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Description

Technical field

[0001] The present invention relates to transmission via optical fibers in satellites and spacecraft and other high radiation environments.

Background

[0002] The Sun emits hazardous radiation in the form of SPEs (Solar Particle Events). These charged and highly energetic particles can interact with materials and cause: lattice deformation via ionization (both directly and indirectly); lattice deformation by direct collision; impurity creation in the lattice by neutron capture (neutrons produced in primary interactions); energy deposition which can lead to build up of charge, thus distorting the lattice. In addition to SPEs, there are also Galactic Cosmic Rays (GCR), energetic charged particles from Deep Space. These are less apparent because the solar activity deflects the GCR. Occasionally, the Sun emits a coronal mass ejection (CME) which is seen alongside a solar flare. CMEs release a much greater flux of SPEs and have been known to cause mission failure in satellites or spacecraft.

[0003] On Earth, the magnetosphere provides protection from the harmful radiation from the Sun and Deep Space by deflecting the majority of high energy particles. In addition, the atmosphere attenuates the energetic particles that do pass through the magnetosphere. However, when in orbit around the Earth, this protection is diminished due to lack of atmosphere and weakening of the magnetosphere with distance from the Earth's core. It is particularly harmful to have the satellites orbiting within the radii of the Van Allen belts due to their nature as regions of trapped electrons and protons within the inner magnetosphere, between 60 and 6000 miles altitude for the inner belt and between 8,400 to 36,000miles for the outer belt. These radii vary with solar activity, so specific orbital tracks must be considered. Different elevation orbits have different associated dose rates, resulting in different total doses depending on the mission lifetime. A higher total dose is more harmful to both humans and equipment. It is also believed that a higher dose rate can have a more detrimental effect. In a geostationary orbit for 20 years, the expected total dose is 137Gy from behind 10mm thick aluminum shielding. In low earth orbit (LEO) the dose is less than half this value.

[0004] Both SPE and GCR lead to distortions in the lattice of a material and have specific effects on different types of materials. In optical materials, this can lead to defect creation via the previously mentioned processes in the fiber lattice structure. Not only is there creation of new defects, but intrinsic defects are also exacerbated. The radiation induced defects will absorb light, so that less light can propagate the fiber, resulting in so-called radiation induced attenuation (RIA). In order to keep the fiber as radiation tolerant as possible, it is therefore important to keep as perfect a lattice structure as possible.

[0005] It has previously been reported that a full recovery from radiation damage to optical fibers can be found from pumping at both 980nm and 532nm. It is, however, not ideal in space to have multiple pumps since this requires more mass, power and adds another layer of complexity in reliability testing.

[0006] It will be appreciated that the opportunities to repair or replace optical fibers located on satellites or spacecraft are very limited. Even if repair or replacement is possible, it is typically a very expensive process.

[0007] Furthermore, given the use typical applications of optical fibers within satellites and/or spacecraft, any damage thereto could have very serious implications. For example, the optical fibers may be utilized within a spacecraft's navigation system, and hence any damage thereto may cause the spacecraft to take an incorrect path.

[0008] It is therefore essential to ensure that optical fibers used on satellites and spacecraft are optimally resistant to damage, particularly radiation damage.

[0009] US2012/0134376 A1 discloses a radiation-insensitive erbium doped amplifying optical fiber pumped at 980nm, with a central core formed of a core matrix and nanoparticles, wherein the nanoparticles are formed of a nanoparticle matrix surrounding the erbium. The nano-particle matrix may include complementary dopants such as aluminum and/or lanthanum.

[0010] Todd S Rose ET AL: "Gamma and Proton Radiation Effects in Erbium-Doped Fiber Amplifiers: Active and Passive Measurements", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 19, no. 12, December 2001, evaluates the relative radiation sensitivity of commercially available Er-doped fibers configured as optical amplifiers using 980nm pump signals.

[0011] Tz-Shiuan Peng ET AL: "Photo-annealing effects for erbium doped fiber sources after gamma irradiation tests by using 532 nm and 976 nm lasers", Proceedings of SPIE, vol. 7503, 5 October 2009, pages 750375-750375-4, investigates two EDFs with different sensitivites to radiation, by comparing photo-annealing efficiencies obtained by using 532nm and 976nm pump lasers. One EDF has an Er^{3+}concentration of approximately 299ppm, and is co-doped with Al and La.

Definitions

[0012] As used herein, "optical" includes all forms of electromagnetic radiation, whether visible or invisible to the human eye.

[0013] As used herein, "extraterrestrial location" is any location outside of the Earth's atmosphere. Examples of extraterrestrial locations include a low earth orbit (LEO) such as that of the International Space Station (ISS), a medium earth orbit (MEO), a geostationary earth orbit (GEO) and a geostationary transfer orbit (GTO).

[0014] As used herein, "high radiation environment" is an environment in which the average radiation dose is greater than approximately 1×10^{-5} Gy/h.

[0015] As used herein, an "active dopant" is a dopant which, when optically pumped, absorbs the pump photons and uses the absorbed energy to amplify the seed or signal transmitted by the optical fiber.

[0016] As used herein, a "passive dopant" is a dopant that, when pumped, does not substantially absorb the pump photons. A passive dopant may, however, modify the optical properties of the optical fiber through modifications of the structure thereof.

Summary of the invention

[0017] In accordance with the present invention, as seen from a first aspect, there is provided a spacecraft or satellite optical transmission apparatus in accordance with claim 1.

[0018] It has been found by the applicant that an optical transmission system in accordance with the present invention demonstrates effective recovery from radiation induced attenuation (RIA). This is contrary to established thinking, which suggests that co-doping an active trivalent dopant with a passive trivalent dopant, particularly in high concentrations, produces an optical fiber with poor performance under radiation. Established thinking, in particular, suggests that co-doping an active trivalent dopant with aluminum produces an optical fiber that demonstrates greatly increased losses under high radiation conditions. It has been found by the applicant that optical pumping reverses this trend, which is believed to be due to the annealing of point defects associated with trivalent materials under such pumping.

[0019] The doping density of the passive trivalent dopants may be varied according to the doping density of the active trivalent dopant. Preferably the ratio of doping densities of passive trivalent dopants to active trivalent dopants is between approximately 20 and approximately 180 to 1.

[0020] The active trivalent dopant and passive trivalent dopants are preferably arranged in a trivalent matrix.

[0021] The optical fiber preferably comprises a single active trivalent dopant, but may comprise additional active trivalent dopants.

[0022] In accordance with the invention the active trivalent dopant is erbium. As will be appreciated by a person skilled in the art, erbium is a trivalent material, but its concentration is fixed by the amount of absorption that is required of the fiber. Erbium constitutes the active component of the fiber, which absorbs the pump photons and uses that energy to amplify a signal carried by the fiber. The erbium doping concentration is therefore varied according to the absorption required for the particular application.

[0023] Erbium is provided at a doping density of between approximately 100 parts per million (ppm) and approximately 3000 ppm.

