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(54) Title: RARE-EARTH DOPED MULTI-COMPONENT GLASS OPTICAL FIBER AMPLIFIERS USING SHORT ACTIVE FIBER LENGTH

(57) Abstract: An optical fiber amplifier utilizing a multi-component glass optical fiber highly doped with rare-earth ions such as erbium to exhibit high gain per unit length, enabling the use of short fiber strands to achieve the needed gain in practical fiber optical communication networks. Suitable multi-component glass optical fiber amplifiers, such as for example high-gain phosphate optical glass fiber amplifiers, can be integrated onto a substrate to form an integrated optics amplifier module. An optical pump such as a semiconductor laser of suitable wavelength is used to promote gain inversion of erbium ions and ultimately provide power amplification of a given input signal. Gain inversion is enhanced in erbium doped phosphate glass fibers by co-doping with ytterbium. A phosphate fiber amplifier or an integrated optics amplifier module utilizing this power amplification can be combined with other components such as splitters, combiners, modulators, optical switches or arrayed waveguide gratings to form lossless or amplified components that do not suffer from insertion loss when added to an optical network. The fiber amplifier can be a single fiber or an array of fibers. Further, multi-component glass optical fibers, such as for example the phosphate glass fibers, can be designed with a temperature coefficient of refractive index close to zero enabling proper mode performance as ambient temperatures or induced heating changes the temperature of the phosphate glass fiber. With the high gain that is achieved, single mode fibers can be pumped by relatively inexpensive multi-mode laser diodes. A phosphate glass composition in the phosphate glass fibers includes erbium concentrations of at least 1.5 weight percentage, preferably further including ytterbium from 0 to 30 weight percentage, and preferably greater than 5 weight percentage.

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TITLE OF THE INVENTION

RARE-EARTH DOPED MULTI-COMPONENT GLASS OPTICAL FIBER AMPLIFIERS USING SHORT ACTIVE FIBER LENGTH

Cross Reference to Related Documents

This application claims benefit of priority to U.S. Serial No. 09/589,764, entitled "ERBIUM AND YTTERBIUM CO-DOPED PHOSPHATE GLASS OPTICAL FIBER AMPLIFIERS USING SHORT ACTIVE FIBER LENGTH" filed in the United States Patent and Trademark Office on 06/09/00, the entire disclosure of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

The invention is related to rare-earth doped glasses and more particularly to rare-earth doped multi-component glass in optical fibers which are optically pumped and may be used as optical amplifiers.

BACKGROUND OF THE INVENTION

Deregulation, long distance price declines, bandwidth stockpiling, and internet usage are driving bandwidth demand in telecom and datacom networks. Data traffic is now growing at 100 per cent or more per annum, straining global fiber capacity. Dense Wavelength Division Multiplexing (DWDM), where multiple wavelength channels propagate within a single fiber multiplies fiber capacity by 2-128 times or more, is an approach for extending carrier capacity without the need of deploying new fiber. Systems being deployed today generally can transmit from 8 up to 128 channels in the 1550 nm low-dispersion window. Channel spacing ranges from 1.6 nm (200GHz) to 0.4 nm (50 GHz).

Optical amplifiers are considered enabling components for bandwidth expansion in DWDM fiber optic communications systems. In particular, silica glass Erbium Doped Fiber Amplifiers (EDFA) exhibit many desirable attributes including high gain, low noise,

negligible crosstalk and intermodulation distortion, bit-rate transparency, and polarization insensitive gain. These properties make optical fiber amplifiers superior to semiconductor devices as amplifiers in fiber optic systems. Moreover, fiber-based amplifiers do not require conversion from electrical energy to photon energy as do semiconductor devices. In a communications system of any significant size, there is typically a distribution network that includes long communication paths and nodes where the network branches. In such a network, amplifiers are required in order to maintain the amplitude of the signal and the integrity of any data in route between a source and destination. For these amplifiers to function properly, the amplifiers must exhibit high small signal gains and/or high output saturation powers.

Application of erbium-doped optical fibers as amplifiers has received considerable attention recently because the characteristic gain bandwidth of these fibers is within the telecommunications window of 1.5 μm commonly used in fiber optic communications systems. Since the announcement of a single mode Er^{3+} doped fiber amplifier (EDFA) in 1987 at the University of Southampton, enormous research has been performed, and more than 400 U.S. patents have been issued in fiber amplifiers. To date, all erbium fiber amplifiers use erbium doped silica fibers more than one meter long to achieve greater than 20 dB gain near the 1.54 μm range. More commonly, the length of the erbium doped silica fiber is approximately 10 to 20 meters. Such lengths are not practical for assembly into integrated optical components. There is a compelling need for amplifiers that can introduce high gain into an integrated, compact package.

To shorten length in fiber amplifiers, high gain must be achieved. In order to enable fiber amplifiers of only a few centimeters in length, magnitudes of doping two orders higher than what is commercially achievable ($\sim 10^{18}$ cm^{-3}) in silica fiber amplifiers is required. However, in silica fiber, cooperative upconversion and ion clustering effects develop from the interactions between nearby ions in silica glass, and electrons depopulate from the erbium metastable level ($^4I_{13/2}$). Thus, increased doping in silica glass does not improve gain.

Other glasses such as for example phosphate glasses exhibit high solubility and large emission cross sections for many rare-earth ions. Phosphate glasses for optical components have been investigated. Y. L. Lu, Y. et al., in "Fluorescence and attenuation properties of Er^{+3} -doped phosphate glass fibers and efficient infrared-to-visible up-

conversion," *Applied Physics B,* Vol. 62, pp.287-291 (1996) and Ya Lin Lu et al., in "Properties of Er^{+3} doped phosphate glasses and glass fibers and efficient infrared to visible upconversion," *Journal of Materials Science,* Vol. 30, No. 22, 15 Nov. 1995, pp.5705-10, (1995) discuss phosphate glass fiber for use in up-conversion schemes. S. Jiang et al., in "Er^{+3} doped phosphate glasses and lasers," *Journal of Non Crystalline Solids,* Vol.239, No.1-3, Oct. 1998, pp. 143-8, show phosphate glasses for application as bulk lasers. T. Nishi et al., in "The amplification properties of a highly Er^{+3} doped phosphate fiber," *Jpn. J Appl. Phys.,* Vol. 31 (1992), Pt. 2, 2B, pp. L177-L179, show phosphate fiber with moderate erbium oxide doping. The maximum gain per unit length reported by Nishi et al. was only 1 dB/cm. S. Jiang, T. Luo et al. in "New Er 3+ doped phosphate glass for ion-exchanged waveguide amplifiers," *Optical Engineering,* Vol. 37, No. 12, Dec. 1998, pp. 3282-6, disclose phosphate glasses for application in ion-exchanged waveguide amplifiers.

