Bidirectionally pumped optical amplifier

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(71) Applicant *(for all designated States except US)*: **PIRELLI SUBMARINE TELECOM SYSTEMS ITALIA S.p.A.** [IT/IT]; Viale Sarca, 222, I-20126 Milano (IT).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **ALDEGHI, Roberto** [IT/IT]; Via Seminario, 15, I-23900 Lecco (IT). **CIGLIUTTI, Roberto** [IT/IT]; Via Genova, 21/10, I-17100 Savona (IT).

(74) Agents: **GIANNESI, Pier, Giovanni** et al.; Pirelli S.p.A., Viale Sarca, 222, I-20126 Milan (IT).

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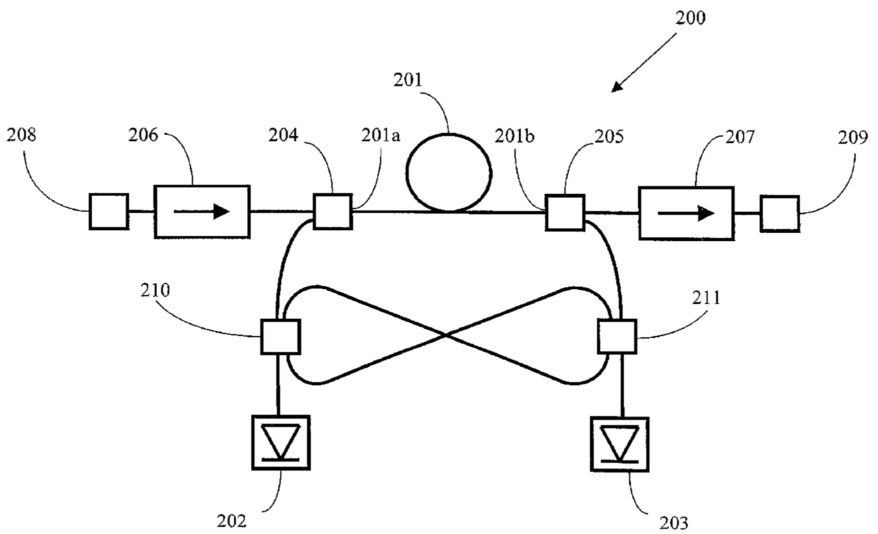

(57) Abstract: An optical amplifier (200) comprises an active fiber (201), a first pump source (202) and a second pump source (203). The amplifier further comprises a first and a second coupling device (210, 211) having at least two input ports and at least two output ports. Said first and second coupling devices, said first and second pump sources and said active fiber are connected in such a manner as: the first input ports of said first and seconed coupling devices are connected to said first and second pump sources, respectively; the first output ports of said first and second coupling devices are connected to a first and a second end of said active fiber, respectively; the second output port of said first coupling devices is connected to the second input port os said second coupling device; the second output port of said second coupling device is connected to the second input port of said first coupling device.

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BIDIRECTIONALLY PUMPED OPTICAL AMPLIFIER

The present invention relates to a method of bidirectionally pumping an optical amplifier, to a method for amplifying optical signals and to a bidirectionally pumped optical amplifier, in particular a rare-earth doped fiber amplifier. The present invention relates also to optical lines and/or systems including bidirectionally pumped optical amplifiers.

Fig.1 shows a configuration of a known bidirectionally pumped optical fiber amplifier 100, comprising an amplifying doped optical fiber section 101, for example an erbium doped amplifying fiber, pump lasers 102, 103, WDM couplers 104, 105, optical isolators 106, 107 for light signals, input and output terminals 108, 109. An optical signal is launched in the amplifier 100 through the input terminal 108, travels along the doped fiber section 101 to be amplified therein and exits through the output terminal 109. Suitable energy for amplification is provided by pump lasers 102, 103, which couple pump light to the doped fiber 101 through WDM couplers 104, 105. In particular, pump light from laser 102 is launched co-directionally in the doped fiber 101, whereas pump light from laser 103 is launched counter-directionally. For an erbium doped fiber amplifier, pump lasers 102, 103 may emit light whose wavelength is comprised, for example, in a pumping band centered around 980 nm or 1480 nm. Herein and in the following of the description, the expressions “co-directionally”, “counter-directionally”, “co-propagating”, “counter-propagating” will be always referred to the propagation direction of the optical signal.

The configuration shown in fig.1 has a problem in that the residual pump light from each pump laser, not fully absorbed by the amplifying fiber, is injected into the opposite pump laser, which can result in optical instabilities in the emission of the latter and in fluctuations in amplification of the optical signal, in particular when pump radiations having wavelength around 980 nm are used.

It is known that such instability can be avoided by placing an isolator on the optical path of each of the pumps. However, isolators are expensive components, in particular for isolating radiations in the wavelength range around 980 nm.

US patent no. 5,640,268, to Alcatel N.V., discloses an amplifier with an amplifying fiber extending between two ends; two pumps, each generating a respective pump wave; two pump injection fibers; two multiplexers connecting the fibers to the amplifying fibers and two pump filters. According to the '268 patent, the reflectances and the parameters of the pump filters are selected so that a resonant cavity for each pump is constituted between the reflection face and the pump filter, formed in the corresponding injection fiber, thereby determining, at least in part, the position and the width of the pumping band. The two pumping bands are offset by a value of several nanometers.

US patent no. 5,995,275, to Fujitsu Ltd., discloses a doped fiber amplifier which provides bidirectional pumping to amplify a signal light, and reduces instability of gain caused by bidirectional pumping. The doped fiber amplifier includes a rare-earth element doped optical fiber, a first light source and a second light source. The optical fiber has first and second ends, with the signal light propagating through the optical fiber from the first end to the second end. The first light source provides pump light which propagates in the optical fiber from the first end to the second end and is at a first wavelength. The second light source provides pump light which propagates in the optical fiber from the second end to the first end and is at a second wavelength. The first wavelength is different from the second wavelength. Reflection type optical devices, such as Bragg reflection grating fibers or interference optical films (e.g. dielectric multilayer films) are included in the pump light sources and have a selectivity in narrow bands having center wavelength λ_1, λ_2 ($\lambda_1 \neq \lambda_2$). The wavelengths λ_1 and λ_2 fall within a 0.98 μm band selected from 0.98 μm bands used as pump bands for an erbium doped fiber. A detuning quantity ($|\lambda_1 - \lambda_2|$) is preferably greater than or equal to 5 nm. More particularly, the patent description discloses the result of an experiment made with an erbium doped fiber amplifier with a configuration according to the above, but including reflection type optical devices with center wavelengths coincident with each other (specifically 975.0 nm). The total output power and the peak wavelength were measured when full pumping was maintained by one laser diode and the drive current supplied to the other laser diode was changed. When such drive current exceeded 50 mA, oscillation at a wavelength of 1020 nm occurred from the interaction between pump light sources, thereby causing a reduction in pumping efficiency.

EP patent application no. 1,170,837, to Optical Technologies Italia S.p.A., discloses a bidirectionally pumped optical amplifier, which comprises an active fiber, a first WDM coupler and a second WDM coupler, a first pump branch coupled to the first WDM coupler, for introducing pump radiation into said active fiber in a first direction, and a second pump branch coupled to the second WDM coupler, for introducing pump radiation into said active fiber in a second direction, opposite to the first direction. The first pump branch comprises a first laser and a first grating. The second pump branch comprises a second laser and a second grating. The second laser has an output power P_F. A first pump residual, having a power P_{inj}, is coupled into the second pump branch from the active fiber and injected into the second laser. The output power of the injected laser and the injected pump power residual are such that $P_F/P_{inj}>2$. The first pump branch further comprises an optical isolator for the pump radiation. In particular, once the operative range of the amplifier (that is, its output power) is known, the ratio P_F/P_{inj} is the result of the proper combination between the output powers of the lasers, the length of the active fiber, the detuning $\Delta\lambda$ between the two selective reflectors.

EP patent application no. 1,170,838, to Infineon Technologies AG, discloses a bidirectionally pumped optical amplifier, which comprises an active fiber having two ends, a first WDM coupler and a second WDM coupler coupled to said ends, a first pump branch coupled to the first WDM coupler, for introducing pump radiation into said active fiber in a first direction, and a second pump branch coupled to the second WDM coupler, for introducing pump radiation into said active fiber in a second direction, opposite to the first direction. The first pump branch comprises a first pump laser and a grating. The second pump branch comprises a second laser. A portion of unabsorbed pump residual propagating in the first direction is coupled in the second pump branch towards the second pump laser and locks the emission wavelength of the second pump laser. In particular, the higher the injected power, the wider the locking bandwidth, i.e., the maximum difference between the free running wavelength of the injected laser and the wavelength of the injection.

The Applicant has experimentally verified that bidirectionally pumped fiber amplifiers having configurations according to the above schemes may suffer from low pump efficiency (i.e. amplifier output power versus driving current provided to pump lasers) and/or limited range of obtainable amplifier output power, unless isolators for pump radiation are used. However, as already mentioned, isolators are expensive components, especially in the wavelength range around 980 nm, so that their use may cause a huge increase of the amplifier costs. Furthermore, isolators are typically critical components with regards to reliability, so that use of isolators for the pump radiation in amplifiers for systems needing a high level of reliability, e.g. submarine systems, may be disadvantageous.