[0024] Preferably the one or more passive trivalent dopants are selected from the group consisting of: lanthanum; aluminum; and phosphorus.

[0025] As set out above co-doping with passive trivalent materials such as aluminium is thought to greatly increase radiation induced attenuation (RIA), which is undesirable. In the case without radiation induced attenuation though the addition of aluminium acts to improve the spectral gain flatness and increase the overall usable spectral bandwidth of a fiber in a fiber amplifier. The addition of aluminium is also beneficial for the incorporation of a higher concentration of erbium and reduces unwanted erbium ion clustering which can improve the amplifier efficiency.

[0026] In accordance with the invention the two or more passive trivalent dopants comprise aluminum and lanthanum.

[0027] The passive trivalent dopants may comprise a member of the lanthanide series of chemical elements.

[0028] The passive trivalent dopants comprise lanthanum, which is provided at a dopant density between approximately 10,000 ppm and approximately 120,000 ppm. It has been found by the applicant that the presence of lanthanum in an optical fiber provides an improved recovery during anneal.

[0029] Additionally the passive trivalent dopants comprise trivalent aluminum, provided at a doping density of between approximately 10,000 ppm and 60,000 ppm.

[0030] Additionally the passive trivalent dopants may comprise phosphorus, which may be provided at a doping density of up to approximately 20,000 ppm.

[0031] The active trivalent dopants and the passive trivalent dopants are preferably disposed within a core of the optical fiber.

[0032] The optical fiber, preferably the core thereof, may comprise silica, which preferably defines a base material.

[0033] The optical fiber, preferably the core thereof, may comprise germanium. Preferably the optical fiber, and more preferably the core thereof, comprises germanosilicate, which preferably defines a base material.

[0034] The core of the optical fiber preferably comprises a diameter of between approximately 2 μm and approximately 20 μm. More preferably, the core of the optical fiber comprises a diameter of between approximately 2 μm and approximately 7 μm.

[0035] The optical fiber preferably comprises a cladding layer that circumferentially surrounds the core. Preferably the cladding layer comprises a diameter of between approximately 60 μm and approximately 200 μm. More preferably, the cladding layer comprises a diameter of between approximately 120 μm and approximately 130 μm. Preferably of the optical fiber comprises an outer dual coating of acrylate.

[0036] The apparatus is configured for optically pumping the optical fiber at a single wavelength only. In this regard, the apparatus comprises exactly one optical pump source configured for optically pumping at least a portion of the optical fiber.

[0037] It has been found by the applicant that an optical fiber comprising a passive trivalent dopant shows excellent recovery under optical annealing at a single pump wavelength. The present invention therefore obviates the requirement for multiple pumps and consequently permits reduction in the mass and complexity of the optical transmission apparatus. It will be appreciated that mass budgeting is vital to any space mission; an estimate from 2004 provided in "Spacecraft Systems Engineering" (Third Edition) gives a cost of $25,000 per kilogram of mass launched into space. Preferably the optical pump source comprises a laser source.

[0038] The optical pump is configured to provide pump energy having a wavelength of between approximately 970 nm and approximately 990 nm. Whilst current space technology uses 1480 nm pumps, it has been found by the applicants that such pumps would not be particularly effective in annealing radiation induced damage.

[0039] Advantageously the pumping of the optical fiber at around 980nm has been seen to reverse the trend of RIA in fibers containing trivalent materials such as aluminium or lanthanum. Also, it follows that the benefits of co-doping with these trivalent materials can now be achieved in high radiation environments. Therefore the fiber and apparatus described may provide superior gain flatness and maintain a wide spectral bandwidth in a high radiation environment for the lifetime of operation. This means that advantageously, the spectral performance of the fiber is maintained.

[0040] In a preferred embodiment, the optical transmission apparatus comprises an optical amplifier.

[0041] The optical amplifier may be included within a spacecraft or satellite data communications system, which may be arranged for internal or external communications.

[0042] In one embodiment, the optical transmission apparatus defines part of a fiber optic gyroscope, which may constitute part of a navigation system of the spacecraft or satellite. The optical transmission apparatus preferably defines an optical source of the fiber optic gyroscope. In use, a pulse of radiation from the optical source, is split by an optical splitter, the two pulses being injected into a closed loop or closed series of loops of optical fiber in different directions. If the fiber optic gyroscope is subjected to rotation in the plane of the loop or loops, the beam travelling against the rotation experiences a marginally shorter path delay than the other beam.

[0043] In accordance with the present invention, also as seen from a first aspect, there is provided a spacecraft or satellite comprising an optical transmission apparatus as hereinbefore described.

[0044] In accordance with the present invention, as seen from a second aspect, there is provided a method for transmitting electromagnetic radiation via an optical fiber in a high radiation environment, in accordance with claim 10.

[0045] The high radiation environment may be an extraterrestrial environment, which includes but is not limited to a low earth orbit (LEO), medium earth orbit (MEO), geostationary earth orbit (GEO) or geostationary transfer orbit (GTO).

[0046] Alternatively or additionally, the high radiation environment may be within or proximal to a nuclear reactor facility.

[0047] Alternatively or additionally, the high radiation environment may be within or proximal to high energy physics (HEP) apparatus such as a particle collider.

[0048] Alternatively or additionally, the high radiation environment may be within radiation sensing apparatus.

[0049] Preferably the optical fiber comprises one or more of the above-mentioned features.

[0050] Preferably the optical pump source comprises one or more of the above-mentioned features.

[0051] Preferably the method comprises optically pumping the optical fiber with radiation from the optical pump source.

[0052] In accordance with the present invention, as seen from a third aspect, there is provided a radiation insensitive fiber laser cavity.

Detailed description

[0053] An embodiment of the present invention will now be described by way of example only and with reference to the accompanying drawings, in which:

Figure 1 is a schematic illustration of an optical transmission apparatus within a satellite or spacecraft in accordance with an embodiment of the present invention as seen from the first aspect;

Figure 2 is a flow diagram of a method for transmitting electromagnetic radiation via an optical fiber in a high radiation environment in accordance with an embodiment of the present invention as seen from the second aspect;

Figure 3 is a schematic illustration of an apparatus used for testing the optical transmission apparatus illustrated in Figure 1;

Figure 4 is a table of results of the testing illustrated in Figure 1; and

Figure 5 is a schematic illustration of an optical transmission apparatus of Figure 1, in accordance with an alternative embodiment of the present invention as seen from the first aspect.

[0054] Referring to Figure 1 of the drawings, there is illustrated an optical transmission apparatus 10 of a satellite or spacecraft. In the illustrated embodiment, the optical transmission apparatus 10 is in the form of an erbium doped fiber amplifier (EDFA) within a satellite communications system.

[0055] The apparatus 10 comprises a first optical fiber 11 and second and third optical fibers 12, 13 at each longitudinal end of the first optical fiber 11. The first, second and third optical fibers 11, 12, 13 are optically coupled such that photons may travel in a first direction from the second fiber 12, through the first fiber 11 and subsequently through the third fiber.

