pump power. Raman pumps can provide co-propagating light travelling in the same direction as a signal passing along a span of optical fibre, or counter-propagating light travelling in the opposite direction to the signal.

- Although Raman amplifiers are used in telecommunications systems, their use has to
35 some extent been limited due to cost limitations and the development of EDFAs as an alternative amplification scheme. However, DRAs which use the system transmission

fibre as the gain medium can improve performance above that with just EDFAs by improving OSNR through the system. The benefit of higher OSNR is that signals can travel further along fibre before needing amplification which is key for long fibre spans to allow for hut skipping or for maintaining existing 10G span lengths when deploying higher bit rates such as 100G systems.

Optimum noise figure (NF) is usually achieved using co-pumped Raman amplifiers. This is because the signal sees gain at the start of transmission in the span before it can reduce in power towards the noise power level, thus reducing impact on the OSNR. For a counter-pumped DRA, signal gain occurs at the end of the fibre transmission so the signal will have reduced in power, moving closer to the noise level, prior to seeing gain, and the OSNR is thus degraded. Another advantage of co-pumped Raman amplifiers is that double Rayleigh backscatter (DRB), also known as multiple path interference (MPI), that has been generated by a full pass along the span, "sees" fibre loss twice as it passes through the mid and end stage of the fibre. The MPI is therefore reduced compared to amplification at the far end of the span.

However, co-pumped Raman amplifiers have problems, including high non-linearity impacts (if the signal gets too high in power), high levels of polarisation dependent gain (PDG) and high susceptibility to pump relative intensity noise (RIN) transfer. In many cases, co-propagating distributed Raman amplification is not used due to these issues, particularly due to RIN transfer which, in a fibre Bragg grating (FBG) pump, nears about -110dB/Hz.

To solve the co-pumped RIN transfer problem, a chirped distributed feedback (DFB) 14xx laser called the Inner Grating Multi-mode (IGM) pump has been developed ("Pump Laser Module for Co-propagating Raman Amplifier" Y. Ohki et al, Furukawa Review no 24 2003 p6). This pump has RIN levels less than -140dB/Hz. However, these are not commonly available at the high optical powers needed in most Raman amplifiers.

An alternative approach is to use counter-pumped Raman amplifiers. The NF is not as good in this scheme when compared to a co-pumped amplifier and DRB MPI is a problem which needs to be controlled. However, counter-pumped Raman amplification is still useful due to averaging effects of pump RIN transfer and PDG since the pump

light is travelling in the opposite direction to the signal. For this reason, counter pumped Raman amplifiers are a more common implementation.

5 Raman amplifiers are also valuable because wide gain bandwidths can be achieved by multiplexing pump lasers of different wavelengths. Conventionally this is achieved by multiplexing a number of fixed wavelength pumps. An alternative approach is to multiplex tuneable pump lasers which provides added flexibility and control when optimising the Raman system.

10 With multiple pump wavelength Raman amplifiers, however, due to pump-pump Raman interaction, longer wavelength pump light travels further into the optical fibre than shorter wavelength pump light, and consequently the NF of longer wavelength signals is lower than that of the shorter wavelength signals ("Independent Control of the Gain and Noise Figure Spectra of Raman Amplifiers using Bi-Directional Pumping" Y. Emori et al, Furukawa Review No 23 2003 p 11). To address this, co and counter pumping can be used to remove the NF tilt if co-pumping is only implemented for the short wavelength pumps.

Summary of the Invention

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According to one aspect of the present invention, there is provided an optical amplifier system comprising an optical fibre for carrying an optical signal. A first light source is provided for emitting co-propagating light into a section of the fibre to induce Raman gain of the optical signal passing along the section of fibre. A second light source is provided for emitting counter-propagating light, travelling in the opposite direction to the optical signal, into the section of the fibre. An OSNR monitor is coupled to the fibre for measuring OSNR of the optical signal and a power monitor is coupled to the fibre for measuring an optical power of the optical signal. A first controller is coupled to at least one of the light sources and the OSNR monitor for controlling the Raman gain by setting the power of the light source to which the controller is coupled based on the measured OSNR. A second controller is coupled to at least the other light source and the power monitor for controlling the power of the other light source based on the measured optical power of the optical signal

35 It will be appreciated that the section of fibre may encompass part or all of the optical fibre span.

The OSNR monitor may be configured to measure the OSNR at a front end of the section of fibre. The OSNR monitor may be configured to measure the OSNR at a back end of the section of fibre. In such an arrangement, a telemetry channel may be used to transmit the OSNR measurement to the controller, which may be located at a front end of the section of fibre. Alternatively, the first light source may be coupled to the fibre downstream of the OSNR monitor for emitting co-propagating light into another section of fibre.

10 The first light source, the OSNR monitor and the controller may be included in a first pump unit which is located at the front of the section of fibre and is arranged to inject co-propagating light into the fibre.

The system may further comprise a second pump unit located at a back end of the section of fibre. The second pump unit may comprise the second light source, the power monitor and the second controller.

It will be appreciated that any combination of OSNR monitors and power monitors, located anywhere in the fibre and used independently or together, may be used to control light sources anywhere along the fibre. Furthermore, it will be appreciated that light may be emitted in either or both directions along the fibre, and one pump unit may emit both co- and counter-propagating light.

The OSNR monitor and power monitor may be configured to measure the OSNR and the optical power, respectively, spectrally by monitoring one or more channels of the optical signal passing along the fibre. Furthermore, the fibre may carry optical signals on channels of different wavelengths, and the OSNR monitor and power monitor may be configured to measure the OSNR and the optical power spectrally by monitoring some or all of the wavelengths.

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The amplifier system may further comprise an erbium doped fibre amplifier, EDFA, coupled to the fibre so as to form a hybrid Raman-EDFA configuration.