The Applicant has faced the problem of obtaining a bidirectionally pumped fiber amplifier having a high pump efficiency and a high output power range, with no necessity of using optical isolators for the pump radiation, in order to avoid huge increase of the amplifier cost and/or a substantial lowering of the amplifier reliability.

The Applicant has found that a configuration of bidirectionally pumped optical amplifier including two couplers interposed in the two pump paths between the pump sources and the active fiber ends, connected so as to form a "crossed loop", explained in detail below, allows to obtain high gain of the bidirectionally pumped amplifier with high pumping efficiency. Higher driving currents of the lasers included in the pump sources may be obtained, with stable pump power emission.

In a first aspect, the invention relates to a method for pumping an optical amplifier comprising an active fiber, a first pump source and a second pump source, the method comprising the steps of:

- emitting a first pump radiation from said first pump source and a second pump radiation from said second pump source;
- splitting said first pump radiation into a first and a second portion;
- splitting said second pump radiation into a first and a second portion;
- coupling said first portion of said first pump radiation in said active fiber in a first direction;
- coupling said first portion of said second pump radiation in said active fiber in a second direction, opposite to said first direction;
- splitting said second portion of said first pump radiation into a third and a fourth portion;

- splitting said second portion of said second pump radiation into a third and a fourth portion;
- coupling said third portion of said first pump radiation in said active fiber in said second direction;
- coupling said third portion of said second pump radiation in said active fiber in said first direction.

In a second aspect, the invention relates to a method for amplifying an optical signal in an optical amplifier comprising an active fiber, a first pump source and a second pump source, the method comprising the steps of:

- coupling said optical signal in said active fiber in a first direction;
- emitting a first pump radiation from said first pump source and a second pump radiation from said second pump source;
- splitting said first pump radiation into a first and a second portion;
- splitting said second pump radiation into a first and a second portion;
- coupling said first portion of said first pump radiation in said active fiber in said first direction;
- coupling said first portion of said second pump radiation in said active fiber in a second direction, opposite to said first direction;
- splitting said second portion of said first pump radiation into a third and a fourth portion;
- splitting said second portion of said second pump radiation into a third and a fourth portion;
- coupling said third portion of said first pump radiation in said active fiber in said second direction;
- coupling said third portion of said second pump radiation in said active fiber in said first direction.

In a third aspect, the invention relates to an optical amplifier comprising an active fiber, a first pump source and a second pump source having an emission wavelength in a predetermined emission pump wavelength range. The amplifier further comprises a first and a second coupling devices having at least two input ports and at least two output ports, said first and second coupling devices, said first and second pump sources and said active fiber being connected in such a manner as:

- the first input ports of said first and second coupling devices are connected to said first and second pump sources, respectively;
- the first output ports of said first and second coupling devices are connected to a first and a second end of said active fiber, respectively;
- the second output port of said first coupling device is connected to the second input port of said second coupling device;
- the second output port of said second coupling device is connected to the second input port of said first coupling device.

Said emission pump wavelength range is preferably comprised between 965 nm and 990 nm, more preferably between 970 nm and 986 nm.

Typically, at least one of said first and second pump sources includes a reflection type optical device. In preferred embodiments, both said first and second pump sources include a respective reflection type optical device.

A reflectivity of said reflection type optical device or devices in said emission pump wavelength range may be preferably lower than 10%, more preferably lower than 8%.

In one embodiment, the first pump source includes a first laser and a respective reflection type optical device, and said second pump source includes a second laser. In this embodiment, a detuning quantity between a center wavelength of said reflection type optical device and a free running wavelength of said second laser is preferably lower than 7 nm in absolute value, more preferably lower than 5 nm in absolute value.

In another embodiment, both pump sources include a respective reflection type optical device and a detuning quantity between a center wavelength of the first reflection type optical device and a center wavelength of the second reflection type optical device is of at least 5 nm in absolute value.

The first and second coupling devices may be, for example, 3 dB couplers.

In a fourth aspect, the invention relates to an optical line having a first end and a second end, comprising at least one transmission optical fiber and at least one optical amplifier according to the third aspect.

In a fifth aspect, the invention relates to an optical system comprising a transmitting station, a receiving station and an optical line according to the fourth aspect, said transmitting station being coupled to said first end of said optical line and said receiving station being coupled to said second end of said optical line.

Further features and advantages of the present invention will be better illustrated by the following detailed description of an example thereof, herein given with reference to the enclosed drawings, in which:

- Figure 1 schematically shows a known bidirectionally pumped optical amplifier;
- Figure 2 schematically shows an embodiment of bidirectionally pumped optical amplifier according to the present invention;
- Figure 3 schematically shows a setup used by the Applicant for an experiment with an embodiment of a known bidirectionally pumped optical amplifier;
- Figure 4 shows a plot resulting from the experiment performed with the setup of fig.3;
- Figure 5 schematically shows a setup used by the Applicant for an experiment with an embodiment of a bidirectionally pumped optical amplifier according to the present invention;
- Figure 6 shows the result of a first experiment performed with the setup of fig.5;
- Figure 7 shows the result of a second experiment performed with the setup of fig.5;
- Figure 8 shows the result of a third experiment performed with the setup of fig.5.

Fig.2 shows an embodiment of a bidirectionally pumped optical fiber amplifier 200 according to the invention, comprising a length of active optical fiber 201, pump sources 202, 203, wavelength-selective (WDM) couplers 204, 205, optical isolators 206, 207 for light signals, input and output terminals 208, 209. Furthermore, the optical fiber amplifier 200 includes two further coupling devices 210, 211, connected within the amplifier 200 so as to form a “crossed loop”, in a way that will be described in detail below. Various optical components described herein are “connected” to each other. The term “connected” refers to optical components being directly connected together by fiber or other waveguide connection, or optically connected using a free propagating (e.g. collimated) beam, or connected through one or more intermediate optical component, such as, for example, an optical filter.

The active optical fiber 201 is an optical fiber which can amplify optical signals in a predetermined wavelength band by stimulated emission of photons. For example, the active optical fiber 201 may be a rare-earth doped optical fiber. The selection of the appropriate rare-earth element depends, at least in part, on the wavelength of the signal light. In the following description, it is assumed that the signal light falls within a range around a wavelength of 1550 nm, and that the doped fiber 201 is doped with the rare earth element erbium (Er), since erbium is a preferable dopant for a signal light in the 1550 nm band. However, the skilled in the art may adapt the teachings of the present invention to optical amplifiers including active fibers doped with different elements, and/or suitable for amplifying signals in different wavelength bands.

Pump source 202 may include for example a semiconductor laser diode, supplied with a direct-current or controlled drive-current from a drive circuit. The wavelength emission of the pump source 202 is included in a range around a predetermined wavelength, which corresponds to obtaining a high gain in the active fiber 201. For erbium doped fiber amplifiers, a preferred emission wavelength range for the pump source 202 is around 980 nm, typically between about 965 and 990 nm, preferably between 970 and 986 nm. Another preferred wavelength range for the pump source 202 is around 1480 nm.

Similarly, pump source 203 may include for example a semiconductor laser diode, supplied with a direct-current or controlled drive-current from a drive circuit. The wavelength emission of the pump source 203 is included in the same range of the wavelength emission of pump source 202.

One or both pump sources 202, 203 may further include a reflection type optical device, such as for example a Bragg reflection fiber grating or an interferometric filter, such as a dielectric multilayer film. The reflectivity of the reflection type device or devices included in the pump sources 202, 203, in the emission wavelength range of such pump sources, is typically lower than 10%, preferably lower than or equal to 8%. The reflection type optical device or devices has/have a relatively narrow spectrum, i.e. narrower than the spectrum of the laser diodes included in the pump sources 202, 203, and is/are used in order to narrow the spectrum of light output from such laser diodes. In such way, the power of the pump radiation may be concentrated in a narrow wavelength range around the center wavelength of the reflection type device, so that the efficiency of the pump absorption in the doped fiber may be increased. Preferably, if both pump sources 202, 203 include a respective reflection type optical device, the center wavelengths λ_1, λ_2 of such reflection type optical devices are different from each other. More preferably, a detuning quantity $|\lambda_1 - \lambda_2|$ between such center wavelengths is of at least 5 nm. In a pump wavelength range around 980 nm, the detuning quantity may preferably be lower than 15 nm, more preferably lower than or equal to 10 nm. Higher values of detuning quantity may cause reduction of the efficiency of the amplification process in the active fiber 201.

However, the Applicant has found that the pump "crossed loop" of the bidirectionally pumped optical amplifier according to the invention may be effectively exploited also in a configuration having a first pump source (for example, pump source 202) including a reflection type optical device and a second pump source (i.e, pump source 203 in the above example) without a reflection type optical device. In such case, the wavelength emission of the laser included in the second pump source 203, not including the reflection type optical device, may be stably locked by the injected residual pump radiation originated from the first pump source 202, including the reflection type optical device. Preferably, in a configuration with a first pump source having a reflection type device and a second pump source not having a reflection type device, a detuning quantity $|\lambda_1 - \lambda_{free}|$ between the center wavelength of the reflector included in the first pump source and the free running wavelength (i.e. the gain peak wavelength) of the laser included in the second pump source is lower than 7 nm, more preferably lower than 5 nm. High values of the detuning quantity may cause reduction of the efficiency of the amplification process in the active fiber 201, due to a poor locking of the second pump source not including the reflector, with the occurrence of cavity modes at long wavelengths, outside the useful pump bandwidth of the doped fiber 201.