[0056] The first fiber 11 comprises a central doped core between 3 and 20μm in diameter, surrounded by 125μm diameter cladding of pure silica. The fiber 11 may be further coated, for example in dual acrylate.

[0057] The core of the first optical fiber 11 is formed of germanosilicate doped with erbium, lanthanum and aluminum in the following doping densities (subject to +/- 20%):

Erbium:	370 parts per million (ppm)
Lanthanum:	between 10,000 and 20,000 ppm
Aluminum:	between 35,000 and 60,000 ppm

[0058] As will be appreciated by a person skilled in the art, erbium is an active trivalent dopant, whereas lanthanum and aluminum are passive trivalent dopants. The active trivalent dopant concentration, namely the erbium concentration, is fixed by the level of absorption required for the particular application but this is not the case for the passive trivalent dopants.

[0059] The second and third optical fibers 12, 13 are identical to one another, each comprising a central core and a surrounding cladding layer. The core of the second and third fibers 12, 13 is formed of germanosilicate; the cladding layer is formed of pure silica. The optical fibers 12, 13 may further comprise a coating, for example a dual; acrylate coating.

[0060] The apparatus 10 further comprises an optical pump source 14 in the form of a 980nm laser source.

[0061] The fiber could be used as an ASE source, amending apparatus 10 by removing the signal input and pumping the fiber with no seed source.

[0062] A wavelength division multiplexing (WDM) coupler 15 is configured to couple a signal 16 to be amplified by the apparatus 10 with the output from the optical pump source 14. The WDM coupler 15 is located at a longitudinal end of the second optical fiber 12 distal to the first optical fiber 11.

[0063] In use, the doping in the first optical fiber 11 facilitates optical amplification: this is achieved by stimulated emission of photons from dopant ions in the core of fiber 11. In detail, the radiation from the laser source 14 excites the dopant ions into a higher energy level. Once in this higher energy level, the ions decay back to a lower energy level through stimulated emission of a photon at the signal wavelength, thereby amplifying the signal.

[0064] The first fiber 11 in the above-described embodiment will henceforth be referred to as fiber A.

[0065] In an alternative embodiment, the core of the first optical fiber 11 is formed of germanosilicate doped with erbium, lanthanum and aluminum the following doping densities (subject to +/- 20%):

Erbium:	1200 ppm
Lanthanum:	between 20,000 and 30,000 ppm
Aluminum:	between 35,000 and 60,000 ppm

[0066] In another alternative embodiment, the core of the first optical fiber 11 is formed of germanosilicate doped with erbium, lanthanum and aluminum in the following doping densities (subject to +/- 20%):

Erbium:	1700 ppm
Lanthanum:	between 80,000 and 120,000 ppm

(continued)

Aluminum:	between 35,000 and 60,000 ppm

[0067] In another alternative embodiment, the core of the first optical fiber 11 is formed of germanosilicate doped with erbium and aluminum in the following doping densities (subject to +/- 20%):

Erbium:	1100 ppm
Lanthanum:	between 10,000 and 20,000 ppm
Aluminum:	between 35,000 and 60,000 ppm

[0068] In yet another alternative embodiment, the core of the first optical fiber 11 is formed of silica doped with erbium, aluminum and germanium in the following doping densities (subject to +/- 20%):

Erbium:	2600 ppm
Lanthanum:	between 10,000 and 20,000 ppm
Aluminum:	between 35,000 and 60,000 ppm

[0069] In certain examples not in accordance with the invention the core of the first optical fiber 11 may be doped with erbium and aluminum but not with lanthanum.

[0070] In one example not in accordance with the invention, herein fiber B, the core of the first optical fiber 11 is formed of silica doped with erbium and aluminum in the following doping densities (subject to +/- 20%):

Erbium:	380 ppm
Aluminum:	between 20,000 and 40,000 ppm

[0071] In another alternative example not in accordance with the invention, herein fiber C, the core of the first optical fiber 11 is formed of germanosilicate doped with erbium and aluminum in the following doping densities (subject to +/- 20%):

Erbium:	450 ppm
Aluminum:	between 35,000 and 60,000 ppm

[0072] Figure 3 illustrates an apparatus 50 used by the applicant to test the effects of ionization on the first optical fiber 11 of the apparatus of Figure 1. The various embodiments of this fiber 11 described above have each been tested by the applicant.

[0073] A gamma source 18 was used to simulate the effects of ionization, which are overwhelmingly responsible for radiation induced attenuation (RIA). The non-ionizing effects, such as lattice displacement, were not simulated but a consensus across the industry demonstrates that using a gamma radiation source to simulate the SEP flux is acceptable.

[0074] 100m lengths of fiber 11 was irradiated passively (without light or pump passing through) using a Co60 source for a period of four hours at a dose rate of 50Gy/hr, confirmed by national standards. The total dose was therefore 200Gy, which is equivalent to 146% the total radiation dose in a 20 year mission lifetime in geostationary earth orbit (GEO). The radiation level tolerance was $\pm$ 10% and the temperature was maintained between 23 and 25 °C. A 100 meter length of each fiber 11 was kept as a control.

[0075] The fiber attenuation, i.e. optical loss, was tested with a PK2500 system across the wavelengths of interest, before and after radiation. RIA was calculated by subtracting the unradiated attenuation values from the post radiated value at each wavelength. The fiber was left for a year to thermally anneal at room temperature; it is assumed that all appreciable thermal annealing would have occurred in this time period.

[0076] Photo annealing was subsequently performed using the optical pump 14 at 974nm at 175mW (measured at the amplifying fiber) with seeds 19 at 1536.61nm, 1541.35nm, 1550.92nm and 1552.52nm. The length of the fiber 11 used was varied as a function of the absorption per meter at 1531nm so that the total absorption over the full length was constant at 80dB for each sample tested. The fiber 11 was pumped continuously at 974nm for several days and the output power was measured at regular intervals by a power meter 20.

[0077] As will be appreciated by a person skilled in the art, radiating the fiber 11 at a high dose rate for a short amount of time then following with annealing is not identical treatment to simultaneously irradiating the fiber and photo-annealing, as would occur under continuous use in Earth orbit or other space applications. Instead, giving the total dosage in a short amount of time and then annealing the fiber 11 simulates a worst case scenario, since all of the damage requires healing. Furthermore, research within the industry reveals that the same total dose provided as a higher dose rate produces more damage than a lower dose rate for a longer period.

[0078] The output power was extrapolated to 20 years using a power curve fit, in keeping with kinetic models of radiation damage such as those discussed by D.L. Griscom, M.E. Gingerich and E.J. Friebele in "Model for the dose, dose rate, and temperature dependence of radiation-induced loss in optical fibers" (IEEE TRANS.NUCL. SCI., VOL. 41, pp. 523-527, 1994) and G. M. Williams and E. J. Frieble in "Space radiation effects on erbium doped fiber devices: sources, amplifiers, and passive measurements" (IEEE Trans. Nucl. Sci., vol. 45, pp. 1531-1536, June 1998).