In addition, a number of patents have addressed doped glasses in various optical applications. For example, Hsu et al. (U.S. Patent No. 5,425,039), Myers (U.S. Patent No. 4,962,067), Myers et al. (U.S. Patent No. 4,333,848), Myers et al. (U.S. Patent No. 4,248,732), Myers et al. (U.S. Patent No. 4,075,120), each disclose doped fibers for application as fiber lasers. In addition, Myers et al. (U.S. Patent No. 5,322,820) and Myers (U.S. Patent No. 5,164,343) disclose various glass compositions for laser applications. Grubb et al. (U.S. Patent No. 5,225,925) disclose silica fibers or phosphorous doped silica fiber. Andrews et al. (U.S. Patent No. 4,962,995) disclose glasses that are optimized for pumping by 800 nm laser light.

Recently, Y. C. Yan et al., in "Net optical gain at 1.53 μm in an Er-doped phosphate glass waveguide on silicon," *Optical Amplifiers and Their Applications, Topical Meeting. OSA Trends in Optics and Photonics Series,* Vol. 16. Opt. Soc. America, Washington, DC, USA; 1997; xlv+526, pp.93-5, investigated doped phosphate glasses as a high gain medium for planar waveguide amplifiers at wavelength of 1.5 μm. Y. C. Yan et al., in "Erbium-doped phosphate glass waveguide on silicon with 4.1 dB/cm gain at 1.535 um," *Applied Physics Letters,* Vol.71, No.20, 17 Nov. 1997, pp. 2922-4 reported a gain of 4.1 dB in a 1 cm long phosphate glass waveguide prepared by an R-F sputtering technique. D. Barbier et al., in "Net gain of 27 dB with a 8.6-cm-long Er/Yb-doped glass-planar-amplifier, " *OFC '98 Optical Fiber Communication Conference and Exhibit, Technical Digest,* Conference Edition

1998 OSA Technical Digest Series Vol.2 (IEEE Cat. No.98CH36177), Opt. Soc. America, Washington, DC, USA; 1998; vii+421, pp.45-6, demonstrated a net gain of 27 dB in a 8.6 cm long ion-exchanged Er/Yb-doped phosphate glass waveguide.

Despite the high gains achieved for example in phosphate glass waveguides, planar waveguide amplifiers have significant disadvantages when compared with fiber amplifiers including polarization sensitivity, optical mode mismatch between waveguides and fiber networks, large propagation losses, and complicated fabrication processes.

SUMMARY OF THE INVENTION

One object of the invention is to provide a multi-component glass optical fiber amplifier that is heavily doped with rare-earth dopants such as erbium or co-doped with, for example, erbium and ytterbium to provide high gain per unit length.

One object of the invention is to provide a multi-component glass optical fiber amplifier with a gain per unit length, greater than 1.0 dB/cm and preferable over 3 dB/cm over a bandwidth.

Another object of the invention is to provide a high gain per unit length doped phosphate glass fiber which can be utilized as a fiber amplifier in an optical communications system.

Another object of the invention is to provide an erbium and ytterbium codoped phosphate glass fiber with high (concentrations well above concentrations deemed practical by current wisdom) erbium and ytterbium co-doping concentrations for high gain amplification within a short length of the optical fiber. A phosphate glass composition provides the solubility to erbium and ytterbium ions necessary to support the elevated doping concentrations without raising the cooperative upconversion rate. A short-length optical fiber amplifier utilizing the high gain, short-length fiber is compatible with V-groove and micro-machining fabrication processes, making the short-length fibers compatible and integratable into optical component modules.

Still a further object of the invention is to provide a phosphate glass fiber with a core containing erbium (as Er_2O_3) and ytterbium (as Yb_2O_3) and a phosphate glass clad without

erbium or ytterbium, wherein the phosphate glass fiber is manufactured using a rod-in-tube technique.

Another object of the invention is the application of the multi-component fiber in an optical amplifier, preferably in an integrated amplified or lossless splitter module, wherein a system signal is amplified (with the assistance of a pump laser diode) and fed to a splitter. The fiber may be only a few centimeters in length but exhibits a minimum gain coefficient greater than about 1.0 dB/cm and preferably as much as about 6 dB/cm over a desired band such as the C-band, from about 1530 to 1565 nanometers; the gain may be, for example, 3 dB/cm at 1.54 microns.

Yet, another object of the invention is the application of the multi-component fiber in an optical amplifier, preferably in an integrated amplified or lossless combiner module, wherein a system signal is amplified (with the assistance of a pump laser diode) and fed to a combiner. The fiber may be only a few centimeters in length but exhibits a minimum gain coefficient greater than about 1.0 dB/cm and preferably as much as about 6 dB/cm over a desired band such as the C-band, from about 1530 to 1565 nanometers; the peak gain may be, for example, 3 dB/cm at 1.54 microns.

A further object of the invention is the application of the multi-component fiber in an optical amplifier, preferably in an integrated amplified or lossless arrayed waveguide grating module, wherein the system signal channels are amplified (with the assistance of a pump laser diode) and fed to an arrayed waveguide grating. The fiber may be only a few centimeters in length but exhibits a minimum gain coefficient greater than about 1.0 dB/cm and preferably as much as about 6 dB/cm over a desired band such as the C-band, from about 1530 to 1565 nanometers; the peak gain may be, for example, 3 dB/cm at 1.54 microns.

Still a further object of the invention is the application of the multi-component fiber in an optical amplifier, preferably in an integrated amplified or lossless modulator module, wherein the system signals are amplified (with the assistance of a pump laser diode) and fed to a Lithium Niobate optical modulator. The fiber may be only a few centimeters in length but exhibits a minimum gain coefficient greater than about 1.0 dB/cm and preferably as much as about 6 dB/cm over a desired band such as the C-band, from about 1530 to 1565 nanometers; the peak gain may be, for example, 3 dB/cm at 1.54 microns.

Yet another object of the invention is the application of the multi-component fiber in an optical amplifier, preferably in an integrated amplified or lossless optical switch, wherein the system signals are amplified (with the assistance of a pump laser diode) and fed to the optical switch. The fiber may be only a few centimeters in length but exhibits a minimum gain coefficient greater than about 1.0 dB/cm and preferably as much as about 6 dB/cm over a desired band such as the C-band, from about 1530 to 1565 nanometers; the peak gain may be, for example, 3 dB/cm at 1.54 microns.

Still another object of the invention to provide an efficient, long-lived erbium and ytterbium glass optical amplifier that is generally suitable for a variety of components in metro and local network applications, specifically in the area of fiber optic communication networks.

As such, one object of the invention is to provide doped multi-component glasses, and in a preferred embodiment doped phosphate glasses, with a temperature coefficient of refractive index close to zero.

Another object is to provide an array of doped phosphate glass fibers mounted in a groove on a substrate such as for example a V-groove, where the array is pumped by a multi-mode laser diode bar orthogonal to the array.