The WDM optical coupler 204 is connected to a first end 201a of the active fiber 201: it allows the coupling of the signal light to be amplified and of co-propagating pump radiation into the active fiber 201. The WDM optical coupler 205 is connected to a second end 201b of the active fiber 201: it allows the coupling of counter-propagating pump radiation into the active fiber 201 and the output of the amplified signal light from the active fiber 201.

Optical isolators 206, 207 for the signal radiation may be used for blocking back-scattered radiation coming from an optical line portion disposed upstream from the optical amplifier 200, or caused by imperfect coupling between the various components included in the optical amplifier 200. In the preferred embodiment shown in fig.2 two isolators 206, 207 are shown. However, a single isolator may be used, either upstream or the downstream from the active fiber 201.

Coupling devices 210, 211 have at least two input ports and at least two output ports. Conveniently, they can be 2x2 couplers, for example 3 dB couplers, which are components having a high reliability, so that they can be used in an amplifier suitable for any kind of optical system, including a submarine system, without substantial loss of reliability. A coupling ratio different from 3 dB may be employed. As shown in fig.2, the coupling devices 210, 211 are interposed between the output of the pump sources 202, 203 and the ends of the active fiber 201 (or, in other words, the WDM couplers 204, 205). For brevity, the ports of the coupling devices 210, 211 facing the pump sources 202, 203 will be referred as the input ports, whereas the ports facing the ends of the active fiber 201 will be referred as the output ports. More particularly, a first input port of the first coupling device 210 is connected to the first pump source 202 and a first input port of the second coupling device 211 is connected to the second pump source 203. Furthermore, a first output port of the first coupling device 210 is connected to the first WDM coupler 204 (in other words, to the first end 201a of the active fiber 201) and a first output port of the second coupling device 211 is connected to the second WDM coupler 205 (in other words, to the second end 201b of the active fiber 201). Furthermore, a second output port of the first coupling device 210 is connected to a second input port of the second coupling device 211. Furthermore, a second output port of the second coupling device 211 is connected to a second input port of the first coupling device 210.

The optical amplifier 200 according to the invention may be part of an optical transmission system, advantageously a WDM transmission system, comprising a transmitting station, a receiving station and an optical line connecting said transmitting station and said receiving station. The transmitting station comprises at least one transmitter adapted to emit the optical signal carrying information. For a WDM transmission, the transmitting station comprises a plurality of transmitters adapted to transmit a corresponding plurality of optical channels, each having a respective wavelength. In this case, the optical signal is a WDM optical signal, comprising different optical channels. The receiving station comprises at least one receiver adapted to receive said optical signal and discriminate said information. For a WDM transmission, the receiving station comprises a plurality of receivers adapted to receive the WDM optical signal and discriminate the information carried by each optical channel received. The optical line comprises at least one transmission optical fiber. At least one optical amplifier 200 according to the invention is provided along the optical line in order to counteract attenuation introduced on the optical signal by at least a portion of said transmission optical fiber or fibers. Other sources of attenuation can be connectors, couplers/splitters and various devices, such as for example modulators, switches, add-drop multiplexers, dispersion compensators and so on, disposed along the optical line.

The optical transmission system comprising at least one optical amplifier 200 according to the invention can be any kind of optical transmission system, such as for example a terrestrial transmission system or a submarine transmission system. Typically, in a submarine system, an optical amplifier 200 according to the invention is enclosed in a sealed container for underwater use.

In operation, an optical signal is launched in the amplifier 200 through the input terminal 208, travels along the active fiber 201 to be amplified therein and exits through the output terminal 209. Suitable energy for amplification is provided by pump sources 202, 203. In particular, the pump radiation emitted by the first pump source 202 is split by the first coupling device 210, so that a first portion is sent towards the first WDM coupler 204 for being coupled co-directionally into the active fiber 201. A second portion of the pump radiation emitted by the first pump source 202 is, in turn, sent towards the second coupling device 211 and further split by the second coupling device 211 into two portions, one of which is sent towards the second WDM coupler 205 to be coupled counter-directionally into the active fiber 201, whereas the other is sent back to the first coupling device 210. This last portion is then split by the first coupling device 210 into two portions, one of which is sent towards the first WDM coupler 204 to be coupled co-directionally into the active fiber 201, whereas the other is sent back to the second coupling device 211, and so on. Thus, pump radiation emitted by the first pump source 202 is split into three portions: a first portion coupled co-directionally into the active fiber 201 through its first end 201a; a second portion coupled counter-directionally into the active fiber 201 through its second end 201b; a third portion "trapped" in a loop between the first and the second coupling devices 210, 211. Similarly, the pump radiation emitted by the second pump source 203 is split by the second coupling device 211, so that a first portion is sent towards the second WDM coupler 205 for being coupled counter-directionally into the active fiber 201. A second portion of the pump radiation emitted by the second pump source 203 is, in turn, sent towards the first coupling device 210 and further split by the first coupling device 210 into two portions, one of which is sent towards the first WDM coupler 204 to be coupled co-directionally into the active fiber 201, whereas the other is sent back to the second coupling device 211. This last portion is then split by the second coupling device 211 into two portions, one of which is sent towards the second WDM coupler 205 to be coupled counter-directionally into the active fiber 201, whereas the other is sent back to the first coupling device 210, and so on. Thus, pump radiation emitted by the second pump source 203 is split into three portions: a first portion coupled counter-directionally into the active fiber 201 through its second end 201b; a second portion coupled co-directionally into the active fiber 201 through its first end 201a; a third portion "trapped" in a loop between the first and the second coupling devices 210, 211. As a whole result, both co-propagating and counter-propagating pump radiations include portions of radiations originated from both pump sources 202, 203. Advantageously, the loop formed between the first and the second coupling devices 210, 211 may also provide for pump redundancy. As a matter of fact, in case of failure of one of the two pump sources 202, 203, pump radiation originated from the functioning pump source may in any case travel both in co- and counter-propagating direction in the doped fiber 201, even if with reduced power. This is of particular importance in amplifiers suitable for optical systems in which prompt intervention after a failure may be difficult, such as for example a submarine system.

With regards to the pump residuals, i.e. to the portions of pump radiation not used for amplification and exiting from the ends of the active fiber 201, they are also split by the coupling devices 210, 211 in the following manner. A first pump residual of the co-propagating pump radiation, exiting from the second end 201b of the active fiber 201 is coupled towards the second coupling device 211 by the second WDM coupler 205. A first portion of the first pump residual is coupled towards the second pump source 203, whereas a second portion is coupled by the second coupling device 211 towards the first coupling device 210. The first coupling device 210 splits such pump residual portion into two further portions, one of which is sent towards the first pump source 202 and the other is sent again towards the second coupling device 211. The portion sent towards the second coupling device 211 is further split into two portions, one of which is sent towards the second pump source 203 and the other is sent again towards the first coupling device 210, and so on. Thus, both pump sources 202, 203 are injected by a portion of pump residual exiting from the active fiber 201 through its second end 201b, whereas another portion is trapped in a loop between the first and the second coupling devices 210, 211. Similarly, a second pump residual of the counter-propagating pump radiation, exiting from the first end 201a of the active fiber 201 is coupled towards the first coupling device 210 by the first WDM coupler 204. A first portion of the second pump residual is coupled towards the first pump source 202, whereas a second portion is coupled by the first coupling device 210 towards the second coupling device 211. The second coupling device 211 splits such pump residual portion into two further portions, one of which is sent towards the second pump source 203 and the other is sent again towards the first coupling device 210. The portion sent towards the first coupling device 210 is further split into two portions, one of which is sent towards the first pump source 202 and the other is sent again towards the first second device 211, and so on. Thus, both pump sources 202, 203 are injected by a portion of pump residual exiting from the active fiber 201 through its first end 201a, whereas another portion is trapped in a loop between the first and the second coupling devices 210, 211.

The Applicant has found that the addition of the coupling devices 210, 211, connected between the active fiber 201 and the pump sources 202, 203 so as to form a "crossed loop", according to the above, allows to obtain an increased pump efficiency in the bidirectionally pumped amplifier 200. Higher output powers have been obtained in comparative experiments performed by the Applicant with embodiments according to the invention versus known embodiments, as it will be explained below. More particularly, the Applicant has found that the laser diodes included in the pump sources 202, 203 may be supplied by higher driving currents, before the occurrence of instabilities in the functioning of the amplifier. Unexpectedly, a high output power without fluctuations in the gain of the amplifier 200 has been obtained even in embodiments including pump sources 202, 203 having gratings with spectrum centered at the same wavelength.

It has to be noticed that these results have been obtained by using simple and reliable coupling devices, such as 3 dB couplers, in place of costly and low reliable optical isolators for pump radiation, i.e. with a lower overall cost of the amplifier and a higher reliability.

Example 1 (comparison)

Fig.3 schematically shows the setup used by the Applicant for an experiment with an embodiment of a known bidirectionally pumped optical amplifier.