[0079] The percentage recovery was found by calculating the extrapolated final output as a percentage of the control fiber output. The results for fibers A, B and C may be seen in Figure 4. It will be appreciated that fiber A cannot recover to above 100%; the figure of 100.63% is due to a small standard error within the experimental process.

[0080] Testing as described above has demonstrated that a satellite or spacecraft optical transmission apparatus in accordance with the present invention 10 shows excellent recovery from radiation damage and is likely to withstand a 20 year mission lifetime. It is believed by the applicants that the recovery mechanism is the annealing of point defects associated with trivalent materials under pumping of 980 nm.

[0081] Furthermore, it can be seen from the results of such tests that an optical fiber doped with lanthanum, such as fiber A, show rapid recovery despite suffering substantial initial radiation damage. Accordingly, such fibers are suitable for use in high radiation environments such as space over prolonged periods. In particular, such fibers are best suited to applications where the pump will be active for more than 20% of the mission lifetime. On the other hand, an optical fiber without lanthanum doping, such as fiber B, is more resistant to initial damage but demonstrates a slower rate of recovery. Accordingly, such fibers are optimal for use for less than 20% of a 20 year mission lifetime.

[0082] With reference to Figure 2 of the drawings, there is illustrated a method 100 for transmitting electromagnetic radiation via an optical fiber in a high radiation environment in accordance with an embodiment of the present invention.

[0083] In the illustrated embodiment, the high radiation environment is an extraterrestrial environment such as a low Earth orbit (LEO). Alternatively, the high radiation environment may be within a nuclear reactor facility, for example.

[0084] The method in accordance with the invention comprises providing, to a high radiation environment, an optical fiber comprising erbium as an active trivalent dopant and at least aluminum and lanthanum as passive trivalent dopants at step 101. The optical fiber may be as hereinbefore described in relation to the apparatus illustrated in Figure 1. For example, the core may be formed of silica doped with erbium, lanthanum, aluminum and trivalent germanium in the following doping densities:

Erbium:	370 parts per million (ppm)
Lanthanum:	between 10,000 and 20,000 ppm
Aluminum:	between 35,000 and 50,000 ppm
Germanium:	10,000 ppm

[0085] Alternatively, the core may comprise doping as described in the alternative embodiments above.

[0086] At step 102, the method comprises providing, to a high radiation environment, an optical pump source configured to provide an output at approximately 980 nm, for example the optical pump source 14 illustrated in the assembly 10 of figure 1.

[0087] The method further comprises, at step 103, transmitting a signal along the optical fiber in a high radiation environment. The signal is amplified during its transmission. The signal may, for example, be a communications signal within an intra-satellite data transfer system.

[0088] The method further comprises pumping the optical fiber at a wavelength of approximately 980nm at step 104, this step preferably being performed in the high radiation environment.

[0089] The method may also comprise creating multiple passes through a fiber laser cavity.

[0090] The apparatus 60 for use with this method is illustrated in Figure 5. The cavity is defined between two reflective or partially reflective surfaces such as mirrors 21a, 21b. Alternatively, the reflective mechanism may be in the form of Bragg gratings.

[0091] A length of optical fiber 11 extends between the two mirrors 21a, 21b. The core of the optical fiber 11 in accordance with the invention comprises as an active trivalent dopant erbium and as passive trivalent dopants lanthanum and aluminum. The optical fiber 11 may be as hereinbefore described in relation to the apparatus illustrated in Figure 1.

[0092] Second and third optical fibers 12, 13 in an embodiment are optically coupled to the first optical fiber 11 at respective longitudinal ends thereof. The second and third optical fibers 12, 13 may be as hereinbefore described in relation to the apparatus illustrated in Figure 1. Alternatively, the second and third optical fibers 12, 13 may be identical to the first optical fiber 11 such that the apparatus 60 comprises only one optical fiber. The apparatus of Figure 5 illustrates a free space set up and includes lenses 22a, 22b and 22c for focusing and collimating.

[0093] An optical pump source 14 is configured to pump the optical fiber 11 12, 13 at approximately 980nm.

[0094] Various modifications may be made to the described embodiments of apparatus and method without departing from the scope of the present invention. For example other dopants in addition to erbium, such as thulium, ytterbium, holium and/or neodymium could be included in the fiber composition. The radiation may be from any source and may be delivered at a constant dose rate or pulsed. All such variations and modifications are intended to be included within the scope of the appended claims. For example the optical transmission apparatus may be included within a steering or other control system for a spacecraft or satellite.

Claims

1. A spacecraft or satellite optical transmission apparatus (10) comprising:

   an optical fiber (11, 12, 13) comprising an active trivalent dopant and at least two passive trivalent dopants wherein in use the optical fiber having recovery from radiation induced attenuation; and
   a single optical pump source (14) operatively coupled to provide photoannealing pump energy to the optical fiber; wherein
   the active trivalent dopant is erbium at a doping density of between approximately 100 ppm and approximately 3,000 ppm and
   one of the passive trivalent dopants is La at a dopant density of between approximately 10,000 and approximately 120,000 ppm and another of the passive trivalent dopants is trivalent aluminum at a doping density of between approximately 10,000 ppm and 60,000 ppm, preferably 35,000 and 60,000 ppm; wherein the optical pump is configured to provide pump energy having a wavelength of between approximately 970 nm and approximately 990 nm; and further wherein the apparatus is configured for optically pumping the optical fiber at a single wavelength only for recovery from radiation induced attenuation.

2. A spacecraft or satellite optical transmission apparatus (10) according to claim 1, wherein the passive trivalent dopants further comprise phosphorus.

3. A spacecraft or satellite optical transmission apparatus (10) according to claim 1 or claim 2, wherein the active trivalent dopant and at least one passive trivalent dopant form a trivalent matrix.

4. A spacecraft or satellite optical transmission apparatus (10) according to claim 1, claim 2 or claim 3, wherein the active trivalent dopant and the une passive trivalent dopants are within a core of the optical fiber.

5. A spacecraft or satellite optical transmission apparatus (10) according to any one of claims 1 to 4, wherein the optical transmission apparatus (10) comprises one or more of an optical amplifier, an amplified spontaneous emission (ASE) source and a fiber laser, and/or forms part of a spacecraft or satellite data communications system.

6. A spacecraft or satellite optical transmission apparatus (10) according to any one of claims 1 to 5, wherein the optical transmission apparatus (10) defines part of a fiber optic gyroscope.

7. A spacecraft or satellite optical transmission apparatus (10) according to any one of the preceding claims, wherein the La is at a dopant density of between approximately 10,000 and approximately 20,000 ppm; or between approximately 20,000 and approximately 30,000 ppm.

8. A spacecraft or satellite optical transmission apparatus (10) according to any one of claims 1 to 6, wherein the La is at a dopant density of between approximately 80,000 and approximately 120,000 ppm.