Another object of the invention is to provide an erbium doped fiber with a large light-guiding region (diameter of the core ranging from 50 to 300 μm, which is much larger than in erbium doped fibers deemed practical by current wisdom). The fiber may be only a few centimeters in length and is pumped with one or more high-power multi-mode 980 nm light-emitting laser diodes, each having an emitting cross-sectional area on the order of 1 μm x 100 μm.

These and other objects are achieved according to a fiber amplifier of the present invention utilizing a phosphate glass optical fiber highly doped with rare-earth ions such as erbium, and preferably co-doped with ytterbium to enhance gain. The phosphate glass optical fibers exhibit high gain per unit length, enabling the use of short fiber strands to achieve the needed gain in practical fiber optical communication networks.

According to one aspect of the present invention, the high-gain phosphate optical glass fiber amplifiers are integrated onto substrates, such as in grooved substrates, to form an integrated optics amplifier module. An optical pump such as a semiconductor laser of

suitable wavelength is used to promote gain inversion of erbium ionic metastable states and ultimately provide power amplification of a given input signal.

According to another aspect of the present invention, a multi-component fiber amplifier is integrated with other components such as splitters, combiners, modulators, optical switches, or arrayed waveguide gratings to form lossless or amplified components that do not suffer from insertion loss when added to an optical network.

According to a further aspect of the present invention, the fiber amplifier includes a single fiber or an array of fibers. Further, the multi-component glass fibers including the phosphate glass optical fibers are designed with a temperature coefficient of refractive index close to zero enabling proper mode performance as ambient temperatures or induced heating changes the temperature of the multi-component glass fiber. Fiber core diameters from standard sizes such as for example 5 μm to large core sizes such as for example 50 -100 μm fibers are used for fiber amplifiers in the present invention.

According to one aspect of the present invention, it is recognized that erbium doped glass fibers, containing erbium concentrations far beyond the generally accepted optimum concentration for erbium ions in silica fiber, show fiber amplification in a short length and thus enable production of integrated high gain optical components.

According to a further aspect of the present invention, the erbium doped glass fibers are co-doped with ytterbium to enhance pumping of the erbium metastable levels and the resultant gain in the phosphate fibers.

Further, according to the present invention, there is provided an optical device comprising an optical pump and an optical fiber amplifier which includes at least one multi-component glass fiber, and in a preferred embodiment at least one phosphate glass fiber, co-doped with erbium and ytterbium. This pump is arranged with respect to the phosphate glass fiber to direct light into the co-doped glass fiber to create a population inversion and to produce, upon introduction of an optical signal into the glass fiber, stimulated emission and amplification of the optical signal. The phosphate glass fiber preferably has a length between about 5 millimeters to about 100 millimeters. A phosphate glass of the phosphate glass fiber may include by weight percentages Er_2O_3 of at least 1.5% and Yb_2O_3 up to 30 percent. Preferably, the optical pump comprises a multi-mode laser, and the phosphate glass includes by weight Yb_2O_3 from 5 to 30 percent. The optical fiber may comprise a single-mode fiber

that is pumped by the multi-mode laser. In one embodiment, the phosphate glass includes by weight percentages P_2O_5 from 30 to 80 percent, L_2O_3 from 5 to 30 percent, MO from 5 to 30 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. The active optical fiber preferably has a temperature coefficient of refractive index ranging from about -2.0 x 10^{-6} to 2.0 x 10^{-6}. Accordingly, the MO may be a mixture of BaO, which exhibits a negative temperature coefficient, and ZnO, which exhibits a positive temperature coefficient. Preferably, the concentration of erbium and ytterbium dopants is sufficient to impart the optical fiber with a gain per unit length of at least 1.0 dB/cm to about 6 dB/cm for an optical signal traveling therethrough. For example, the active optical fiber may exhibit gain per unit length of at least 1.0 dB/cm over a range of 1530 nm to 1565 nm.

In another aspect of the invention, a phosphate glass comprises the following ingredients by weight percentages, P_2O_5, from 30 to 80 percent, Yb_2O_3, up to 30 percent, Er_2O_3, from 1.5 to 12 percent, L_2O_3, from 5 to 30 percent, and MO, from 5 to 30 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. Preferably, Yb_2O_3 comprises 5% or greater by weight percentage, also, the phosphate glass preferably comprises 3.5 weight % erbium.

In yet another aspect of the invention, an optical fiber amplifier comprises a glass fiber comprising a phosphate glass and an optical pump that outputs pump radiation. The phosphate glass includes by weight percentages, P_2O_5 from 30 to 80 percent, Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, MO from 5 to 30 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. The optical pump is configured to direct the pump radiation into the fiber and thereby populate excited energy states therein. The introduction of an input optical signal into the glass fiber produces stimulated emission and amplification of the input signal.

In another aspect of the invention, a phosphate glass comprises the following ingredients by weight percentages, P_2O_5, from 45 to 70 percent, Yb_2O_3, 5 to 30 percent, Er_2O_3, from 2 to 5 percent, L_2O_3, from 5 to 15 percent, and MO, from 15 to 28 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the present invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

Figure 1 is a schematic energy level diagram of the Yb^{+3} /Eb^{+3} co-doped system;

Figure 2 is a graph depicting energy transfer efficiency from Yb^{3+} ionic energy levels to Er^{3+} ionic energy levels under different pumping powers for different doping concentrations of Yb_2O_3 and Er_2O_3;

Figure 3 is a graph depicting the influence of glass composition with different alkali earth ions on refractive index and on the effective emission linewidth;

Figure 4 is a graph depicting the influence of glass composition with different BaO and Al_2O_3 concentrations on refractive and effective emission linewidth;

Figure 5 is a graph showing the absorption and emission cross sections for the $^4I_{15/2}$ < > $^4I_{13/2}$ transition band;

Figure 6 is a flowchart showing the method steps for producing doped single mode phosphate glass fibers;

Figure 7 is a diagram showing schematically the stages of the fabrication process for producing the single mode doped phosphate glass fibers;

Figure 8 is a schematic diagram showing the experimental setup used to determine gain characterization of a co-doped phosphate glass fiber;

Figure 9 is a graph showing the net gain and noise figure for an erbium doped phosphate glass fiber as a function of pump power;

Figure 10 is a graph showing the net gain and noise figure for an erbium doped phosphate glass fiber as a function of signal wavelength;

Figure 11 is a graph showing the gain saturation at 1535 nm and 1550 nm for an erbium doped phosphate glass fiber;

Figure 12 is a schematic of an amplifying splitter according to the present invention;

Figure 13 is a schematic of a fiber amplifier pumped with a multi-mode laser;

Figure 14 is a schematic of a fiber array amplifier according to the present invention;

Figure 15a is a schematic of one embodiment of the fiber array amplifier;

Figure 15b is a schematic of another embodiment of the fiber array amplifier;

Figure 15c is a schematic of another embodiment of the fiber array amplifier;

Figure 16 is a schematic of an amplifying combiner according to the present invention;

Figure 17 is a schematic of an amplifying arrayed waveguide grating according to the present invention;

Figure 18 is a schematic of an amplifying modulator according to the present invention;

Figure 19 is a schematic illustration of a large core fiber amplifier.