35 According to another aspect of the present invention, there is provided a method for controlling Raman gain in an optical amplifier system having an optical fibre for carrying

an optical signal. The method comprises emitting co-propagating light into the fibre to induce Raman gain of the optical signal passing along the fibre, emitting counter-propagating light of the fibre, measuring OSNR of the optical signal, measuring an optical power of the optical signal, controlling the power of the emitted co-propagating light on the basis of the measured OSNR, and controlling the power of the emitted counter-propagating light on the basis of the measured optical power.

The invention also provides a computer program configured so that, when run in an optical amplifier system as described above, it will cause the system to carry out the methods described above.

Brief Description of the Drawings

In order that the invention may be more fully understood, some of embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig. 1a is a schematic illustration of a Raman amplifier system;
Fig. 1b is a schematic illustration of an alternative Raman amplifier system;
Fig. 2 is a schematic illustration of an alternative Raman amplifier system;
Fig. 3 is a schematic illustration of an alternative Raman amplifier system;
Fig. 4 is a schematic illustration of an alternative Raman amplifier system; and
Fig. 5 is a schematic illustration of an alternative Raman amplifier system.

Detailed Description of Preferred Embodiments

Fig. 1a is a schematic illustration of a Raman amplifier system 100 for use in a fibre optic communication link having an optical fibre span 101. The system 100 includes a "co-pump" Raman unit 102, which is located at the front 125 of the span 101. The co-pump unit 102 is arranged to inject co-propagating light 121 into the span 101. The co-propagating light 121 travels in the same direction as an optical signal 120 passing along the span 101.

The co-pump unit 102 in Fig. 1a has one or more light sources such as a laser 107. The laser 107 is capable of supplying pump light at a power into the span 101 to induce Raman gain of the optical signal 120 in the span 101. It will be appreciated that the

term “pump light” as used herein refers to light intended to induce amplification of the optical signal, but which does not normally “pump” the fibre to cause a population inversion, as is the case with conventional amplifiers. However the term is used herein for consistency with the art. The co-pump unit 102 also has an optical unit 106 for manipulating the light, a controller 108 and an OSNR monitor 109. Light output from the laser 107 passes through the optical unit 106 which may include inter alia depolarisers, wavelength combiners and isolators. Light output from the optical unit 106 is injected into the span 101 through a signal/pump combiner 104. A signal tap 105 is located upstream of the signal/pump combiner 104 and diverts a small proportion of signal light travelling along the fibre to the monitor 109, which can be used to measure OSNR of the optical signal 120. The controller 108 then sets the power of the laser 107 based on the OSNR measurement received from the monitor 109 to achieve the optimum Raman gain performance.

Fig. 1b is a schematic illustration of an alternative Raman amplifier system 100 for use in the fibre optic communication link. Many features of Fig. 1b are similar to those of the Fig. 1a, and are referred to by the same reference numerals where appropriate. In this example, an OSNR monitor 139 is located at the back 130 of the span instead of (or in addition to) the OSNR monitor 109 in the co-pump unit 102 at the front 125 of the span 101 as shown in Fig. 1a. The OSNR of the optical signal 120 at the back 130 of the span 101 is measured by the monitor 139, and a telemetry channel 140 is used to feed the OSNR measurements to the controller 108 located at the front 125 of the span 101. The controller 108 then sets the power of the laser 107 based on the measured OSNR to achieve the optimum Raman gain.

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It will be noted that it is also possible for the OSNR monitor 135 at the back end of the span to provide control for a co-pump module (not shown) further forward (*i.e.* downstream) in the span, as well as backward in the span as shown in Fig. 1b. In this case the controller for the laser(s) in the downstream co-pump module may be connected to the OSNR monitor, or a forward telemetry channel (not shown) may be used to set the controller that then defines the co-propagating pump power(s). In this case the co-propagating pumps could be set to correct for OSNR variations in the span where the signals have passed the OSNR monitor rather than before reaching the OSNR monitor.

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Fig. 2 is a schematic illustration of an alternative Raman amplifier system 200 for use in a fibre optic communication link having an optical fibre span 201. The system includes a “counter-pump” Raman unit 202 which is located at the back 230 of the span 201. Many features of the counter-pump unit 202 are similar to those of the co-pump unit 102 of Fig. 1a, i.e. a laser 207, an optical unit 206, an OSNR monitor 209, a controller 208, and a signal/pump combiner 204 and a signal tap 205. The counter-pump unit 202 is arranged to inject counter-propagating light 221 into the span 201. The counter-propagating light travels in the opposite direction to an optical signal 220 transmitted through the span 201. The OSNR of the optical signal 220 at the back 230 of the span 201 is measured by the monitor 209 coupled to the span 201 by the signal tap 205 and forwarded to the controller 208. The controller 208 uses the measured OSNR to set the power of the laser 207 to achieve the optimum Raman gain performance.

Fig. 3 is a schematic illustration of an alternative Raman amplifier system 300 used in a fibre optic communications link having an optical fibre span 301. The system 300 has a co-pump Raman unit 302 and a counter-pump Raman unit 303. The co-pump unit 302 is located at the front 325 of the span 301 and has the same features and reference numerals as the co-pump unit 102 of Fig. 1a.

The counter-pump unit 303 of Fig. 3 is located at the back 330 of the span 301 and has similar features to the counter-pump unit 202 of Fig. 2, i.e. an optical unit 312, a laser 314, a controller 315 and a signal/pump combiner 310 and a signal tap 311. A power monitor 313 in the counter-pump unit 303 measures the total power of the optical signal which has been carried to the back 330 of the span 301. A controller 315 of the counter-pump unit 303 controls the power of the laser 314 of the counter-pump unit 303 on the basis of feedback of the power measurements received from the monitor 313.