The setup included a length of erbium doped fiber (EDF) 18.7 m long, produced by Corning OTI, having the following specifications: numerical aperture of 0.29 ± 0.02; cut-off wavelength lower than 970 nm; mode field diameter of 4.3 ± 0.5 μm; peak absorption of 3.5 ± 1 dB/m; absorption at 980 nm of 2.6 ± 1 dB/m; background loss at 1200 nm lower than 10 dB/km.

Two 980/1550 2x1 wavelength-selective couplers (WDM1, WDM2), produced by ADC, were connected at the ends of the EDF, having the following specifications: operating temperature in the range 0-45 °C; pump wavelength range 973-985 nm; signal wavelength range 1530-1570 nm; maximum insertion loss in the range 973-985 nm in the pump path (from 980 nm port to common port) 0.20 dB; maximum wavelength dependent loss in the pump path 0.1 dB; minimum insertion loss in the range 1530-1570 nm in the pump path 18 dB; maximum insertion loss in the range 1530-1570 nm in the signal path (from 1550 nm port to common port) 0.30 dB; maximum wavelength dependent loss in the signal path 0.20 dB; minimum insertion loss in the range 973-985 nm in the signal path 20 dB; polarization dependent loss in both signal and pump paths 0.1 dB; return loss in both signal and pump paths 50 dB; polarization mode dispersion in the signal path 0.075 ps.

Two 980 nm/160 mW class pump lasers (L1, L2), provided with respective stabilizing fiber gratings (G1, G2) were connected to the 980 nm ports of the WDM couplers WDM1, WDM2. The pump lasers L1, L2 had no Peltier cell for temperature stabilization. The reflectivity of the stabilizing gratings was between 6% and 7%. The center wavelength of the grating G1, disposed at the output of the pump laser L1 coupling co-propagating pump radiation, was 977 nm. The center wavelength of the grating G2, disposed at the output of the pump laser L2 coupling counter-propagating pump radiation, was 982 nm.

One isolator (ISO) for radiation in a range around 1550 nm, produced by JDS Uniphase, was coupled at the output of the EDF, having the following specifications: operating temperature range 0-45 °C; operating wavelength range 1528-1570 nm; insertion loss lower than 1 dB; polarization dependent loss lower than 0.1 dB; maximum wavelength dependent loss of about 0.3 dB; signal return loss (1528-1570 nm) higher than 40 dB; polarization mode dispersion lower than 0.1 ps.

An optical signal having an input power of 4 dBm, spectrally distributed in a wavelength range between 1536 nm and 1563 nm, was introduced at the 1550 nm port of the WDM coupler WDM1. The same driving current was supplied to both pump lasers L1, L2. The output power of the amplifier was measured versus the driving current supplied to the pump lasers L1, L2. Furthermore, measures were also taken of the residual pump radiation exiting from the WDM coupler WDM2 directed towards the second laser L2, and of the output power of the laser L2, in order to check behavior of the laser L2 when injected by such pump residual.

The signal input power, the signal output power, the pump residual exiting from coupler WDM2 and the output power of the laser L2 were monitored by interposing suitable tap couplers (TAP1, TAP2, TAP3, TAP4), connected to a power meter. More particularly, two 13 dB/1550 nm couplers were used for monitoring input and output signal powers (TAP1, TAP2), whereas two 23 dB/980 nm couplers were used for monitoring the pump residual and the output power from laser L2 (TAP3, TAP4).

Fig.4 shows the result of the experiment. In particular, curve 41 shows the amplifier output power (expressed in dBm) versus the driving current (expressed in mA) supplied to each of lasers L1, L2, curve 42 shows the output power (expressed in mW) of the pump laser L2 versus the driving current, curve 43 shows the pump residual power (expressed in mW) exiting from coupler WDM2. As it can be seen, the three curves show a linear behavior of the amplifier up to about 175 mA of driving current value, which corresponds to about 190 mW for the sum of the output powers exiting from pump lasers L1, L2, and to about 15.3 dBm of output power of the amplifier. Over 175 mA, the curve showing the output power of the laser L2 begins to deviate from a linear characteristic, with kinks that are unacceptable for a reliable behavior of the amplifier. Such kinks are caused by the occurrence of spurious pump modes in the range around 980 nm, which add to the principal ones at 977 nm and 982 nm, but at wavelengths outside the useful pumping bandwidth of erbium. Such spurious modes subtract power to the principal ones, thus reducing the pump efficiency, and generate fluctuations in time of the output power of the amplifier.

Example 2 (invention)

Fig.5 schematically shows the setup used by the Applicant for an experiment with an embodiment of a bidirectionally pumped optical amplifier according to the invention. The setup of fig.5 differs from the setup of fig.3 in that two 2x2 3dB/980 nm couplers (C1, C2) were interposed between the erbium doped fiber EDF and the pump lasers L1, L2, connected according to the above teachings. The other components were the same described with reference of example 1. The two 3 dB couplers, produced by ADC, had the following specifications: coupling ratio 50/50, wavelength range 973-985 nm; temperature range 0-45 °C; maximum insertion loss (all paths) 3.5 dB; maximum wavelength dependent loss (all paths) 0.2 dB; maximum polarization dependent loss (all paths) 0.2 dB; minimum return loss (all paths) 50 dB.

Fig.6 shows the result of the experiment. In particular, curve 61 shows the amplifier output power (expressed in dBm) versus the driving current (expressed in mA) supplied to each of lasers L1, L2, curve 62 shows the output power (expressed in mW) of the pump laser L2 versus the driving current, curve 63 shows the pump residual power (expressed in mW) exiting from coupler WDM2. As it can be seen, the three curves show a linear behavior of the amplifier up to about 240 mA of driving current value, which corresponds to about 240 mW for the sum of the output powers exiting from pump lasers L1, L2, and to about 17.3 dBm of output power of the amplifier. Thus, an increase of 70 mA of driving current per pump laser was obtained with a configuration according to the invention, with respect to the previous example. Furthermore, an amplifier output power and gain higher by about 2 dB was obtained.

At a given value of driving current provided to the pump lasers, the pump residual injected into both lasers results to have a lower power in an amplifier configuration according to the invention: this can be seen, for example, by comparing the slope of the curve 43 in fig.4 (in the linear region up to about 200 mA) with the slope of the curve 63 in fig.6. According to the Applicant, in such conditions the pump lasers can reach a high output power with substantially no disturb derived from the injected residual. Thus, more pump power can reach the doped fiber, at a given driving current value, i.e. a higher output power of the amplifier. In other words, the pump efficiency (i.e. amplifier output power versus driving current) is increased in the amplifier configuration according to the invention.

Furthermore, thanks to the lower injected residual, higher driving currents may be provided to the pump lasers in the amplifier configuration according to the invention, before reaching a condition of instability. In other words, a higher functioning range of the pump lasers can be exploited, and thus a higher amplifier output power range can be obtained with no necessity of using expensive and low reliable isolators for the pump radiation.

Example 3 (invention)

The Applicant has repeated the experiment with the setup described with reference to example 2 (fig.5), but using gratings G1, G2 having the same center wavelength (977 nm).

Fig.7 shows the result of the experiment. In particular, curve 71 shows the amplifier output power (expressed in dBm) versus the driving current (expressed in mA) supplied to each of lasers L1, L2, curve 72 shows the output power (expressed in mW) of the pump laser L2 versus the driving current, curve 73 shows the pump residual power (expressed in mW) exiting from coupler WDM2. As it can be seen, the three curves show a linear behavior of the amplifier up to about 275 mA of driving current value, which corresponds to about 280 mW for the sum of the output powers exiting from pump lasers L1, L2, and to about 17.9 dBm of output power of the amplifier. However, the Applicant has verified that such output power is not in all cases stable in time: an amplifier output power stable in time can be obtained up to about 200 mA of driving current, corresponding to about 200 mW of total pump power and 15.7 dBm of output power of the amplifier. In other words, a stable gain of more than 11 dB is obtained with this amplifier configuration: this value is unexpectedly high, as compared, for example, to the experimental results disclosed in the above cited US patent no. 5,995,275 (see fig.4B of such patent), in which no stable behavior can be obtained even for very low values of driving currents. The Applicant believes that the good result obtained even in this configuration may depend, at least in part, on the fact that the loop between the first and the second coupling devices 210, 211 may cause the pump radiation "trapped" within the crossed loop to lose, at least partially, its coherence, after a number of turns within the loop. According to the Applicant, this may lower the disturb caused by the portions of pump residuals injected into the lasers included in the pump sources 202, 203.

Example 4 (invention)

The Applicant has repeated the experiment with the setup described with reference to example 2 (fig.5), but using only one grating G1 having a center wavelength of 982 nm in front of laser L1 and no grating in front of laser L2. The laser L2 had a free running wavelength (i.e. a gain peak wavelength) of 984 nm.