DETAILED DESCRIPTION OF THE INVENTION

The invention can provide fiber amplifiers with multi-component glass fibers that are highly doped with rare-earth dopants such as erbium and preferably co-doped with erbium and ytterbium. Multi-component glasses can provide more sites for hosting rare-earth dopants thereby producing more gain per unit length of fiber without clustering problems.

Multi-component glasses contain one or more glass network formers (P_2O_5 phosphate, SiO_2 silicate, GeO_2 germanate, TeO_2 tellurite, B_2O_3 borate), one or more glass network modifiers (alkaline metal oxides such as K_2O, Na_2O, Li_2O, Rb_2O; and alkaline-earth oxides such as BaO, CaO, MgO, Sro, ZnO, PbO and mixtures thereof) and one or more glass network intermediators (Y_2O_3, La_2O_3, Al_2O_3, B_2O_3 and mixtures thereof). The modifier modifies the glass network, thereby reducing its melting temperature and creating additional dopant sites. The intermediator bridges some of the bonds in the network thereby increasing the network's strength and chemical durability without raising the melting temperature

appreciably. The multi-component glasses of interest thus have a much lower softening temperature than silica (SiO_2), which greatly simplifies processing. The modified network provides many more sites for hosting high concentrations of rare-earth dopants without clustering problems. The modifier can be at least 5% and typically 15% by weight and the intermediator can be at least 2% and typically 10% by weight of the multi-component glass. The fiber core is then doped with high concentrations of rare-earth dopants such as erbium or co-doped with, for example, erbium and ytterbium. The cladding layer(s) are typically suitably undoped.

As was mentioned above, one species of multi-component glass uses a phosphate glass network former, which is now described in detail and without loss of generality.

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, Figure 1 is a schematic energy level diagram of a Yb^{3+} and Er^{3+} ionic energy levels in a phosphate glass host.

According to one embodiment of the present invention, pumping of an erbium-doped phosphate glass populates the erbium metastable state creating a population inversion which under an input signal produces stimulated emission and amplification of the input signal. More specifically, the amplification process is explained in reference to energy levels shown in Figure 1. The Er^{3+} ionic energy states are shown on the right hand side of Figure 1. Typically, a pump light excites electrons from the ground state $^4I_{15/2}$ to an upper energy state such as $^4I_{11/2}$. Higher erbium doping levels allows more absorption of the pump light and ultimately higher gain. Once electrons are excited to the $^4I_{11/2}$ state, relaxation occurs through phonon processes in which the electrons relax to the $^4I_{13/2}$ state, giving up energy as phonons to the glass host material. The state $^4I_{13/2}$ is a metastable state which normally does not readily emit a photon and decay to the ground state (i.e., the $^4I_{15/2}$ state). In the fiber amplifiers of the present invention, stimulated emission occurs when an input signal at 1.5 μm is introduced into the optical fiber. The stimulated emission amplifies the input 1.5 μm signal.

According to another embodiment of the present invention, co-doping with ytterbium enhances population inversion and stimulated emission from the erbium $^4I_{13/2}$ metastable state. More specifically, the enhancement process is explained in reference to energy levels shown in Figure 1. As shown in Figure 1, the Yb^{3+} excited state $^2F_{5/2}$ are pumped from the Yb^{3+} $^2F_{7/2}$ ground state with the same pump wavelength that is used to excite upward

transitions from the erbium ground state $^4I_{15/2}$. Energy levels of the excited ytterbium $^2F_{5/2}$ state coincide with energy levels of the erbium $^4I_{11/2}$ state permitting energy transfer (i.e. electron transfer) from the pumped ytterbium $^2F_{5/2}$ state to the erbium $^4I_{11/2}$ state. Thus, pumping ytterbium ionic energy states provides a mechanism for populating the metastable erbium $^4I_{13/2}$ state, permitting even higher levels of population inversion and more stimulated emission than with erbium doping alone.

Ytterbium ions exhibit not only a large absorption cross section but also a broad absorption band between 900 and 1100 nm. Furthermore, the large spectral overlap between Yb^{3+} emission ($^2F_{7/2}$ -$^2F_{5/2}$) and Er^{3+} absorption ($^4I_{15/2}$- $^4I_{13/2}$) results in an efficient resonant energy transfer from the Yb $^{3+}$ $^2F_{5/2}$ state to the Er $^{3+}$ $^4I_{13/2}$ state. The energy transfer mechanism in a Yb^{3+}/Er^{3+} co-doped system is similar to that for cooperative upconversion processes in an Er^{3+} doped system. However, interactions are between Yb^{3+} (donor) and Er^{3+} (acceptor) ions instead of between two excited Er^{3+} ions.

Thus, the present invention utilizes either erbium doped or erbium/ytterbium co-doped phosphate glass fibers doped at concentrations orders of magnitude higher than what is available in silica fibers. The increased doping levels in the phosphate glass fibers do not suffer from a high cooperative upconversion rate. Thus, cooperative upconversion effects in phosphate glass at high levels of erbium doping concentration, while significantly smaller than in silica glass, can be further reduced in phosphate glasses by the introduction of ytterbium doping. Further, it can be seen from Figure 2, a graph depicting energy transfer efficiency from Yb^{3+} ions to Er^{3+} ions, that the energy transfer efficiency is greater than 91% for the co-doping concentrations shown. Figure 2 shows that 6 weight % Yb_2O_3 and 2 weight % Er_2O_3 produce measured lifetimes for the ytterbium $^2F_{5/2}$ state of about 180 μs with a transfer efficiency to the erbium $^4I_{13/2}$ state of 92%. Compared to silicate glasses, the large phonon energy in the phosphate host increases the transition probability for $^4I_{11/2}$ - $^4I_{13/2}$ relaxation which prevents the back energy transfer from Er^{3+} to Yb^{3+}.

In one embodiment of the present invention, optical fibers utilize a doped phosphate glass fiber containing the following ingredients by weight percentages: P_2O_5 from 30 to 80 percent, Yb_2O_3 from 0 to 12 percent, Er_2O_3 from 2.5 to 12 percent, L_2O_3 from 5 to 30 percent, MO from 5 to 30 percent, , where the sum of the weight percentages of Yb_2O_3 and Er_2O_3 is 2.5 % or greater, MO is selected from the alkaline earth oxide group consisting of BaO, BeO,

MgO, SrO, CaO, ZnO, PbO and mixtures thereof, and L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof. As a result, an active fiber length for 20 dB gain is expected to be less than 7 cm.