Optimum Raman gain and NF can be achieved by using the combined arrangement of the co- and counter-pump units 302, 303 of Fig. 3. In this example, the monitored OSNR is used to control the pump power provided by the co-pump unit 302 and the monitored power is used to control the pump power provided by the counter-pump unit 303. It is thus possible to optimise both parameters (OSNR and power) independently. In some circumstances, the OSNR measurement at the front 325 of the span 301 may be used to set the wavelength of the laser 107 if a tuneable or set of tuneable pump lasers have been installed. It may also be appropriate for the laser 314 of the counter-

pump unit 303 to cover the whole bandwidth, but for the laser 107 of the co-pump unit 302 to cover the short wavelengths. This is to because when pump lasers of more than one wavelength are coupled into a fibre, the Raman gain process also acts on the pump light, so energy from the short wavelength pump light is passed to the long wavelength pump light as they travel into the fibre. For a counter pumped scheme this results in the longer wavelength pump light travelling further towards the front of the fibre span and so provides gain at the longer wavelengths closer to the start of the span. The result is better NF for the longer wavelength channels compared to the shorter wavelength channels. To remedy this if co-propagating pump light at only the shorter wavelengths is injected into the fibre span this improves the NF of the short wavelength channels as described above and thus this can even out the NF across all channels (as described in "Independent Control of the Gain and Noise Figure Spectra of Raman Amplifiers Using Bi-Directional Pumping" Y. Emori et al Furukawa Review No 23 2003 p 11).

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It will be appreciated that the power for the laser 107 of the co-pump unit 302 may not need to be too high compared to that of the laser 314 of the counter-pump unit 303 as the aim is to even out the NF at the short wavelength channels rather than to provide very high gain. Therefore, the power of the laser 107 in the co-pump unit 302 may be low enough for a DFB type laser design with low RIN, for example.

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It will be further appreciated that the optical signal 320 of Fig. 3 may have one or more channels and the measurements of the OSNR and the power can be achieved by spectral monitoring of all or some of the channels. It is possible that the span 301 may carry optical signals on channels of different wavelengths. If so, the signal tap couplers 105, 311 may divert a single signal channel for the OSNR and power measurements. It may also be possible that the OSNR and power measurement techniques use a reference channel that exists within the Raman gain bandwidth but not within the signal channel band. It will be also appreciated that the same principle applies for signals 120, 220 and 420 of Figs. 1a, 1b, 2 and 4, and measurement of OSNR and/or power can occur on one, some or all of the applied signal channels.

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Fig. 4 is a schematic illustration of an alternative Raman amplifier system 400 for use in a fibre optic communications link having an optical fibre span 401. The system 400 has a co-pump Raman unit 402 which has the same features and reference numerals

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as those of the co-pump unit 102 of Fig. 1a. The system 400 also has an EDFA 440 at the back 430 of the span 401. It will be appreciated that it may be possible to use a counter-pump unit (as shown in Fig. 2) instead of or as well as the co-pump unit 402. It may be possible to provide further co-pump and/or counter-pump units following the EDFA 440. Such an arrangement would provide a Raman-EDFA-Raman hybrid configuration.

The co-pump unit 402 of Fig. 4 optimises the OSNR in Raman gain, and gain flatness is optimised by the EDFA 440 as well as providing high power output. It is also possible that other components such as a dynamic gain equaliser or a wavelength selective switch gain flattening filter (WSS GFF) may be used instead of the EDFA 440.

Fig. 5 is an illustration of an alternative Raman Amplifier system 500 that includes a Raman pump module 502 incorporating both co-propagating pump laser (s) 107 and counter-propagating pump laser(s) 207 which are controlled using a controller 508 connected to a single OSNR Monitor 109. The OSNR monitor 109, pump lasers 107, 207, optical units 106, 206, signal/pump combiners 104, 204, signal tap 105 and system spans 101 and 201 shown in Fig. 5 are the same as would be used in those illustrations of Fig. 1 and Fig. 2. The controller 508 in this case takes OSNR information and set pumps 107 and 207 to provide the overall best performance through the spans. All other performance description is the same as detailed for other embodiments above.

It will be further appreciated that the topology within pump units 102, 202, 302, 303, 402 and 502 of all preceding illustrations are representations of the Raman amplifier module, and other combinations of units, lasers, controllers, monitors, taps and combiners, and other suitable functional blocks, could be used to provide a similar function. It will be further appreciated that the arrangements of the foregoing description may be applied to a lumped Raman amplifier .

Although the invention has been described in terms of preferred embodiments as set forth above, it should be understood that these embodiments are illustrative only and that the claims are not limited to those embodiments. Those skilled in the art will be able to make modifications and alternatives in view of the disclosure which are contemplated as falling within the scope of the appended claims. Each feature

disclosed or illustrated in the present specification may be incorporated in the invention, whether alone or in any appropriate combination with any other feature disclosed or illustrated herein.