9. A spacecraft or satellite comprising an optical transmission apparatus (10) according to any one of claims 1 to 8.

10. A method for transmitting electromagnetic radiation via an optical fiber in a high radiation environment in which the average radiation dose is greater than approximately 1×10^{-5} Gy/h, and in which there is used:

    an optical fiber (11, 12, 13) comprising an active trivalent dopant and at least two passive trivalent dopants wherein in use the optical fiber having recovery from radiation induced attenuation; and,
    a single optical pump source (14) operatively coupled to provide photoannealing pump energy to the optical

fiber; whereby the active trivalent dopant is erbium, one of the passive trivalent dopants is La, and another of the passive trivalent dopants is aluminum;
wherein the ratio of doping density measured in ppm of passive trivalent dopants to active trivalent dopants is 20:1 to 180:1; wherein the erbium is at a doping density of between approximately 100 ppm and approximately 3,000 ppm, the La is at a dopant density of between approximately 10,000 and approximately 120,000 ppm and the aluminum is at a doping density of between approximately 10,000 ppm and 60,000 ppm, and wherein the optical pump is configured to provide pump energy having a wavelength of between approximately 970 nm and approximately 990 nm; and further wherein the optical pump source is configured for optically pumping the optical fiber at a single wavelength only for recovery from radiation induced attenuation.

11. A method according to claim 10, wherein the high radiation environment is an extraterrestrial environment, or is within or proximal to a nuclear reactor facility, or is within or proximal to high energy physics, HEP, apparatus.

12. A method according to claim 10 or claim 11, wherein the trivalent aluminum is at a doping density of between approximately 35,000 and 60,000 ppm.

13. A method according to claim 10, claim 11 or claim 12, wherein the La is at a dopant density of between approximately 10,000 and approximately 20,000 ppm.

14. A method according to claim 10, claim 11 or claim 12, wherein the La is at a dopant density of between approximately 20,000 and approximately 30,000 ppm.

15. A method according to claim 10, claim 11 or claim 12, wherein the La is at a dopant density of between approximately 80,000 and approximately 120,000 ppm.

Patentansprüche

1. Eine optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10), die Folgendes beinhaltet:

eine Glasfaser (11, 12, 13), die ein aktives trivalentes Dotierungsmittel und mindestens zwei passive trivalente Dotierungsmittel beinhaltet, wobei die Glasfaser bei Verwendung Erholung von strahlungsinduzierter Dämpfung aufweist; und
eine einzelne optische Pumpquelle (14), die operativ gekoppelt ist, um der Glasfaser photoglühende Pumpenergie bereitzustellen; wobei:

das aktive trivalente Dotierungsmittel Erbium mit einer Dotierungsdichte von zwischen annähernd 100 ppm und annähernd 3 000 ppm vorliegt und
eines der passiven trivalenten Dotierungsmittel La mit einer Dotierungsdichte von zwischen annähernd 10 000 und annähernd 120 000 ppm vorliegt und ein weiteres der passiven trivalenten Dotierungsmittel trivalentes Aluminium mit einer Dotierungsdichte von zwischen annähernd 10 000 ppm und 60 000 ppm, vorzugsweise 35 000 und

60 000 ppm vorliegt; wobei die optische Pumpe konfiguriert ist, um Pumpenergie mit einer Wellenlänge von zwischen annähernd 970 nm und annähernd 990 nm bereitzustellen; und wobei die Vorrichtung ferner zum optischen Pumpen der Glasfaser nur bei einer einzelnen Wellenlänge zur Erholung von strahlungsinduzierter Dämpfung konfiguriert ist.

2. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß Anspruch 1, wobei die passiven trivalenten Dotierungsmittel ferner Phosphor beinhalten.

3. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß Anspruch 1 oder Anspruch 2, wobei das aktive trivalente Dotierungsmittel und mindestens ein passives trivalentes Dotierungsmittel eine trivalente Matrix bilden.

4. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß Anspruch 1, Anspruch 2 oder Anspruch 3, wobei das aktive trivalente Dotierungsmittel und die passiven trivalenten Dotierungsmittel innerhalb eines Kerns der Glasfaser liegen.

5. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß einem der Ansprüche 1 bis 4, wobei die optische Übertragungsvorrichtung (10) eines oder mehrere von einem optischen Verstärker, einer verstärkten spontanen Emissionsquelle (ASE, engl. Amplified Spontaneous Emission) und einem Faserlaser beinhaltet und/oder Teil eines Raumfahrzeug- oder Satellitendatenkommunikationssystems bildet.

6. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß einem der Ansprüche 1 bis 5, wobei die optische Übertragungsvorrichtung (10) einen Teil eines Glasfasergyroskops definiert.

7. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß einem der vorhergehenden Ansprüche, wobei das La mit einer Dotierungsdichte von zwischen annähernd 10 000 und annähernd 20 000 ppm; oder zwischen annähernd 20 000 und annähernd 30 000 ppm vorliegt.

8. Optische Raumfahrzeug- oder Satellitenübertragungsvorrichtung (10) gemäß einem der Ansprüche 1 bis 6, wobei das La mit einer Dotierungsdichte von zwischen annähernd 80 000 und annähernd 120 000 ppm vorliegt.

9. Ein Raumfahrzeug oder Satellit, das/der eine optische Übertragungsvorrichtung (10) gemäß einem der Ansprüche 1 bis 8 beinhaltet.

10. Ein Verfahren zum Übertragen von elektromagnetischer Strahlung über eine Glasfaser in einer Hochstrahlungsumgebung, in der die durchschnittliche Strahlungsdosis größer als annähernd 1×10^{-5} Gy/h ist und in der Folgendes verwendet wird:

    eine Glasfaser (11, 12, 13), die ein aktives trivalentes Dotierungsmittel und mindestens zwei passive trivalente Dotierungsmittel beinhaltet, wobei die Glasfaser bei Verwendung Erholung von strahlungsinduzierter Dämpfung aufweist; und
    eine einzelne optische Pumpquelle (14), die operativ gekoppelt ist, um der Glasfaser photoglühende Pumpenergie bereitzustellen; wobei:

        das aktive trivalente Dotierungsmittel Erbium ist, eines der passiven trivalenten Dotierungsmittel La ist und ein weiteres der passiven trivalenten Dotierungsmittel Aluminium ist;
        wobei das Verhältnis von Dotierungsdichte, gemessen in ppm von passiven trivalenten Dotierungsmitteln zu aktiven trivalenten Dotierungsmitteln, 20 : 1 bis 180 : 1 beträgt;
        wobei das Erbium mit einer Dotierungsdichte von zwischen annähernd 100 ppm und
        annähernd 3 000 ppm vorliegt, das La mit einer Dotierungsdichte von zwischen annähernd 10 000 und annähernd 120 000 ppm vorliegt und das Aluminium mit einer Dotierungsdichte von zwischen annähernd 10 000 ppm und 60 000 ppm vorliegt, und

    wobei die optische Pumpe konfiguriert ist, um Pumpenergie mit einer Wellenlänge von zwischen annähernd 970 nm und annähernd 990 nm bereitzustellen; und wobei die optische Pumpquelle ferner konfiguriert ist, um die Glasfaser nur bei einer einzelnen Wellenlänge zur Erholung von strahlungsinduzierter Dämpfung optisch zu pumpen.