Fig.8 shows the result of the experiment. In particular, curve 81 shows the amplifier output power (expressed in dBm) versus the driving current (expressed in mA) supplied to each of lasers L1, L2, curve 82 shows the output power (expressed in mW) of the pump laser L2 versus the driving current, curve 83 shows the pump residual power (expressed in mW) exiting from coupler WDM2. As it can be seen, the three curves show a linear behavior of the amplifier up to about 280 mA of driving current value, which corresponds to about 211 mW for the sum of the output powers exiting from pump lasers L1, L2, and to about 15.3 dBm of output power of the amplifier. Apparently, this configuration shows a wider dynamics with respect to the previous ones, in that higher driving currents can be reached. However, a lower amplifier output power is obtained, which means that the pump efficiency is actually lower. By analyzing the spectrum of the pump radiation, the Applicant has verified that the emission of the laser L2 is stably locked on the same center wavelength of the grating G1 up to driving currents of 280 mA.

CLAIMS

1. A method for pumping an optical amplifier (200) comprising an active fiber (201), a first pump source (202) and a second pump source (203), said method comprising the steps of:
   - emitting a first pump radiation from said first pump source (202) and a second pump radiation from said second pump source (203);
   - splitting said first pump radiation into a first and a second portion;
   - splitting said second pump radiation into a first and a second portion;
   - coupling said first portion of said first pump radiation in said active fiber (201) in a first direction;
   - coupling said first portion of said second pump radiation in said active fiber (201) in a second direction, opposite to said first direction;
   - splitting said second portion of said first pump radiation into a third and a fourth portion;
   - splitting said second portion of said second pump radiation into a third and a fourth portion;
   - coupling said third portion of said first pump radiation in said active fiber (201) in said second direction;
   - coupling said third portion of said second pump radiation in said active fiber (201) in said first direction.

2. A method for amplifying an optical signal in an optical amplifier (200) comprising an active fiber (201), a first pump source (202) and a second pump source (203), said method comprising the steps of:
   - coupling said optical signal in said active fiber (201) in a first direction;
   - emitting a first pump radiation from said first pump source (202) and a second pump radiation from said second pump source (203);
   - splitting said first pump radiation into a first and a second portion;
   - splitting said second pump radiation into a first and a second portion;
   - coupling said first portion of said first pump radiation in said active fiber (201) in said first direction;
   - coupling said first portion of said second pump radiation in said active fiber (201) in a second direction, opposite to said first direction;

- splitting said second portion of said first pump radiation into a third and a fourth portion;
- splitting said second portion of said second pump radiation into a third and a fourth portion;
- coupling said third portion of said first pump radiation in said active fiber (201) in said second direction;
- coupling said third portion of said second pump radiation in said active fiber (201) in said first direction.

3. An optical amplifier (200) comprising an active fiber (201), a first pump source (202) and a second pump source (203) having an emission wavelength in a predetermined emission pump wavelength range, characterized in that it further comprises a first and a second coupling device (210, 211) having at least two input ports and at least two output ports, said first and second coupling devices (210, 211), said first and second pump sources (202, 203) and said active fiber (201) being connected in such a manner as:
   - the first input ports of said first and second coupling devices (210, 211) are connected to said first and second pump sources (202, 203), respectively;
   - the first output ports of said first and second coupling devices (210, 211) are connected to a first and a second end of said active fiber (201), respectively;
   - the second output port of said first coupling device (210) is connected to the second input port of said second coupling device (211);
   - the second output port of said second coupling device (211) is connected to the second input port of said first coupling device (210).

4. An optical amplifier (200) according to claim 3, characterized in that said emission pump wavelength range is comprised between 965 nm and 990 nm.

5. An optical amplifier (200) according to claim 4, characterized in that said emission pump wavelength range is comprised between 970 nm and 986 nm.

6. An optical amplifier (200) according to any one of claims 3 to 5, characterized in that at least one of said first and second pump sources (210, 211) includes a reflection type optical device.

7. An optical amplifier (200) according to claim 7, characterized in that both said first and second pump sources (210, 211) include a respective reflection type optical device.

8. An optical amplifier (200) according to claim 6 or 7, characterized in that a reflectivity of said reflection type optical device in said emission pump wavelength range is lower than 10%.

9. An optical amplifier (200) according to claim 8, characterized in that said reflectivity is lower than 8%.

10. An optical amplifier (200) according to any one claims 6, 8 or 9 characterized in that said first pump source (202) includes a first laser and said reflection type optical device, said second pump source (203) includes a second laser, a detuning quantity between a center wavelength of said reflection type optical device and a free running wavelength of said second laser is lower than 7 nm in absolute value.

11. An optical amplifier (200) according to claim 10, characterized in that said detuning quantity is lower than 5 nm in absolute value.

12. An optical amplifier (200) according to any one of claims 7 to 9, characterized in that a detuning quantity between a center wavelength of said first reflection type optical device and a center wavelength of said second reflection type optical device is of at least 5 nm in absolute value.

13. An optical amplifier (200) according to any one of claims 3 to 12, characterized in that said first and second coupling devices (210, 211) are 3 dB couplers.

14. An optical line having a first end and a second end, comprising at least one transmission optical fiber and at least one optical amplifier (200) according to any one of claims 3 to 13.

15. An optical system comprising a transmitting station, a receiving station and an optical line according to claim 14, said transmitting station being coupled to said first end of said optical line and said receiving station being coupled to said second end of said optical line.