In another embodiment of the invention, glass for phosphate glass optical fiber amplifiers comprises the following ingredients by weight percentages: P_2O_5 from 30 to 80 percent, Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, and MO from 5 to 30 percent, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. The phosphate glass composition improves the solubility to erbium ions thereby allowing higher erbium dopant levels than previously deemed practical without raising the upconversion rate. To achieve even higher gains per unit length, this embodiment may further comprise up to 30 percent by weight of Yb_2O_3. Preferably, the sum of weight percentages of Yb_2O_3 and Er_2O_3 is at least 2.5 percent. The glass composition described above also provides a high solubility to ytterbium ions, which facilitates elevated Yb doping levels. The elevated ytterbium levels in particular greatly enhance the fiber's ability to absorb pump power while the elevated erbium levels enhance the gain per unit length of the fiber. Together these attributes provide greater than 1.0 dB per cm gain over a desired bandwidth, e.g. the telecomm C-band from 1530-1565 nm, with a very short fiber (5 to 100 mm), a less expensive scheme of using a low power multi-mode pump to pump a single-mode fiber. To absorb sufficient power with the single-mode fiber, the Yb levels is preferably greater than 5% by weight. In known fiber lasers, a multi-mode fiber with its larger core is required to absorb sufficient pump energy. This embodiment may further comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof. This R_2O component, however, is not required. For example, if the temperature coefficient of refractive index is close to zero for the fiber the concentration of R_2O does not have to be elevated and can be very low, less than 5 percent by weight. The temperature coefficient of refractive index is set close to zero by balancing the mixture of MO. For example, BaO and ZnO have negative and positive temperature coefficients of refractive index such that the proper mixture provides a temperature coefficient of about zero.

In another embodiment, a phosphate glass comprises the following ingredients by weight percentages, P_2O_5, from 45 to 70 percent, Er_2O_3, from 2 to 5 percent, L_2O_3, from 5 to 15 percent, and MO, from 15 to 28 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. This embodiment may further comprise 5 to 30 percent by weight of Yb_2O_3. In addition, this embodiment may comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; alternatively, R_2O may be excluded.

In another embodiment of the invention, glass for phosphate glass optical fiber amplifiers comprises the following ingredients by weight percentages: P_2O_5 from 30 to 80 percent, Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, and MO from 10 to 28 percent, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. This embodiment may further comprise up to 12 percent by weight of Yb_2O_3. In addition, this embodiment may comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; alternatively, R_2O may be excluded.

In another embodiment of the invention, glass for phosphate glass optical fiber amplifiers comprises the following ingredients by weight percentages: P_2O_5 from 30 to 80 percent, Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, and MO from 20 to 26 percent, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. This embodiment may further comprise up to 30 percent by weight of Yb_2O_3. In addition, this embodiment may further comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; however the R_2O may be excluded.

In another embodiment of the invention, glass for phosphate glass optical fiber amplifiers comprises the following ingredients by weight percentages: P_2O_5 from 30 to 80

percent, Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, and MO of about 26 percent, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. This embodiment may further comprise up to 30 percent by weight of Yb_2O_3. In addition, this embodiment may further comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; however, the R_2O component may be excluded.

A phosphate glass composition according to an embodiment of the invention comprises the following ingredients by weight percentages: Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, from 10 to 26 percent of BaO, and from 0.5 to 10 percent ZnO, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof. This embodiment may further comprise up to 30 percent by weight of Yb_2O_3. In addition, this embodiment may further comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; however R_2O can be excluded.

A phosphate glass composition according to another embodiment of the invention comprises the following ingredients by weight percentages: Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, from 20 to 25 percent of BaO, and from 1 to 4 percent ZnO, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof. This embodiment may further comprise up to 30 percent by weight of Yb_2O_3. In addition, this embodiment may further comprise R_2O, where R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; however R_2O can be excluded.

A phosphate glass composition according to yet another embodiment of the invention comprises the following ingredients by weight percentages: Er_2O_3 from 1.5 to 12 percent, L_2O_3 from 5 to 30 percent, about 24 percent of BaO, and about 2 percent ZnO, where L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3 and mixtures thereof. This embodiment may further comprise up to 30 percent by weight of Yb_2O_3. In addition, this embodiment may further comprise where R_2O is selected from the

alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; however R_2O can be excluded.

The high doping concentrations possible, the low cooperative upconversion rate, the high transfer efficiencies, and the high gains make doped phosphate glass fibers ideal for high gain optical fiber amplifiers.

Besides these properties, doped phosphate glasses in one embodiment of the present invention can be comprised of components which yield a temperature coefficient of refractive index close to zero or negative. Athermal performance can be achieved when the temperature coefficient of refractive index is negative. An optical path length for a glass is a product of a length of the glass and the refractive index. Achieving athermal performance results in a temperature coefficient for the optical path length close to zero, which can be described by the following equation:

$$G = \alpha (n-1) + dn/dt \qquad (2)$$

where, G is the temperature coefficient of optical path length, α is the linear coefficient of thermal expansion, dn/dt is the temperature coefficient of refractive index. Since α is always positive, dn/dt has to be negative in order to make G equal to zero.

In active laser glass elements, heating occurs from the pump source. In order to dissipate the heat, laser glass elements are typically gas or liquid cooled to maintain the laser glass elements within a specified operating temperature range. Cooling of the active laser glass elements creates a thermal gradient. The temperature near the center is higher than the temperature close to the cooling. When dn/dt is positive, the optical path length near the center becomes longer, causing a distortion of laser beam. For a typical silicate glass, the refractive index increases with temperature because polarizability of electron clouds in the silicate glasses increases with increased spacing (i.e. expansion of the material upon heating).

In optical fiber amplifiers, the mode profile of the optical fiber changes with the index of the core glass and the cladding glass. However, maintaining a temperature coefficient of the optical path length is not as critical as in a laser glass since the beam in the fiber amplifier is confined by the cladding layer. Nonetheless, a fiber amplifier for telecommunication application has to pass a standard Bellcore test, where the temperature changes from -40°C to

80°C. The multi-component phosphate glasses must achieve a temperature coefficient of refractive index close to zero by adjusting components in the glass composition. Achieving a temperature coefficient of refractive index close to zero eliminates the influence of changing temperatures from heat generated by unused pumping power and changing environmental temperatures on the mode profile of the fiber. By adjusting BaO and ZnO content in the phosphate glass structure, an approximately zero temperature coefficient of refractive index can be achieved since BaO and ZnO exhibit negative and positive temperature coefficient of refractive index, respectively. Preferably, therefore, BaO and ZnO are included in concentrations up to about 26%. Glass network intermediates such as B_2O_3 and Al_2O_3 are used to fortify the phosphate glass structure. The combination of an aluminum-oxygen tetrahedron or a boron-oxygen tetrahedron with a neighboring phosphorus-oxygen tetrahedron increases the number of bridging oxygen, resulting in a stronger glass structure. In one embodiment of the present invention, Al_2O_3 in concentrations from 6 to 11 mole % is used to fortify the glass structure.

Tables 1, 2, and 3 (see below) list glass compositions in mole % of phosphate glasses designed and fabricated, the temperature coefficients of refractive index for aluminum phosphate, barium phosphate and zinc phosphate, and the predicted temperature coefficient of refractive index for the fabricated glasses.