11. Verfahren gemäß Anspruch 10, wobei die Hochstrahlungsumgebung eine außerirdische Umgebung ist oder innerhalb oder proximal zu einer Kernreaktoranlage ist oder innerhalb oder proximal zu einer Hochenergiephysikvorrichtung, HEP-Vorrichtung, ist.

12. Verfahren gemäß Anspruch 10 oder Anspruch 11, wobei das trivalente Aluminium mit einer Dotierungsdichte von zwischen annähernd 35 000 und 60 000 ppm vorliegt.

13. Verfahren gemäß Anspruch 10, Anspruch 11 oder Anspruch 12, wobei das La mit einer Dotierungsdichte von zwischen annähernd 10 000 und annähernd 20 000 ppm vorliegt.

14. Verfahren gemäß Anspruch 10, Anspruch 11 oder Anspruch 12, wobei das La mit einer Dotierungsdichte von zwischen annähernd 20 000 und annähernd 30 000 ppm vorliegt.

15. Verfahren gemäß Anspruch 10, Anspruch 11 oder Anspruch 12, wobei das La mit einer Dotierungsdichte von zwischen annähernd 80 000 und annähernd 120 000 ppm vorliegt.

Revendications

1. Un appareil de transmission optique (10) de véhicule spatial ou de satellite comprenant :

   une fibre optique (11, 12, 13) comprenant un dopant trivalent actif et au moins deux dopants trivalents passifs dans lequel, à l'utilisation, la fibre optique présente une récupération d'une atténuation induite par rayonnement ; et
   une source de pompe optique unique (14) couplée de manière fonctionnelle afin de fournir une énergie de pompe de recuit photo à la fibre optique ; dans lequel le dopant trivalent actif est de l'erbium à une densité de dopage comprise entre environ 100 ppm et environ 3 000 ppm, et
   un des dopants trivalents passifs est du La à une densité de dopant comprise entre environ 10 000 et environ 120 000 ppm et un autre des dopants trivalents passifs est de l'aluminium trivalent à une densité de dopage comprise entre environ 10 000 ppm et 60 000 ppm, de préférence entre 35 000 et 60 000 ppm ; dans lequel la pompe optique est configurée pour fournir une énergie de pompe ayant une longueur d'onde comprise entre environ 970 nm et environ 990 nm ; et dans lequel en outre l'appareil est configuré pour pomper optiquement la fibre optique à une longueur d'onde unique seulement en vue d'une récupération d'une atténuation induite par rayonnement.

2. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon la revendication 1, dans lequel les dopants trivalents passifs comprennent en outre du phosphore.

3. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon la revendication 1 ou la revendication 2, dans lequel le dopant trivalent actif et au moins un dopant trivalent passif forment une matrice trivalente.

4. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon la revendication 1, la revendication 2 ou la revendication 3, dans lequel le dopant trivalent actif et les dopants trivalents passifs se trouvent à l'intérieur d'un noyau de la fibre optique.

5. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon l'une quelconque des revendications 1 à 4, dans lequel l'appareil de transmission optique (10) comprend un ou plusieurs éléments parmi un amplificateur optique, une source d'émission spontanée amplifiée (ASE) et un laser à fibre et/ ou fait partie d'un système de communication de données de véhicule spatial ou de satellite.

6. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon l'une quelconque des revendications 1 à 5, dans lequel l'appareil de transmission optique (10) définit une partie d'un gyroscope à fibre optique.

7. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon l'une quelconque des revendications précédentes, dans lequel le La est à une densité de dopant comprise entre environ 10 000 et environ 20 000 ppm ; ou entre environ 20 000 et environ 30 000 ppm.

8. Un appareil de transmission optique (10) de véhicule spatial ou de satellite selon l'une quelconque des revendications 1 à 6, dans lequel le La est à une densité de dopant comprise entre environ 80 000 et environ 120 000 ppm.

9. Un véhicule spatial ou un satellite comprenant un appareil de transmission optique (10) selon l'une quelconque des revendications 1 à 8.

10. Un procédé pour transmettre un rayonnement électromagnétique par l'intermédiaire d'une fibre optique dans un environnement à rayonnement élevé dans lequel la dose de rayonnement moyenne est supérieure à environ 1×10^{-5} Gy/ h et dans lequel sont utilisées :

    une fibre optique (11, 12, 13) comprenant un dopant trivalent actif et au moins deux dopants trivalents passifs dans lequel, à l'utilisation, la fibre optique présente une récupération d'une atténuation induite par rayonnement ; et
    une source de pompe optique unique (14) couplée de manière fonctionnelle afin de fournir une énergie de pompe de recuit photo à la fibre optique ;
    le dopant trivalent actif étant de l'erbium, un des dopants trivalents passifs étant du La et un autre des dopants trivalents passifs étant de l'aluminium ;
    dans lequel le rapport de la densité de dopage mesurée en ppm de dopants trivalents passifs aux dopants

trivalents actifs est de 20:1 à 180:1 ; dans lequel l'erbium est à une densité de dopage comprise entre environ 100 ppm et environ 3 000 ppm, le La est à une densité de dopant comprise entre environ 10 000 et environ 120 000 ppm et
l'aluminium est à une densité de dopage comprise entre environ 10 000 ppm et 60 000 ppm et dans lequel la pompe optique est configurée de façon à fournir une énergie de pompe ayant une longueur d'onde comprise entre environ 970 nm et environ 990 nm ; et dans lequel en outre la source de pompe optique est configurée pour pomper optiquement la fibre optique à une longueur d'onde unique seulement en vue d'une récupération d'une atténuation induite par rayonnement.

11. Un procédé selon la revendication 10, dans lequel l'environnement à rayonnement élevé est un environnement extraterrestre, ou est à l'intérieur ou à proximité d'une installation de réacteur nucléaire, ou est à l'intérieur ou à proximité d'un appareil de physique des hautes énergies, HEP.