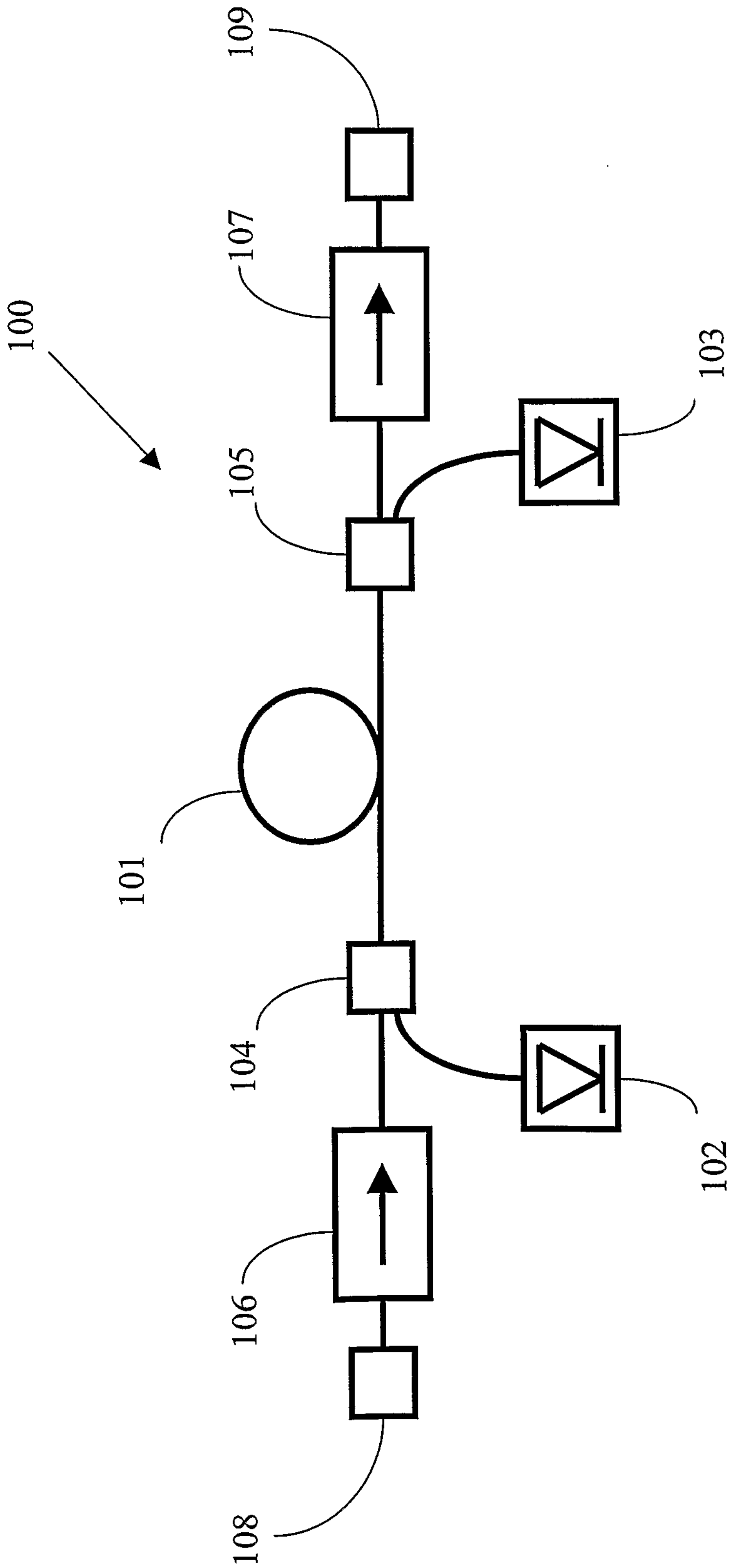


Fig.1

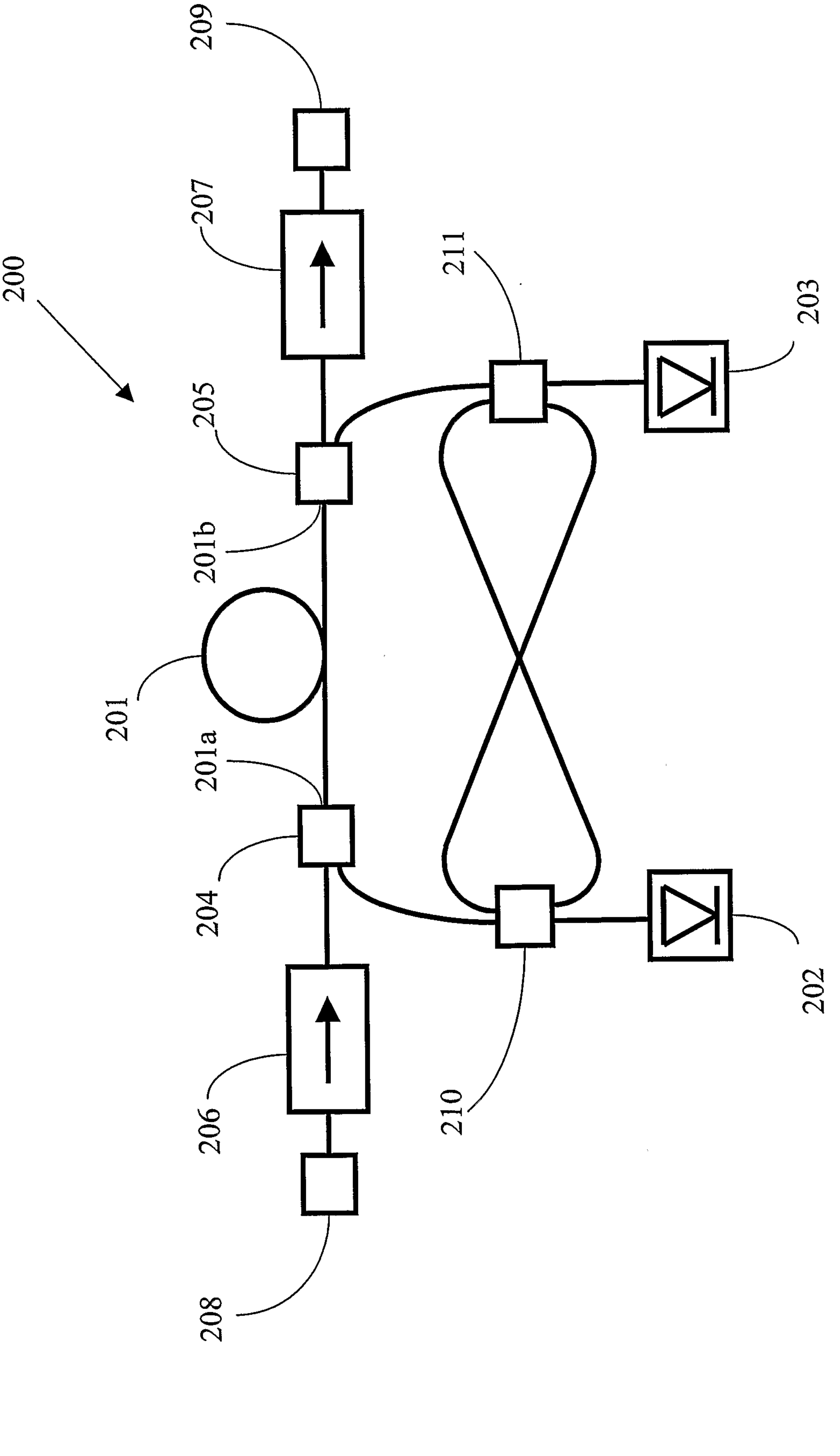
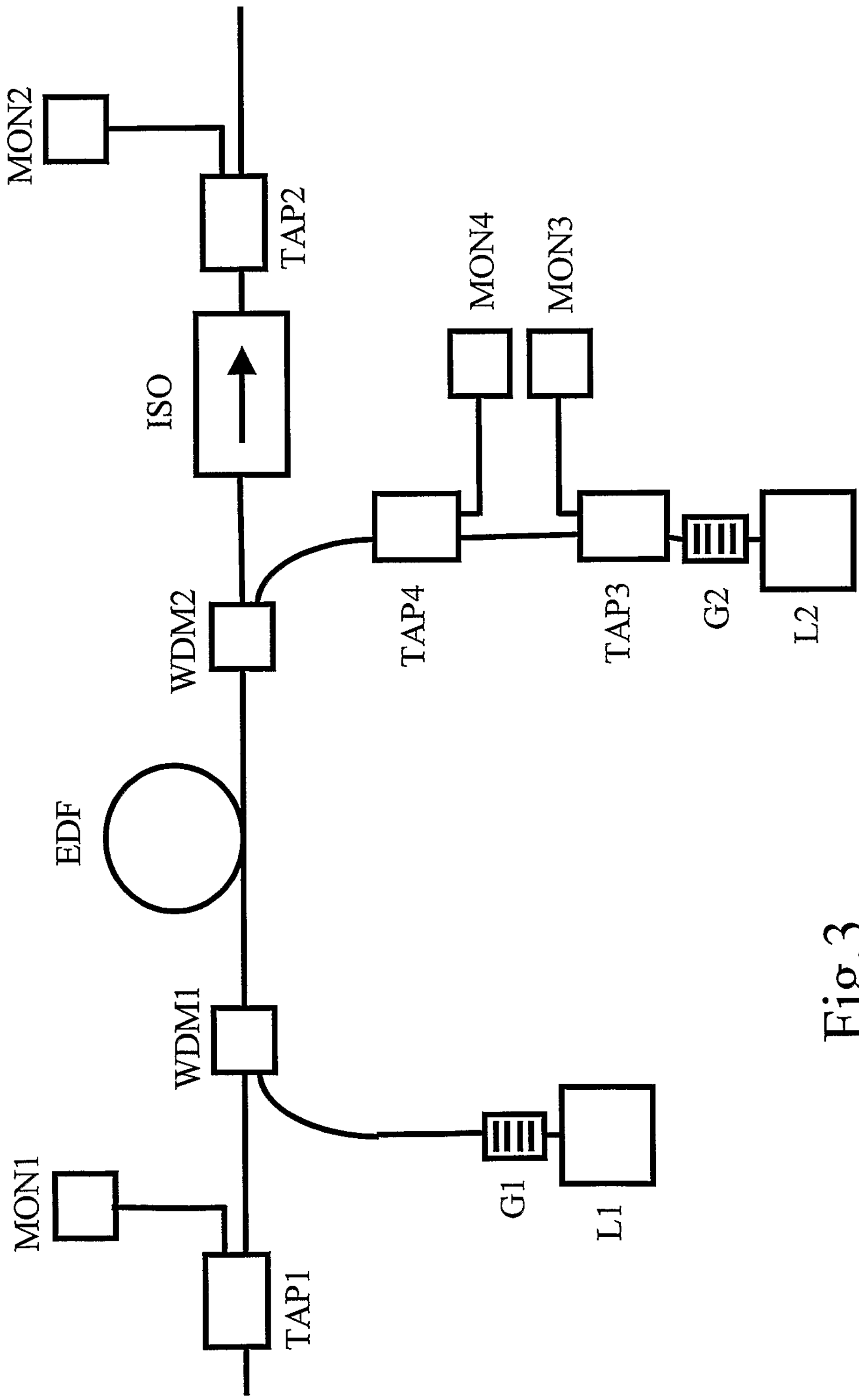