Table 1. Glass compositions designed and fabricated

Glass	P2O5	Al2O3	Er_2O_3+Yb_2O_3+La_2O_3	BaO	ZnO
PZI	63	8.5	3.0	25.5	0
PZ2	63	8.5	3.0	25.5CaO*	0
PZ3	63	8.5	3.0	25.5MgO*	0
PZ4	63	8.5	3.0	0	25.5
PZ5	63	8.5	3.0	9.0	16.5
PZ6	63	8.5	3.0	19	6.5
PZ7	63	9.5	3.0	21	4.5
PZ8	63	8.5	3.0	23	2.5

*where 25.5 CaO indicates CaO has been substituted for the BaO additive and 25.5 MgO indicates MgO has been substituted for the BaO additive.

Table 2. The temperature coefficient of refractive index of common phosphate glasses

Glass	dn/dt (10^{-6})
$Al(PO)_3$	+5.0
$Ba(PO)_2$	-10.6
$Zn(PO)_2$	+5.1

Table 3. Predicted temperature coefficient of refractive index of the fabricated glasses

Glass	dn/dt (10^{-6})	
	Using Reference [1]	Using Reference [2]
PZI	-1.8	-1.4
PZ2	+0.3	+3.4
PZ3	+1.6	+5.5
PZ4	+2.2	+6.5
PZ5	+0.8	+3.7
PZ6	-0.8	+0.6
PZ7	-1.1	0
PZ8	-1.4	-0.6

Although there are some numerical differences in the predicted temperature coefficient of refractive index using reference [1]: Optical Properties of Glass, Edited by Donald R. Uhlmann and Norbert J. Kreidl, The American Ceramic Society, Inc., 1991 and reference [2]: Optical Glasses (Chinese), Edited by Fuxi Gan, Academic Publication, Beijing, 1985, Table 3 indicates that the temperature coefficient of refractive index of the glass decreases when the ZnO content increases and the BaO content decreases. The temperature coefficient of refractive index can be adjusted by changing the content of ZnO and BaO. Glasses with a temperature coefficient close to zero can be obtained near the composition of PZ6.

Thus, according to another embodiment of the present invention, the phosphate glass fibers of the present invention can be composed with compositions such that a temperature coefficient close to zero or negative is realized and these compositions can be fortified with B_2O_3 or Al_2O_3.

Accordingly, the phosphate glass may comprise by weight percentages P_2O_5 from 30 to 80 percent, L_2O_3 from 5 to 30 percent, and MO from 5 to 30 percent, wherein L_2O_3 is

selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof. The glass may or may not include R_2O, wherein R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof; the concentration of R_2O is not critical to maintaining athermal performance. Rather athermal performance is achieved with the temperature coefficient of refractive index set close to zero by balancing the mixture of MO. Since BaO and ZnO have negative and positive temperature coefficients of refractive index respectively, a proper mixture can provide a temperature coefficient of about zero. The fiber the concentration of R_2O will not need to be elevated and can be very low, less than about 5 percent by weight.

Phosphate Glasses

The following disclosure describes in more detail the manufacture and characterization of phosphate glasses suitable for utilization as core or cladding glasses in the phosphate glass fibers of the present invention.

First, two series of glass specimens, $64P_2O_5 \cdot 12Al_2O_3 \cdot 3.5(Er_2O_3 + La_2O_3) \cdot 20.5MO$ (M = Mg, Ca, Ba) (mole %) and $64P_2O_5 \cdot 3.5(Er_2O_3 + La_2O_3) \cdot (21.5\text{-}x)Al_2O_3 \cdot (11+x)BaO$, (x = 0, 3.5, 6.5, and 9.5) (mole %) were prepared to investigate the influence of glass composition on spectral properties, refractive index, and thermal properties. Compounds with less than 10 ppm of iron or copper were used as the starting chemicals for glass preparation. The mixed chemicals were melted in an electric furnace using a quartz crucible at 1250°C. The liquid was then held at temperature for thirty minutes. After fusing, the glass liquid was transferred to a platinum crucible, and the temperature was increased to 1350°C. Nitrogen gas was purged through the liquid to remove hydroxyl ions (OH^{-1}). The liquid was cast into an aluminum mold. A variety of samples from these specimens were prepared for the measurements. The refractive index of glass was measured with a prism coupler (e.g., a Metricon Model 2010) at 632.8 nm and 1550 nm. The optically polished glass samples with a size of 2 cm x 2 cm x 0.5 cm were used in the measurements of the absorption spectrum. The thermal expansion coefficient, glass transition temperature, and softening temperature of

each sample were measured on a dilatometer. The absorption spectra were recorded on a spectrophotometer (e.g., a Cary 5G).

The effect of glass compositions on the absorption linewidth of the $^4I_{15/2}$ - $^4I_{13/2}$ transition of the emission spectrum of erbium ions was investigated. The linewidth becomes increasingly important due to the emerging wavelength division multiplexing (WDM) technology. Figure 3 and 4 show the influence of glass composition on the refractive index and the effective linewidth. Figure 3 shows that the refractive index of phosphate glass increased when the ionic size of alkaline earth metal increased from Mg, to Ca, to Ba. Figure 4 illustrates the effect of the concentration of BaO and Al_2O_3 on the refractive index of the samples. The refractive index increased when the concentration of BaO increased and the concentration of Al_2O_3 decreased. The effective linewidth is defined as the integration of a band over wavelength and dividing by the maximum. Figure 3 indicates that the effective emission linewidth for the $^4I_{13/2}$ - $^4I_{15/2}$ transition increases with increasing ionic size of alkaline earth ions. When the concentration of BaO increases and the concentration of Al_2O_3 decreases, the effective emission linewidth of the $^4I_{13/2}$ - $^4I_{15/2}$ transition increases, as illustrated in Figures 4.

Emission spectra were measured on samples with a thickness of 0.4 mm to reduce reabsorption. The emission spectrum measurement at 1.5 μm was carried out using a 980 nm diode as a pumping source. Absolute emission cross section were calculated using McCumber theory. According to McCumber theory, the absorption and emission cross sections are related by equation (1) if the time required to establish a thermal distribution within each manifold is short compared with the lifetime of that manifold.

$$\sigma_e(\upsilon) = \sigma_a(\upsilon)\exp[(\varepsilon - h\upsilon)/kT] \qquad (1)$$

where σ_a and σ_e are the absorption and stimulated emission cross section, respectively, υ is the photon frequency, ε is the net free energy required to excite one Er^{3+} ion from the $^4I_{15/2}$ - $^4I_{13/2}$ state at temperature T, h is the Planck constant, and k is the Boltzman constant. The absorption cross section was determined from the absorption coefficient. The peak absorption cross section for a $63P_2O_5 \cdot 8.5Al_2O_3 \cdot 3(Er_2O_3 + La_2O_3) \cdot 9.5BaO \cdot 16\ LiO$ (mole %) glass is 0.75 x 10^{-20} cm^2/ion at 1.5335 μm. The peak stimulated emission cross section is calculated to be 0.82 x 10^{-20} cm^2/ion at 1.5335 μm. The absorption and fluorescence spectra in the phosphate glass bulk exhibit wide linewidths for $^4I_{13/2}$ - $^4I_{15/2}$

transition of erbium ions (48.63 nm). The absorption and fluorescence spectra of erbium doped phosphate glass bulk are illustrated in Figure 5.