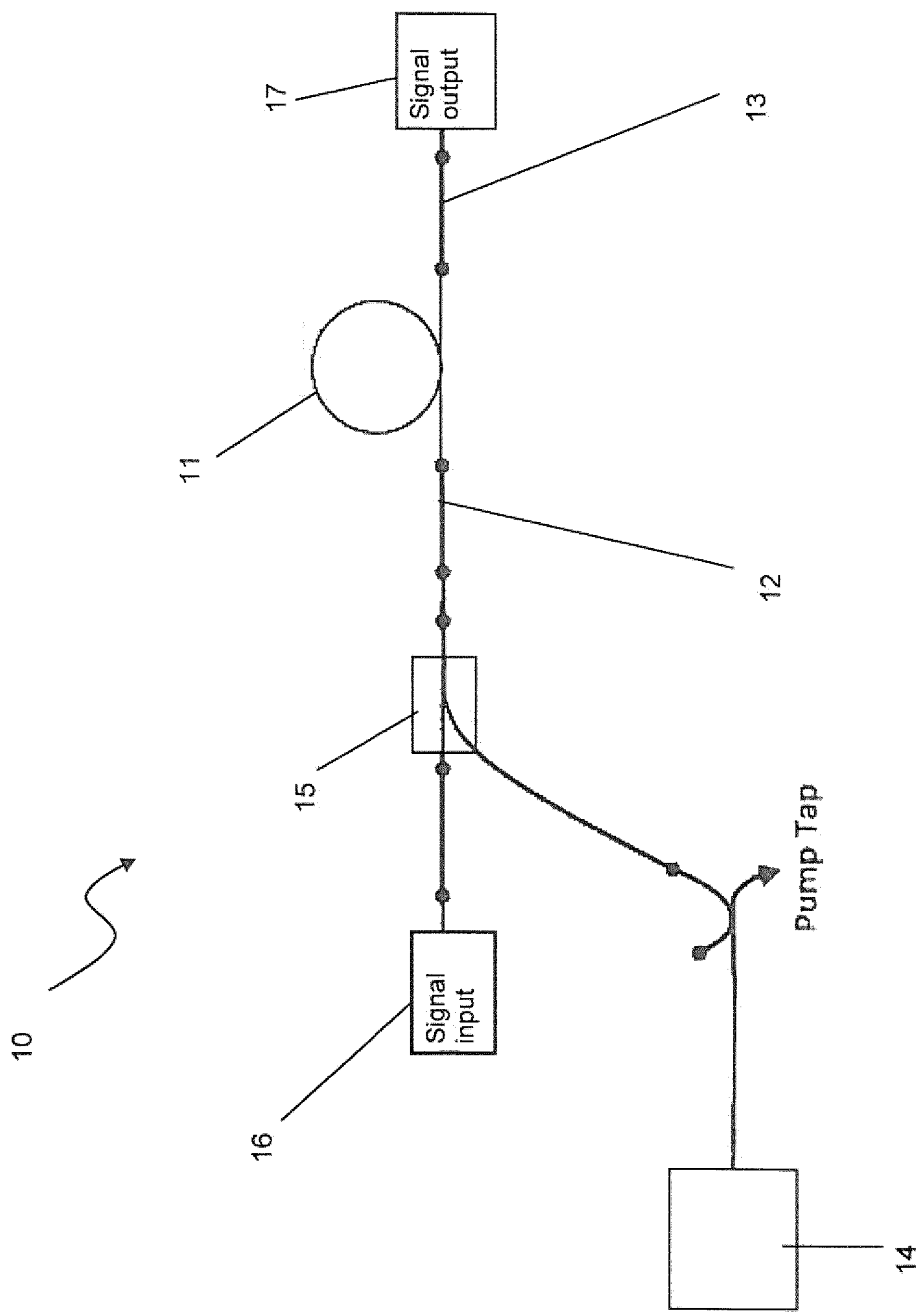
12. Un procédé selon la revendication 10 ou la revendication 11, dans lequel l'aluminium trivalent est à une densité de dopage comprise entre environ 35 000 et 60 000 ppm.

13. Un procédé selon la revendication 10, la revendication 11 ou la revendication 12, dans lequel le La est à une densité de dopant comprise entre environ 10 000 et environ 20 000 ppm.

14. Un procédé selon la revendication 10, la revendication 11 ou la revendication 12, dans lequel le La est à une densité de dopant comprise entre environ 20 000 et environ 30 000 ppm.

15. Un procédé selon la revendication 10, la revendication 11 ou la revendication 12, dans lequel le La est à une densité de dopant comprise entre environ 80 000 et environ 120 000 ppm.

Fig. 1



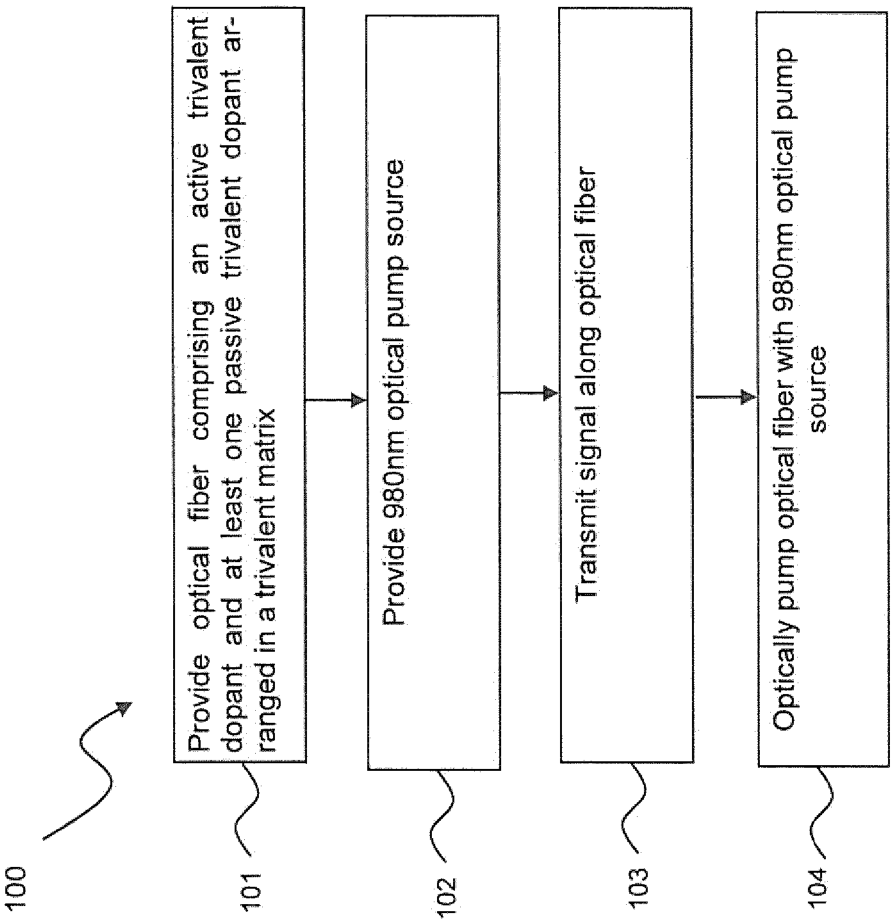

100
Provide optical fiber comprising an active trivalent dopant and at least one passive trivalent dopant arranged in a trivalent matrix
101
Provide 980nm optical pump source
102
Transmit signal along optical fiber
103
Optically pump optical fiber with 980nm optical pump source
104