CLAIMS:

1. An optical amplifier system comprising:
 - an optical fibre for carrying an optical signal;
 - 5 a first light source for emitting co-propagating light, travelling in the same direction as the optical signal, into a section of the fibre to induce Raman gain of the optical signal passing along the section of the fibre;
 - a second light source for emitting counter-propagating light, travelling in the opposite direction to the optical signal, into the section of the fibre;
 - 10 an optical signal to noise ratio, OSNR, monitor coupled to the fibre for measuring OSNR of the optical signal;
 - a power monitor coupled to the fibre for measuring an optical power of the optical signal;
 - a first controller coupled to at least one of the light sources and the OSNR
 - 15 monitor for controlling the Raman gain by setting the power of the light source to which the first controller is coupled based on the measured OSNR; and
 - a second controller coupled to at least the other light source and the power monitor for controlling the power of the other light source based on the measured optical power of the optical signal.
 - 20
2. An optical amplifier system according to claim 1, wherein the OSNR monitor is configured to measure the OSNR at the front of the section of fibre.
3. An optical amplifier system according to claim 1 or 2, wherein the OSNR
- 25 monitor is configured to measure the OSNR at the back of the section of fibre.
4. An optical amplifier system according to claim 3, wherein a telemetry channel is used to transmit the OSNR measurement to the controller.
- 30 5. An optical amplifier system according to claim 3 or 4, wherein the first light source is coupled to the fibre downstream of the OSNR monitor for emitting co-propagating light into a subsequent section of fibre.
6. An optical amplifier system according to any preceding claim, further comprising
- 35 a subsequent optical component coupled to the fibre for flattening a profile of the Raman gain.

7. An optical amplifier system according to claim 6, wherein the optical component is selected from the group comprising:

- 5 erbium doped fibre amplifier;
dynamic gain equaliser;
gain flattening filter; and
wavelength selective switch.

8. An optical amplifier system according to any preceding claim, wherein the first
10 light source, the OSNR monitor and the first controller are included in a first pump unit which is located at the front of the section of fibre and is arranged to inject co-propagating light into the fibre.

9. An optical amplifier system according to claim 8, wherein the second light
15 source, the power monitor and the second controller are included in a second pump unit located at the back of the section of fibre.

10. An optical amplifier system according to claim 9, wherein the OSNR and optical
20 power measurements are used to adjust the power of the light sources to control the Raman gain of the optical signal.

11. An optical amplifier system according to claim 9 or 10, wherein the OSNR
25 monitor and power monitor are configured to measure the OSNR and the optical power, respectively, spectrally by monitoring one or more channels of the optical signal passing along the fibre.

12. An optical amplifier system according to claim 9 or 10, wherein the fibre carries
30 optical signals on channels of different wavelengths, and wherein the OSNR monitor and power monitor are configured to measure the OSNR and the optical power spectrally by monitoring some or all of the wavelengths.

13. An optical amplifier system according to any of claims 9 to 12, further
35 comprising an erbium doped fibre amplifier, EDFA, coupled to the fibre so as to form a hybrid Raman-EDFA configuration.

14. An optical amplifier system according to any preceding claim, wherein the first and second light sources are each a laser or set of lasers.
15. An optical amplifier system according to any preceding claim, having one or more OSNR monitors and one or more power monitors coupled to the fibre at a plurality of locations along the fibre, each coupled to a controller for controlling the power of light sources emitting light into the fibre to induce Raman gain in the optical signal passing along the fibre.
16. A distributed Raman amplifier comprising the optical amplifier system according to any preceding claim.
17. A lumped Raman amplifier comprising an optical amplifier system according to any of claims 1 to 15.
18. A method for controlling Raman gain in an optical amplifier system having an optical fibre for carrying an optical signal, the method comprising:
emitting co-propagating light into a section of the fibre to induce Raman gain of the optical signal passing along the section of fibre;
emitting counter-propagating light into the section of the fibre;
measuring optical signal to noise ratio, OSNR, of the optical signal;
measuring an optical power of the optical signal;
controlling the power of the emitted co-propagating light on the basis of the measured OSNR; and
controlling the power of the emitted counter-propagating light on the basis of the measured optical power.
19. A method according to claim 18, wherein the co-propagating and counter-propagating light is emitted simultaneously into the fibre.
20. A computer program, comprising computer readable code which, when run in an optical amplifier system, causes the system to perform the method of claim 18 or 19.

21. A computer program, comprising computer readable code which, when run by an optical amplifier system, causes the system to operate as the system of any of claims 1 to 17.
- 5 22. A computer program product comprising a computer readable medium and a computer program according to claim 20 or 21, wherein the computer program is stored on the computer readable medium.