Next, undoped glasses (no erbium or ytterbium ions) were fabricated as cladding glasses. In order to insure a low stress and birefringence in the fiber, similar thermal characteristics between the core glass and the cladding glass are required. To form waveguide in the core glass with good confinement, a slight lower refractive index of the cladding glass is also required. Theoretical calculation was performed based upon experimental results listed previously (Figure 3 and 4). Several melts were made to achieve a thermal behavior match and a required difference of refractive index by modifying the Al_2O_3, alkali ions and alkaline earth ions content. The thermal expansion coefficient, glass transition temperature, and softening temperature of each melt were measured on a dilatometer. The refractive index at various wavelengths was determined by prism coupling technique. Cladding glasses were developed with differences in thermal expansion coefficients between the cladding glasses and the core glass less than 3 % in the temperature range from 80°C to 400°C. In addition, glass transition temperatures and softening temperatures of these cladding glasses are also very close to that of the core glass (see Table 4 below). The 10% difference in thermal expansion coefficient between the core glass and the cladding glass is acceptable for fiber fabrication without serious stress in the fiber. Small differences in thermal expansion coefficient, glass transition temperature and softening temperature between the core and cladding glasses ensures high quality of the fiber.

Table 4. Glass transition and softening temperatures of core and cladding glasses

Glass type	Glass transition temperature (T_g)	Softening temperature (T_f)
Core glass (P25)	439 °C	480 °C
Cladding 1-1	435 °C	479 °C
Cladding 2-1	436 °C	470 °C
Cladding 3-1	443 °C	486 °C

The respective compositions of a core glass co-doped with erbium and ytterbium and various cladding glasses are given as follows:

Core Glass P25: $63P_2O_5 \cdot 8.5Al_2O_3 \cdot 3 (Er_2O_3+La_2O_3+Yb_2O_3) \cdot 9.5BaO \cdot 16Li_2O$ (mole %)

Cladding 1-1: $63P_2O_5 \cdot 10Al_2O_3 \cdot 1.5La_2O_3 \cdot 7BaO \cdot 17Li_2O \cdot 1.5Na_2O$ (mole %)

Cladding 2-1: $63P_2O_5 \cdot 11Al_2O_3 \cdot 4BaO \cdot 17Li_2O \cdot 2.5Na_2O \cdot 2.5CaO$ (mole %)

Cladding 3-1: $62P_2O_5 \cdot 12Al_2O_3 \cdot 4BaO \cdot 17Li_2O \cdot 2.5Na_2O \cdot 2.5CaO$ (mole %)

A good refractive index match with the core glass is another key parameter for the cladding glass besides the thermal behavior match. The refractive index of the cladding and core glasses is listed in the Table 5 (see below). The refractive index at 1.55 μm of cladding glass is 0.48 % to 1.14 % lower than the core glass P25, which results in numerical apertures from 0.149 to 0.230. With such values of numerical aperture, erbium doped optical fibers with a mode profile perfectly matched with standard telecommunication fiber can be fabricated.

Table 5. Refractive index of core and cladding glasses

Glass type	Refractive index			
	632.8 nm	830 nm	1300 nm	1550 nm
Core glass (P25)	1.5431	1.5389	1.5318	1.5290
Cladding 1-1	1.5365	1.5309	1.5249	1.5217
Cladding 2-1	1.5298	1.5250	1.5187	1.5158
Cladding 3-1	1.5257	1.5206	1.5150	1.5116

Finally, an ytterbium-doped glass composition of $63P_2O_5 \cdot 8.5Al_2O_3 \cdot 3(Er_2O_3+La_2O_3+Yb_2O_3) \cdot 9.5BaO \cdot 16Li_2O$ (mole %), chosen based upon modeling and the spectral characterization results of the non-ytterbium doped glasses, was melted at 1350°C in a platinum crucible using high purity starting chemicals. This glass composition contains 3.5 weight % erbium. The refractive index of this glass composition was measured with a prism coupler at 632.8 nm, 1300 nm and 1550 nm. The absorption and emission cross sections were determined to be $0.75 \times 10^{-20} cm^2$ and $0.82 \times 10^{-20} cm^2$ at 1534 nm, respectively. The thermal expansion coefficient, glass transition temperature, and softening temperature of the ytterbium-doped core glass were measured to be 8.7×10^{-6} °C^{-1}, 439 °C, and 480 °C, respectively. The cladding glass was designed to match the thermal performance of the

ytterbium-doped core glass to ensure low stress in the fiber. The difference in thermal properties between the ytterbium-doped core glass and the designed cladding glass is less than 3%.

In one preferred embodiment, a fiber comprises a cladding that includes

66.63% by weight P_2O_5,

6.46 % by weight Al_2O_3,

23.42% by weight BaO,

2.59% by weight B_2O_3, and

0.9% by weight MgO and

a core that includes

55.21% by weight P_2O_5,

5.36 % by weight Al_2O_3,

22.2% by weight BaO,

0.99% by weight ZnO,

3% by weight Er_2O_3, and

15% by weight Yb_2O_3.

Fabrication and characterization of erbium-doped phosphate glass fiber

In another embodiment of the present invention, a rod in tube technique was utilized to prepare single mode phosphate glass fibers. Figure 6 illustrates the steps of producing the single mode phosphate glass fibers. Referring to Figure 6, a phosphate glass ingot containing dopants is formed in step 200. Once the ingot is formed, the ingot is cored to produce in step 210 a first core glass rod. The first core glass rod has a barrel of the glass rod polished in step 220. In step 230, a cladding glass tube (i.e. a tube without erbium or ytterbium dopants) is drilled to have an inside diameter within 0.1 mm of the outside diameter of the first core glass rod. In step 240, the first core glass rod is placed inside the first cladding glass tube, and the assembly is drawn to form a second core glass rod. The second core glass rod is placed, in step 250, inside a second cladding glass tube, and the assembly is drawn into a single mode fiber. Fiber drawings were performed in an argon gas atmosphere to reduce absorption of water from air exposure which causes fluorescence quenching of Er^{3+} ions.

Figure 7 shows schematically the representative steps of the present invention. A bulk glass rod (not shown) was doped for example with 3.5 weight % erbium. A first core glass rod 2 was drilled from a bulk glass, and the barrel of the first core glass rod 2 was polished. Both inside and outside surfaces of a glass cladding tube 4 made from the cladding glass were polished. The inside diameter of the cladding tube 4 was matched to within 0.1 mm of the diameter of the first core glass rod 2. Next, the 3 mm core glass rod 2 and the 12 mm cladding tube 4 were drawn into a second core glass rod 6 with a 3 mm outside diameter. The second core glass rod 6 together with a second cladding tube 8 were drawn into a single mode fiber 10. The fiber drawing was performed at 765°C. No plastic coating was applied to the fiber.