Fig.2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MON4
MON3
WDM2
TAP4
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G2
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EDF
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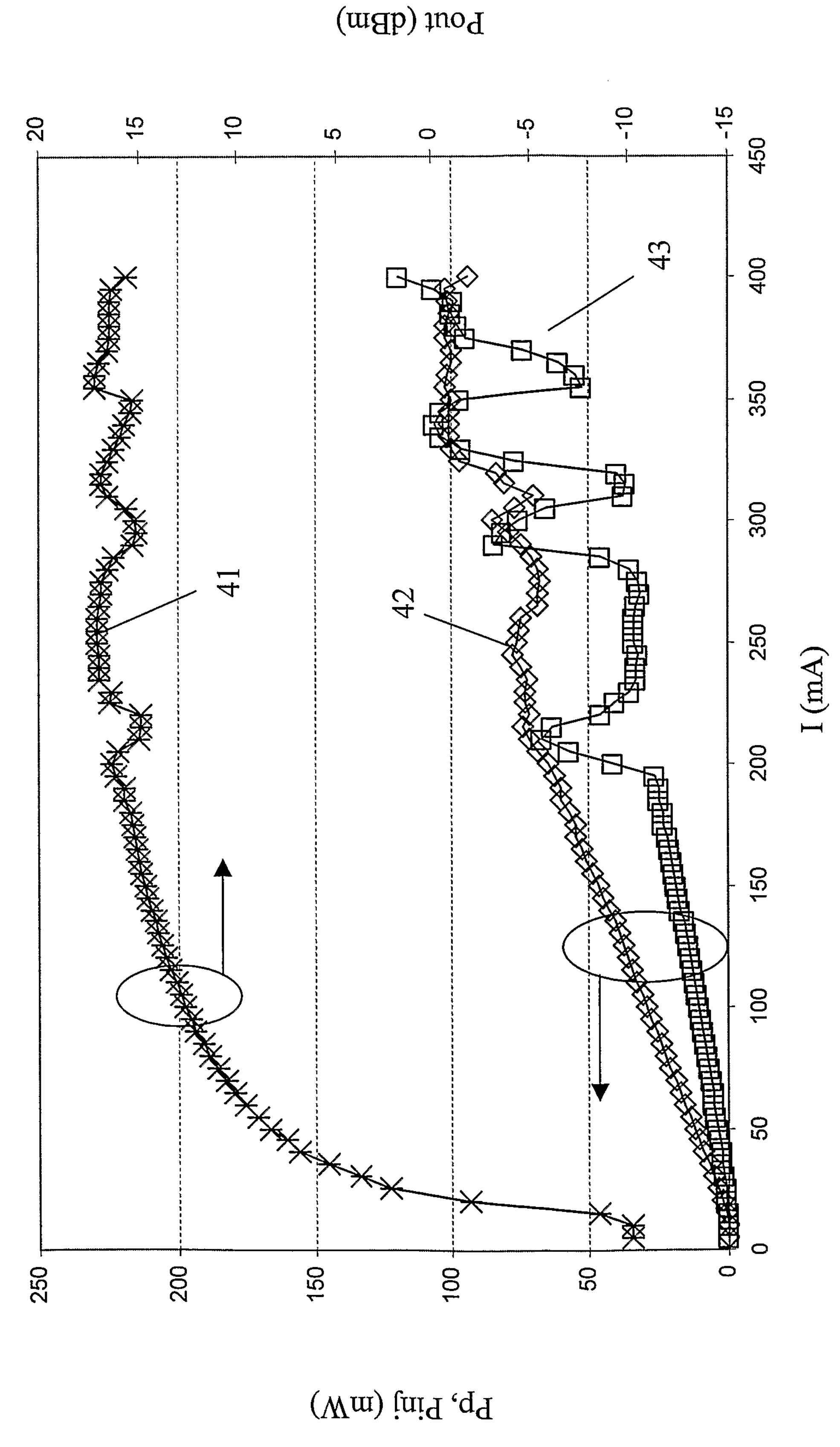
G1
L1

Fig.3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-10
-15
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200
150
100
50
0
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150
200
250
300
350
400
450
I (mA)
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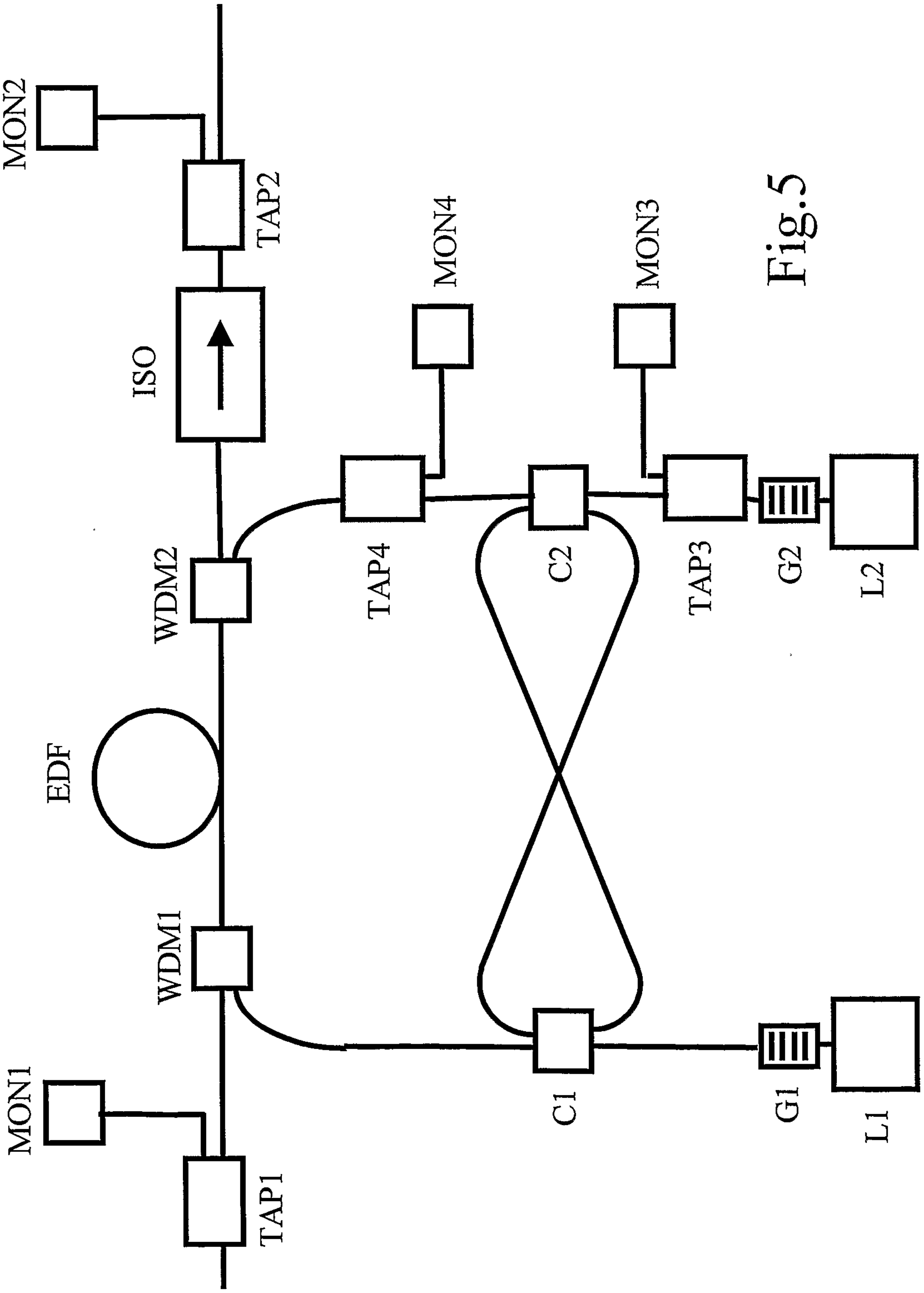
42
43

Fig.4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TAP2
ISO
MON4
MON3
WDM2
TAP4
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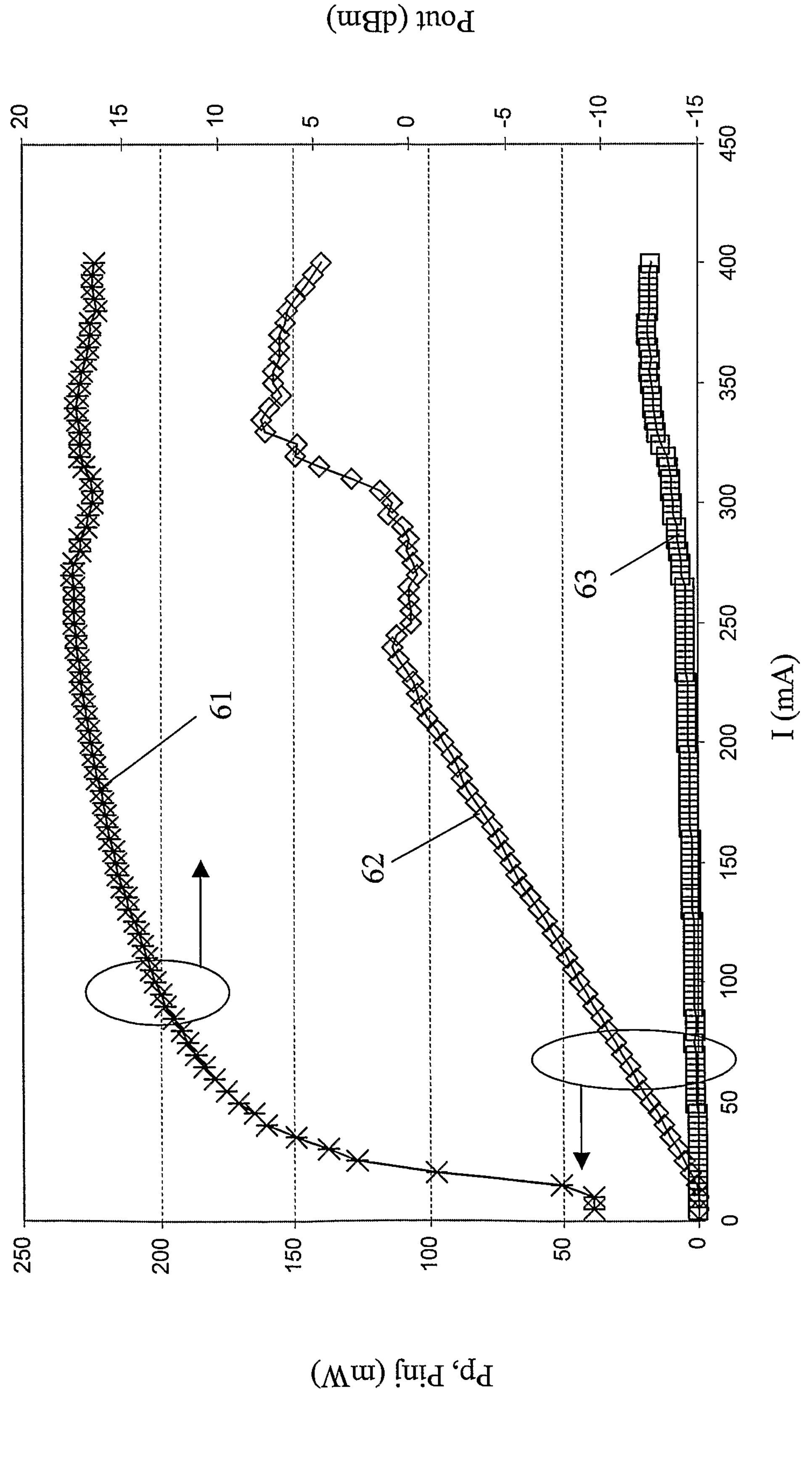
G1
L1