FIG. 2

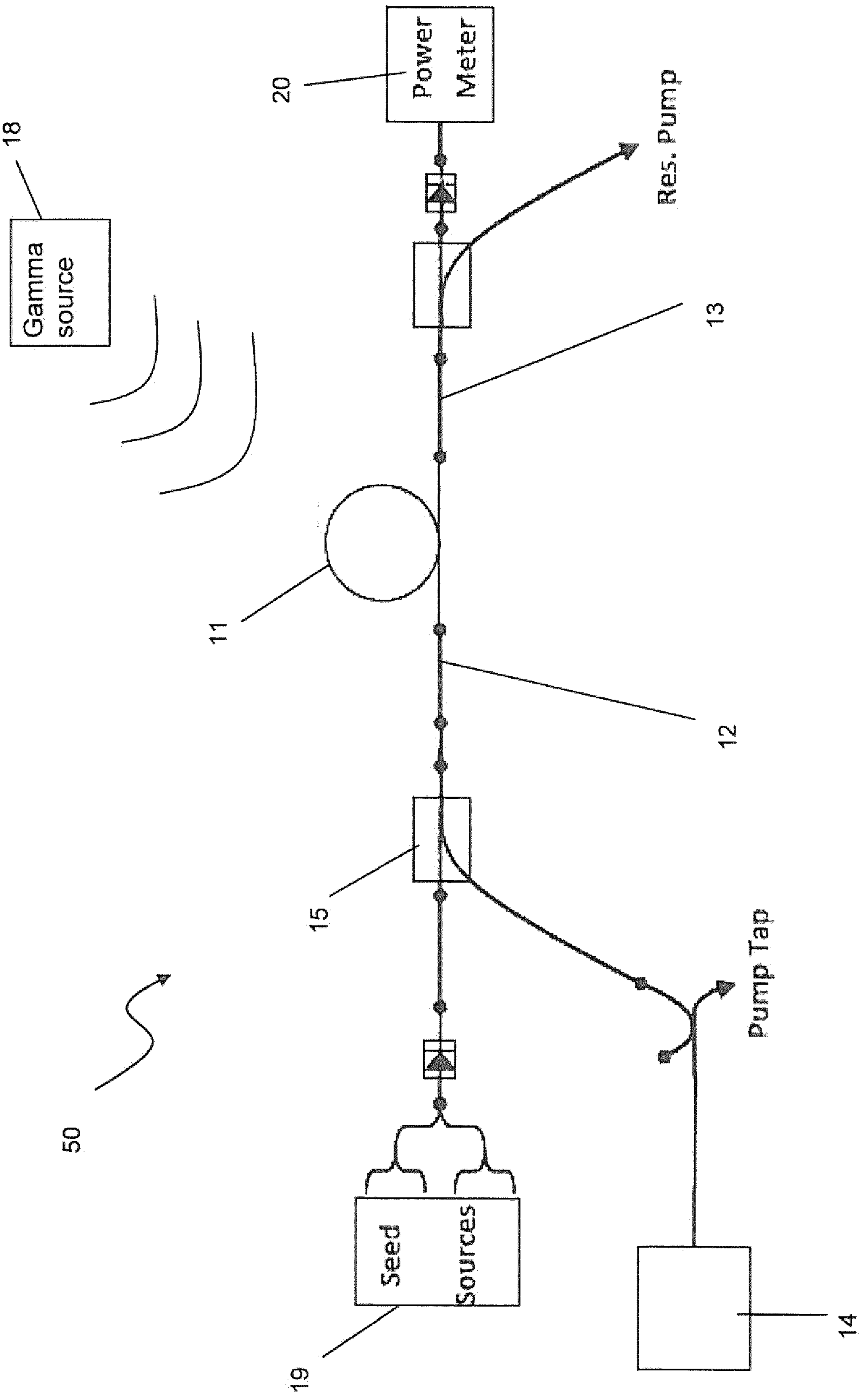

Power Meter
20
18
Gamma source
Res. Pump
13
11
12
15
Pump Tap
50
Seed Sources
19
14

FIG. 3

Percentage of optical activity time with pumping which creates recovery through annealing	Fiber B	Fiber C	Fiber A
0.00%	64.06%	48.68%	18.54%
0.01%	71.34%	62.53%	37.80%
0.10%	75.21%	68.67%	48.28%
1.00%	79.30%	75.41%	61.67%
10.00%	83.60%	82.81%	78.78%
50.00%	86.74%	88.41%	93.48%
100.00%	88.14%	90.94%	100.63%

FIG. 4

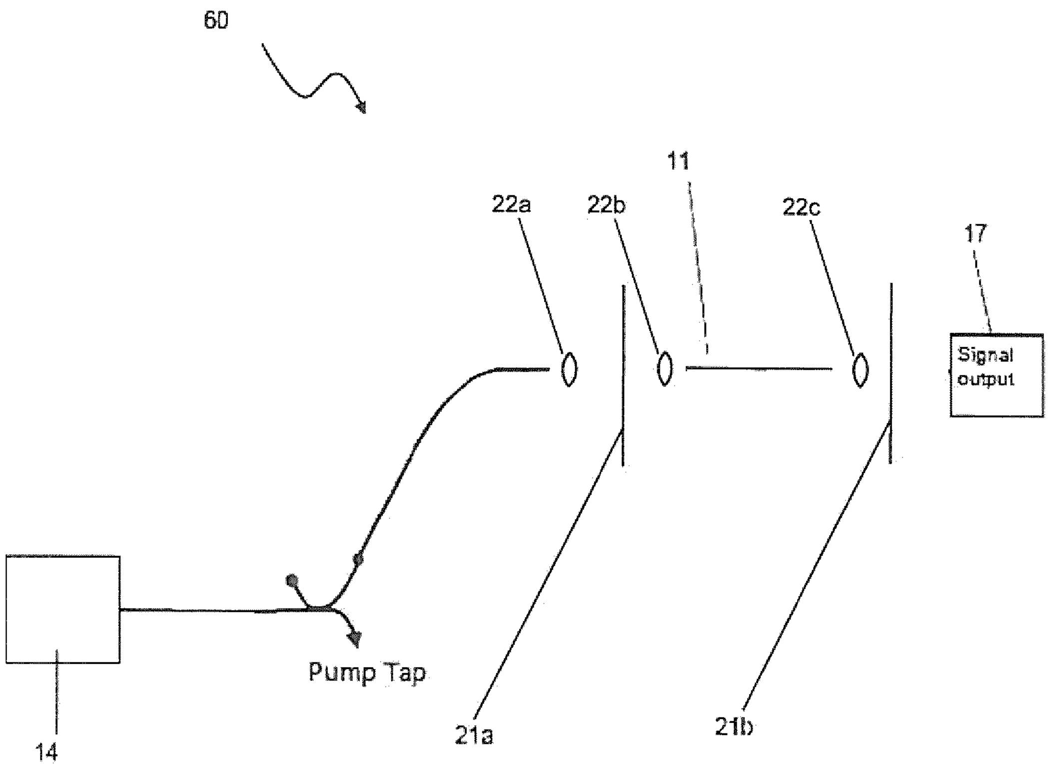


FIG. 5

REFERENCES CITED IN THE DESCRIPTION

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