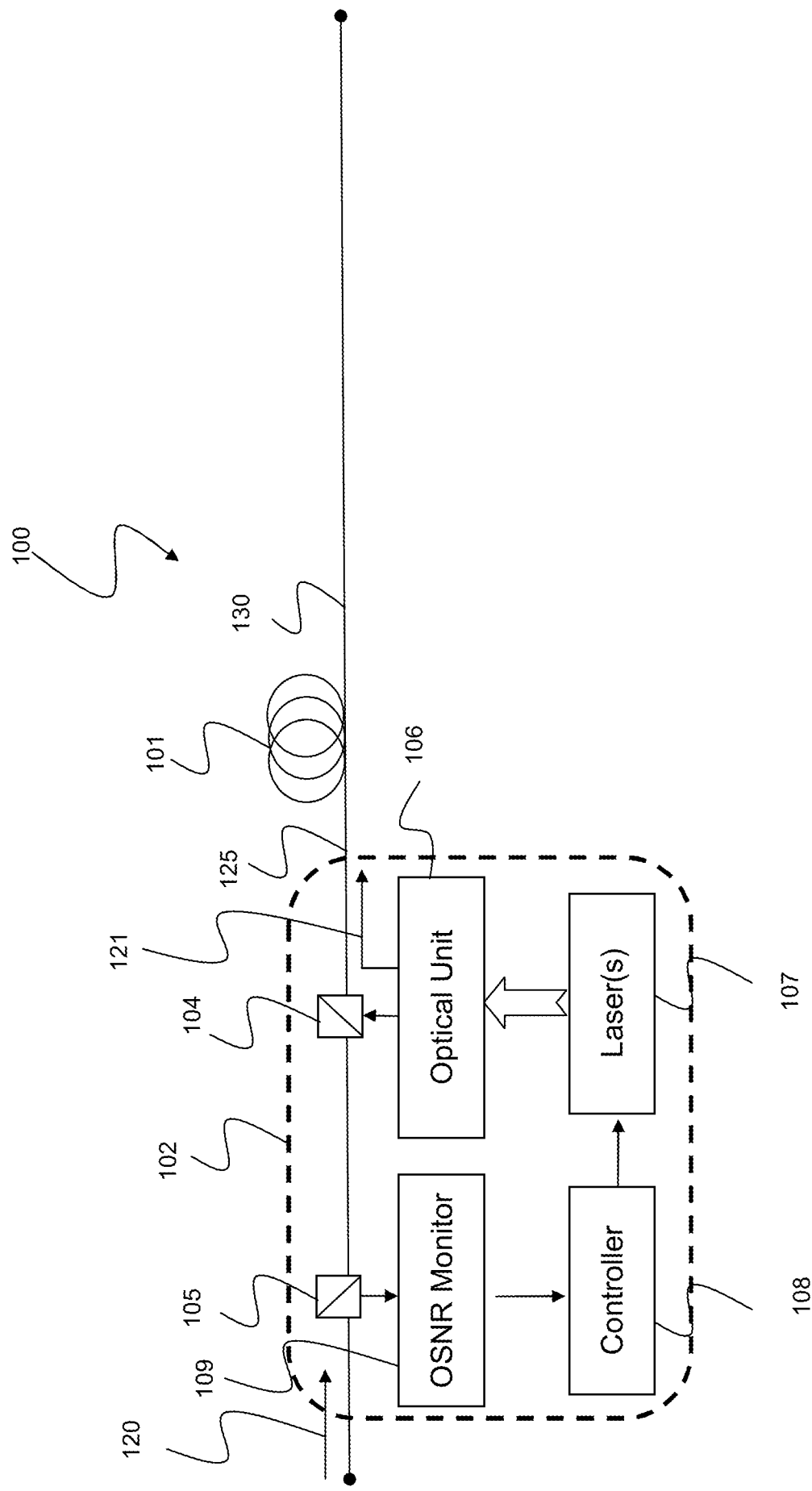


Fig. 1a

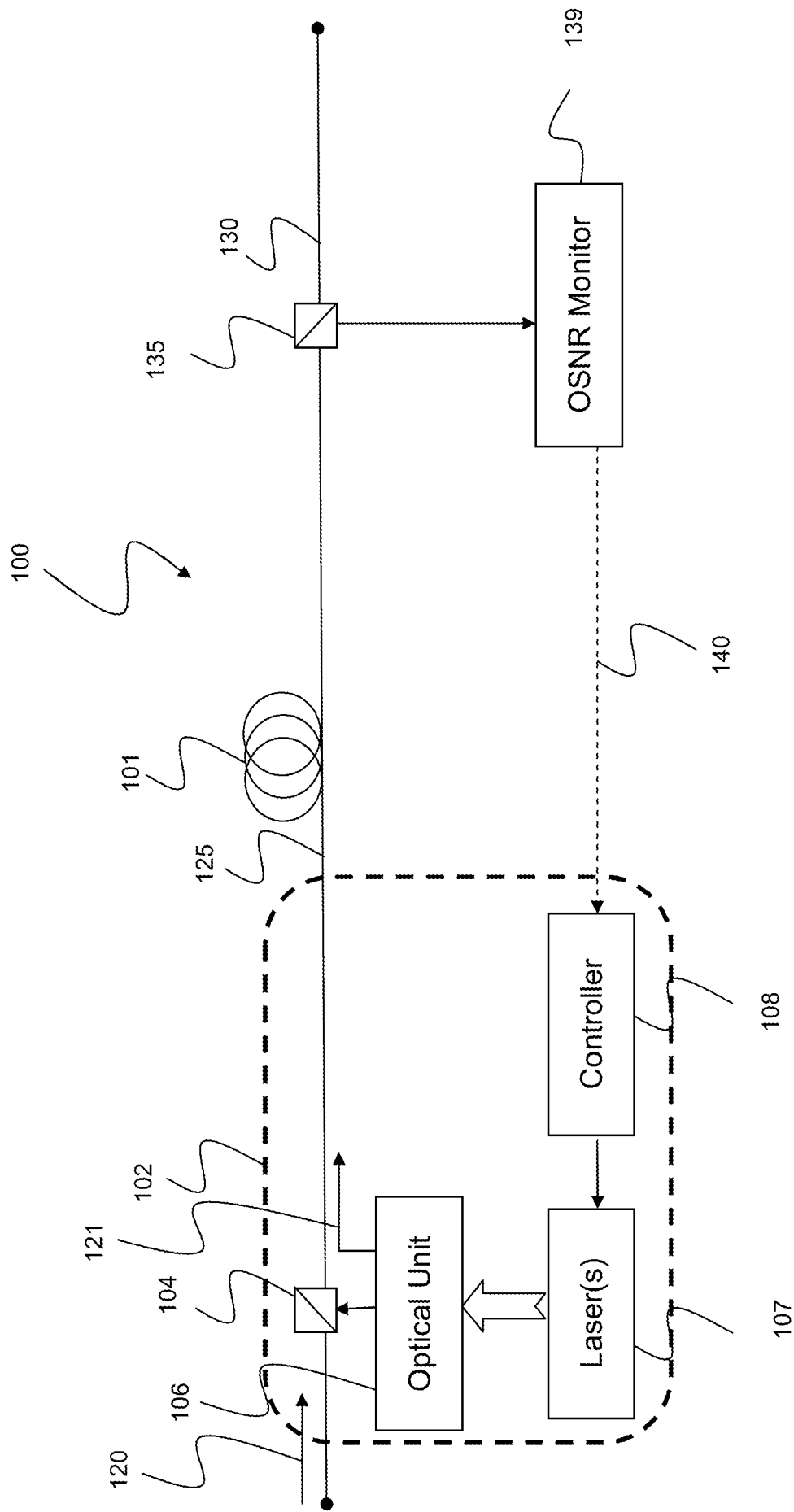


Fig. 1b

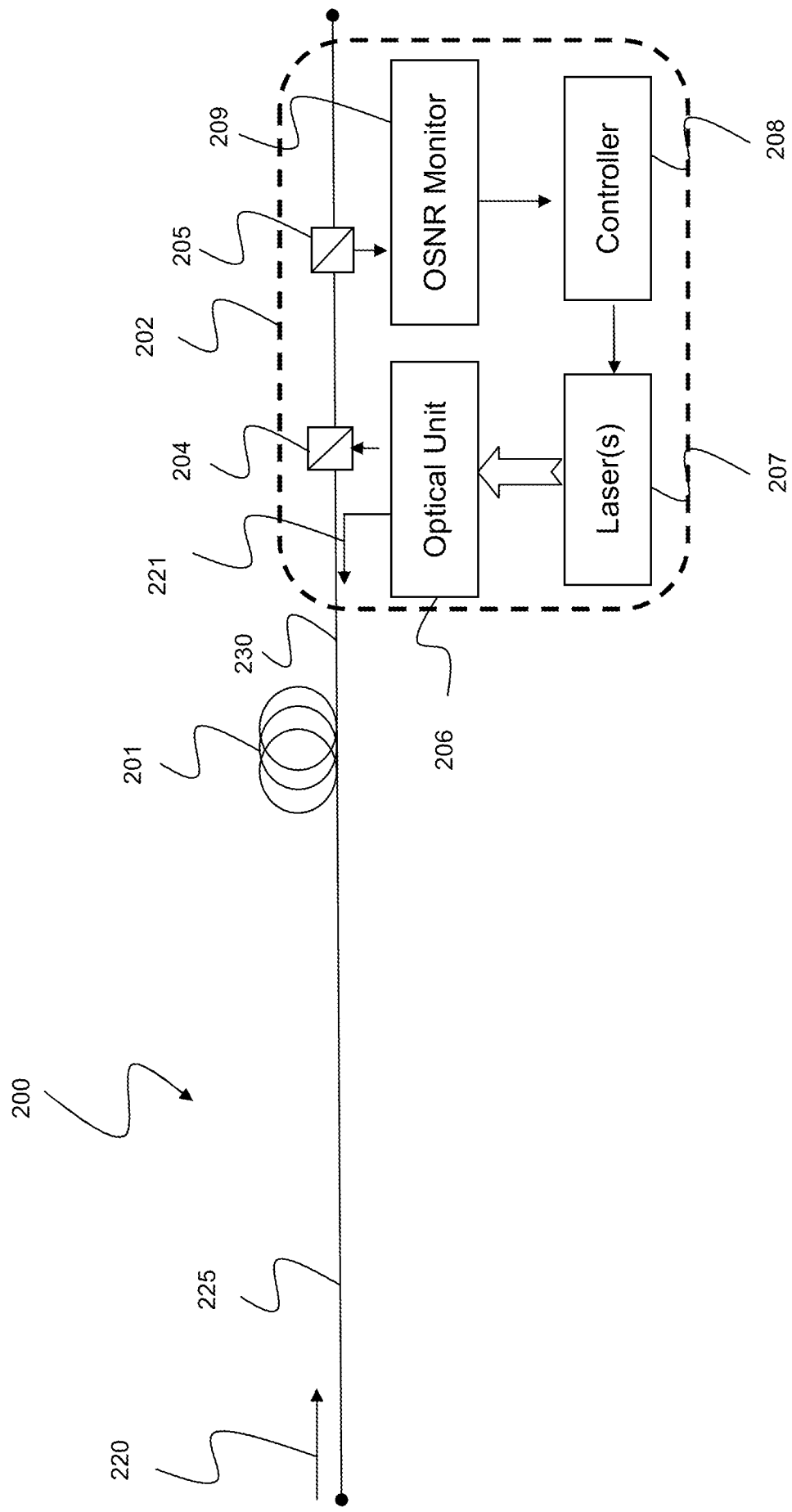


Fig. 2

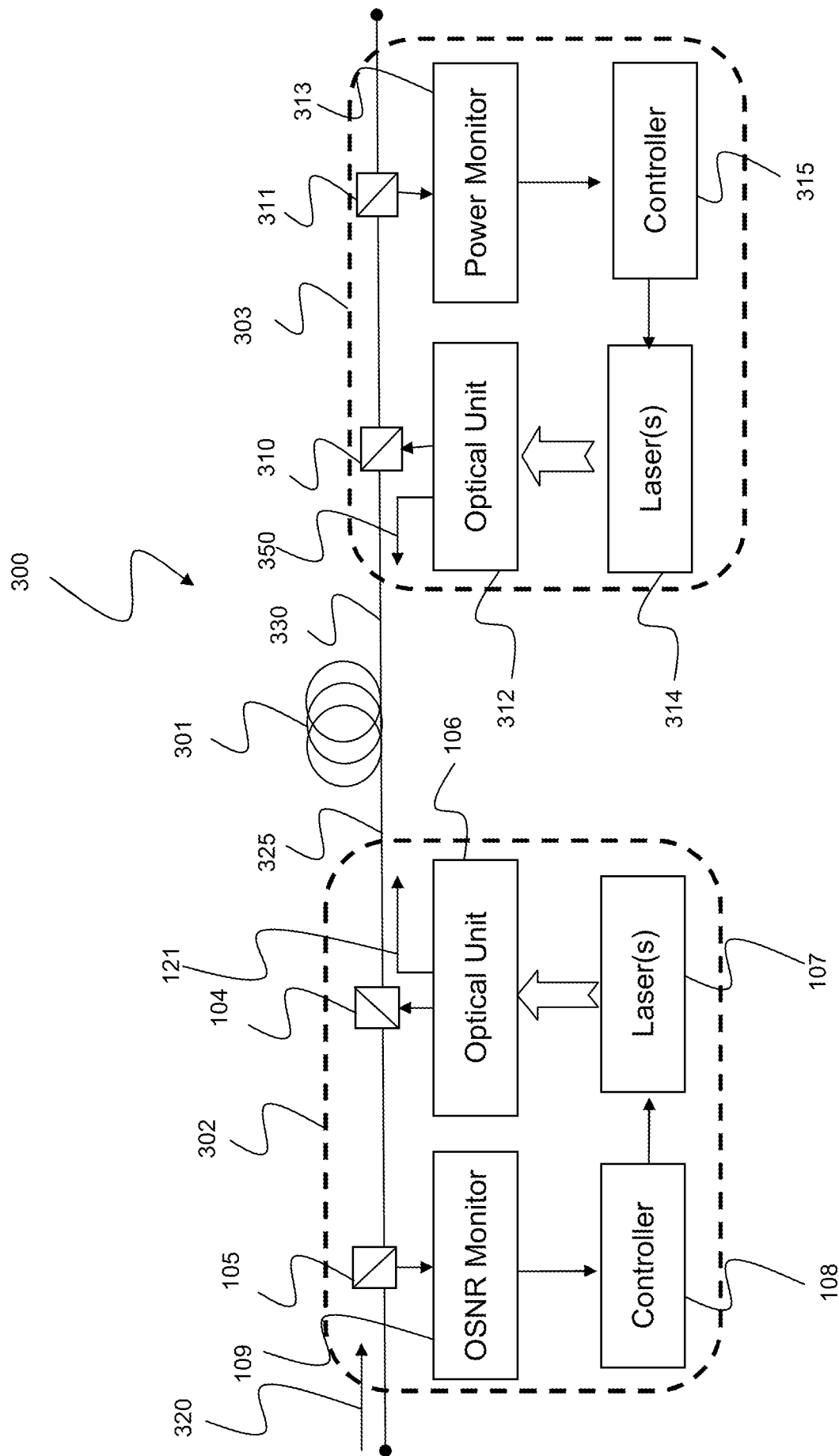


Fig. 3

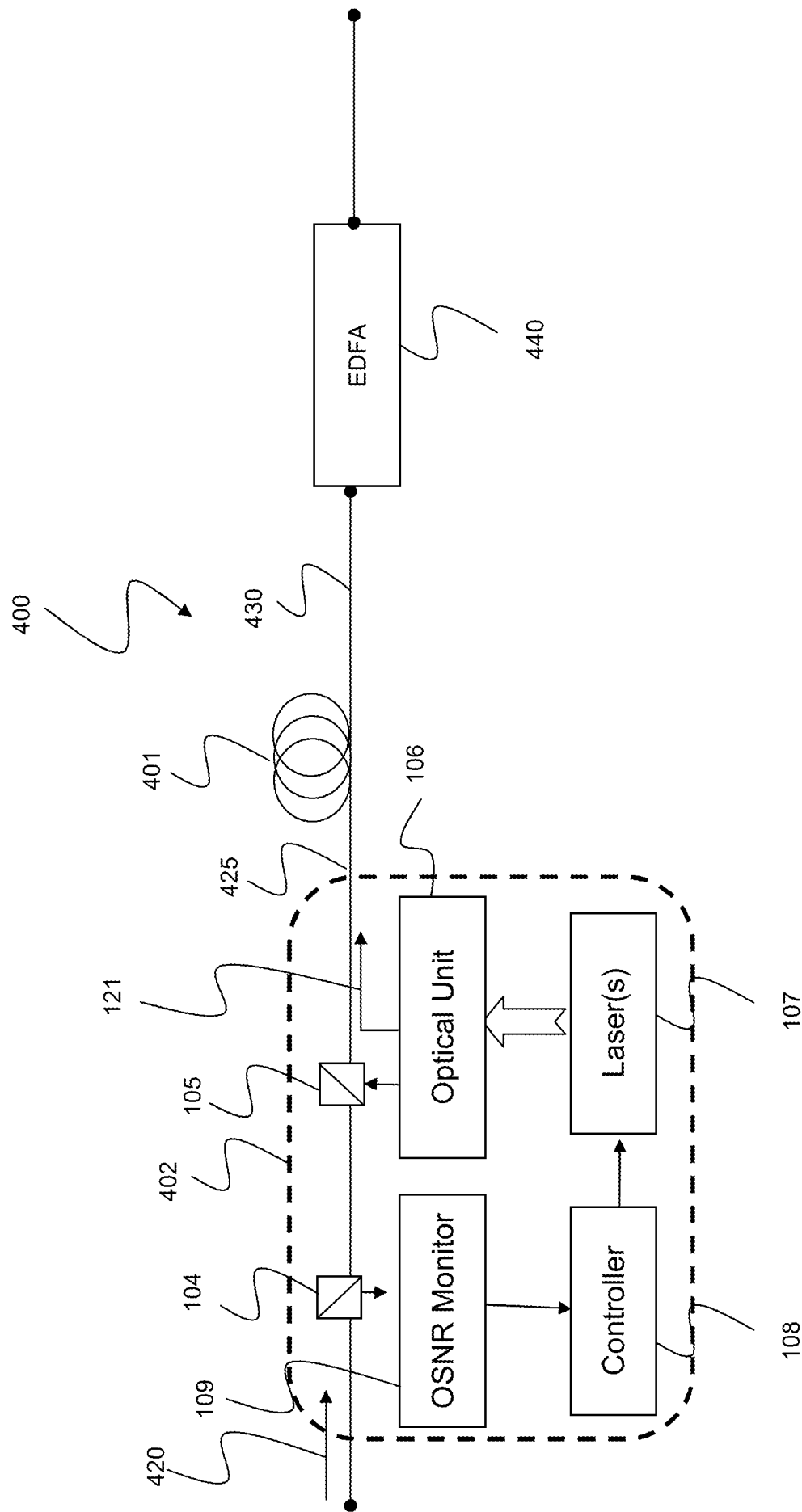


Fig. 4

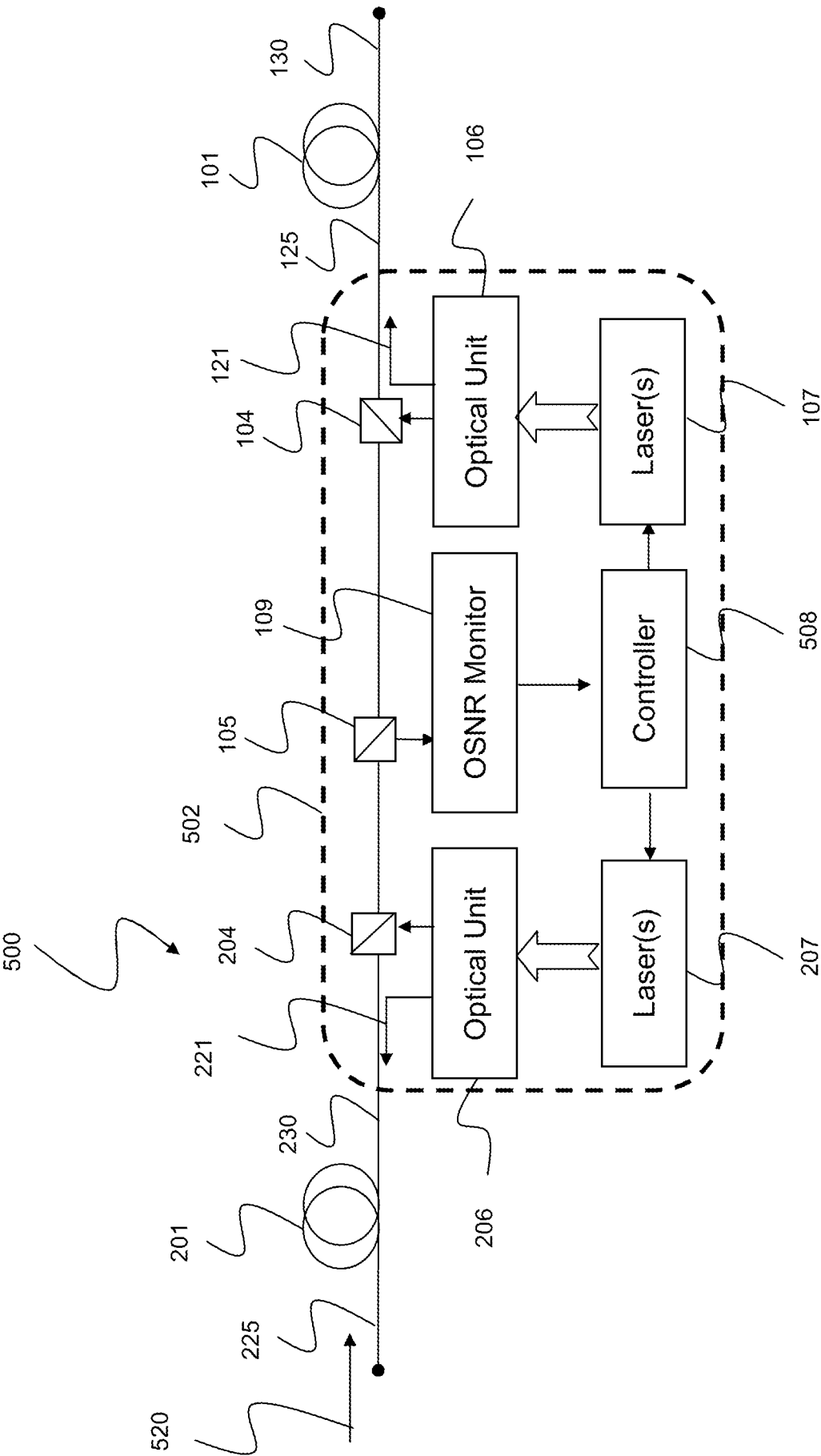


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2011/052537

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S3/067 H01S3/102 H01S3/10 H04B10/17
ADD. H01S3/094 H01S3/16 H01S3/30 H01S3/13

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 H04B

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 practical, search terms used)

EPO-Internal, COMPENDEX, INSPEC, 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	KADO S ET AL: "Gain and noise tilt control in multi-wavelength bi-directionally pumped Raman amplifier", OPTICAL FIBER COMMUNICATIONS CONFERENCE. (OFC). POSTCONFERENCE TECHNICAL DIGEST. POSTDEADLINE PAPERS (IEEE CAT. NO.02CH37339) OPT SOC. AMERICA WASHINGTON, DC, USA; [TRENDS IN OPTICS AND PHOTONICS SERIES. (TOPS)],, vol. TOPS. VOL. 70, 17 March 2002 (2002-03-17), pages 62-63, XP010617626, DOI: 10.1109/OFC.2002.1036204 ISBN: 978-1-55752-701-1	1-5, 8-12, 14-22
Y	page 62, left-hand column - page 63, left-hand column; figures 1-3; table 1 ----- -/--	6,7,13

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

☒ See patent family annex.

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