Fig.5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I (mA)
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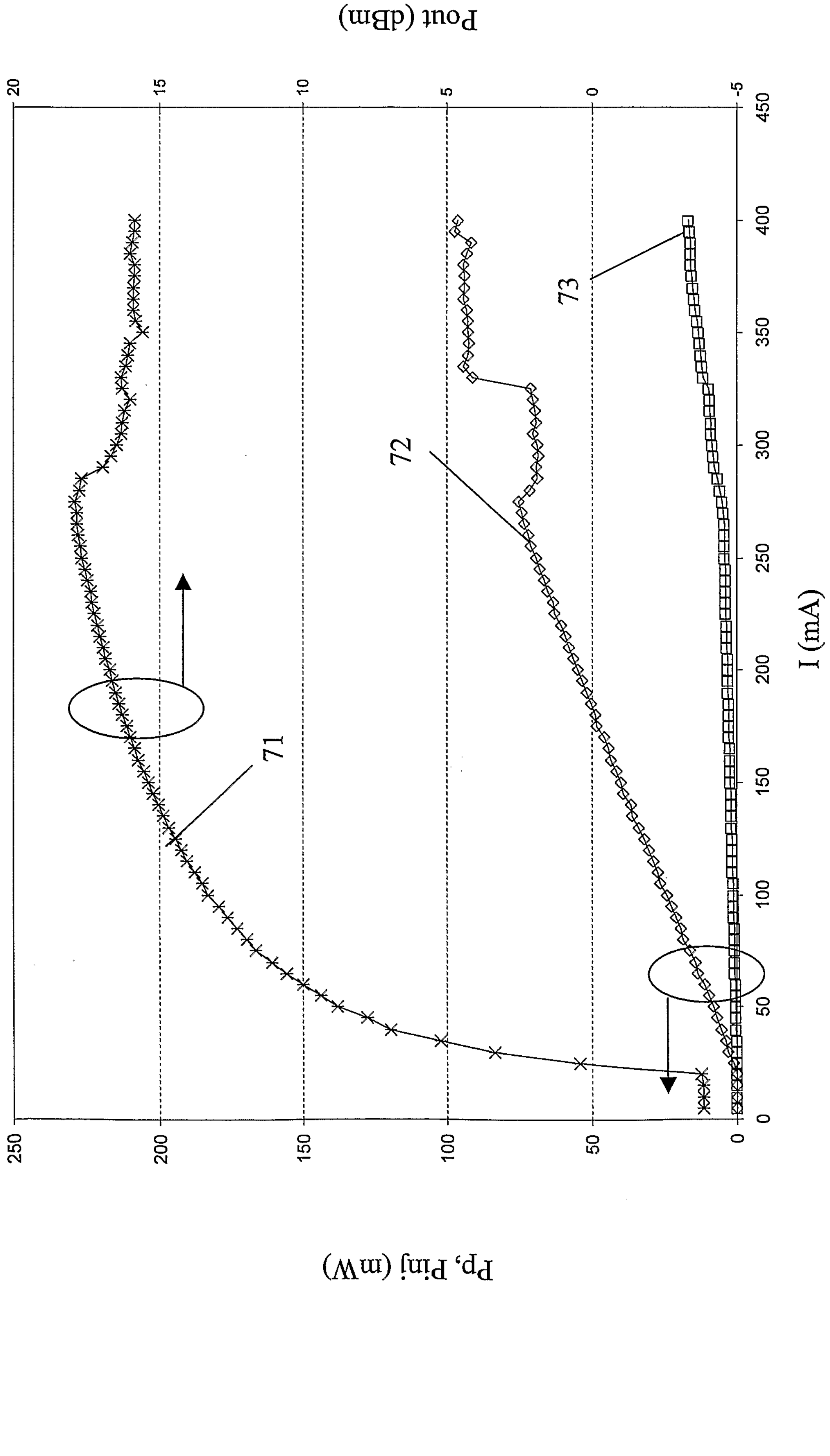
15
20

Fig.6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I (mA)
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0
50
100
150
200
250
300
350
400
450

Fig.7

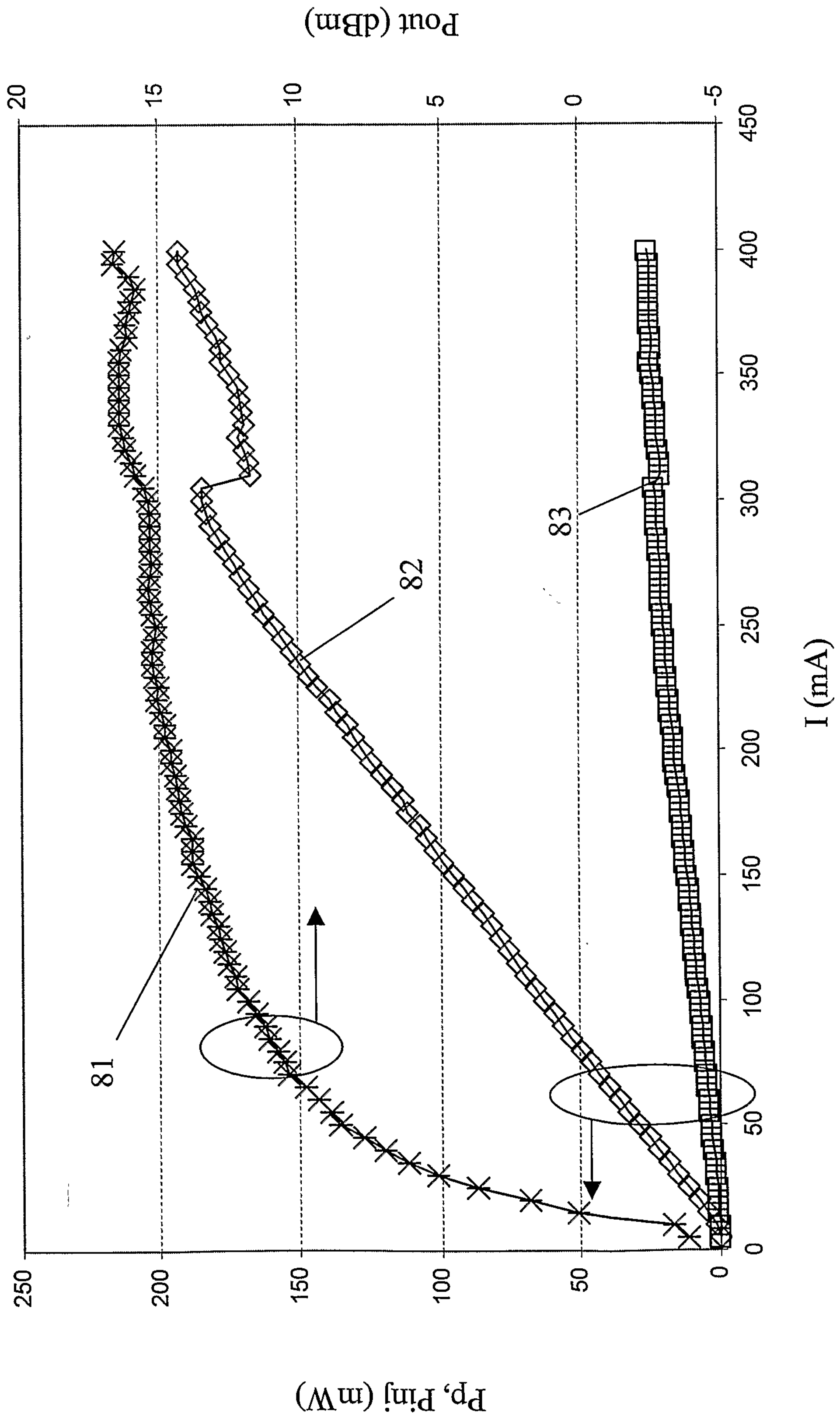

Fig.8

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 02/12034

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S3/067

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)
IPC 7 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 practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 015, no. 274 (P-1226), 11 July 1991 (1991-07-11) & JP 03 092827 A (KOKUSAI DENSHIN DENWA CO LTD), 18 April 1991 (1991-04-18) figure 8 ---	1-3
A	US 5 521 753 A (FAKE MICHAEL ET AL) 28 May 1996 (1996-05-28) figure 2 ---	1-3
A	EP 1 180 833 A (CIT ALCATEL) 20 February 2002 (2002-02-20) page 8, column 13 -column 14; figures 3A,3B -----	1-3

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents:

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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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 September 2003	18/09/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hervé, D

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 02/12034

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