After fabrication of erbium doped glass fibers, gain characterizations of the fibers were made. Figure 8 shows the experimental setup for gain characterization. An erbium-doped fiber 20 whose core contained 3.5 weight % erbium was pumped using a 980 nm laser diode 22 stabilized by fiber Bragg gratings (not shown). An external cavity tunable laser diode 24, tunable from 1530 nm to 1570 nm was used as a signal source. An attenuator 26 was used to vary the input signal strength. Pump and signal beams were combined by a 980/1550 fiber multiplexer (not shown). The erbium-doped fibers were placed on V-grooves. Two fiber in-line isolators 28 for the signal were used. The output fiber is connected to the optical spectrum analyzer (OSA) 30. A pump monitor 32 was used to ensure that the pump signal did not vary during measurement of optical gain.

A single mode fiber consisting of a 3.5 weight percent concentration erbium doped phosphate glass core with an undoped glass cladding was fabricated using the rod in tube technique previously discussed. The phosphate glass fibers with the 3.5 weight percent concentration of erbium were fabricated by the rod in tube technique. One phosphate glass rod uniformly doped with 3.5 weight % erbium and two phosphate glass tubes without erbium doping were used in the drawing processes. A single mode fiber was obtained. The fiber core was 4 μm in diameter with an erbium concentration of 3.7×10^{20} cm^{-3}.

A 980 nm semiconductor laser diode was used as pumping source. An external cavity tunable laser diode, tunable from 1530 nm to 1570 nm was used as a signal source. A net gain of 15.5 dB was achieved at 1535 nm from a 5.1 cm long fiber. The internal gain is 17.5

dB. The net gain per unit length is 3 dB/cm, which is the highest erbium doped fiber net gain ever obtained.

The refractive indices were measured by the prism coupling method. The numerical aperture of erbium-doped fiber was calculated to be 0.25 using the measured refractive indices of the core and cladding glasses at the wavelength of 1535 nm. Absorption cross section was calculated from the measured absorption spectrum. The effective linewidth is 46 nm for the $^4I_{15/2}$ - $^4I_{13/2}$ transition. Emission cross section was calculated from the absorption cross section and emission spectrum by McCumber theory. The emission spectrum and fluorescence lifetime for the $^4I_{13/2}$ - $^4I_{15/2}$ transition of Er^{+3} were measured in a 2 mm long phosphate fiber at low pump power. The measured emission spectrum for 1.5 μm band in the fiber was similar to that in the bulk material. The propagation loss of 0.1 dB/cm was measured at a wavelength of 1.3 μm.

The rod-in-tube technique was once again utilized to fabricate erbium doped phosphate glass fibers. A core glass rod was drilled from the bulk glass material formed in the melt at 1350°C, and the barrel of the rod was polished. The inside diameter of a cladding tube was matched to within 0.1 mm with the diameter of the core glass. The fiber drawing temperature was 765 °C. As before, two drawings were used. The erbium ion concentration of the fiber core is 3.5 weight %. No plastic coating was applied to the fiber. The numerical aperture of the erbium-doped fiber was calculated to be 0.216 at 1550 nm. Fibers with core diameters of 4 μm, 5 μm, and 6 μm were fabricated. The propagation loss of 0.3 dB/cm was estimated at 1.3 μm using the cut-back method.

A fiber with a core diameter of 5 μm was tested. A 5.1 cm long erbium doped fiber was pumped using a 980 nm laser diode stabilized by fiber Bragg gratings. An external cavity tunable laser diode, tunable from 1530 nm to 1570 nm was used as a signal source. Pump and signal beams were combined by a 980/1550 fiber multiplexer. 245 mW of pump power were available at the output of the multiplexer. The 5 μm fiber was placed on a V-groove. Two in-line isolators for the signal were used. The output fiber was connected to the optical spectrum analyzer. The coupling loss was estimated to be 1 dB at 1.3 μm.

Figure 9 illustrates the net gain and noise figure versus the pump power at 1535 nm and 1550 nm for the 3.5 weight % erbium, 5 μm core diameter erbium-doped fiber of the present invention. The input signal power was -31 dBm. A net gain of 15.5 dB was achieved

at 1535 nm, and the internal gain is 17.5 dB. The net gain per unit length of 3 dB/cm, was once again obtained. The internal noise figures are approximately 1 dB below noise figures shown in Figure 9, which indicates that a noise figure close to 4 dB could be readily achieved by reducing the coupling losses. Gain saturation was not observed in this experiment, suggesting a higher gain is achievable at higher pumping power.

According to the present invention, doping with erbium improves the gain of the phosphate glass fibers. Based on internal modeling results, the pump power needed to reach a 15 dB net gain is around 100 mW, given the high energy transfer efficiency.

Figure 10 illustrates net gain as a function of signal wavelength with different signal powers for the 5 μm core diameter erbium-doped optical fiber of the present invention. The pump power is 245 mW. The signal wavelength was tuned from 1530 to 1570 nm. As shown in Figure 10, the gain profile extends towards longer wavelengths and decreases dramatically at shorter wavelengths. This profile agrees well with the above-noted absorption and emission cross section results and numerical modeling. Figure 10 shows that the net gain decreases significantly near the peak wavelength when the signal power was increased from -6 dBm to 0 dBm. This decrease is caused by gain saturation.

Figure 11 shows gain saturation at 1535 nm and 1550 nm for the 5 μm core diameter erbium-doped fiber of the present invention. The saturation output power (defined as the output power where the gain is 3 dB below the maximum gain) at 1535 nm and 1550 nm are 8 dBm and 10 dBm, respectively. The input saturation power at 1550 is 5.5 dBm. This result agrees with the results in Figure 10 where the net gain at the longer wavelength with different signal power does not change too much.

Thus, the phosphate fibers of the present invention, manufactured according to one embodiment of the present invention using a rod in tube technique, show minimal inefficiency from cooperative upconversion. Consequently, with respect to manufacture, cost, and performance, the phosphate fibers of the present invention are integrated into optical components such as splitters, couplers, waveguide gratings, optical switches, and modulators. An integrated approach dramatically reduces component cost and meets the demand for high amplification in metro and local network applications.

Amplifying splitter

An amplifying splitter 40 of the present invention shown in Figure 12 includes a splitter 42 and a phosphate glass fiber amplifier 44 of the present invention. The amplifying splitter 40 is a 1 × n device with one input port 46 and multiple output ports 48 for dividing optical signals about 1.54 μm, the optical fiber communication window. The amplifying splitter 40 divides optical signals without any intensity loss by employing the phosphate glass fiber amplifier 44 with high gain per unit length. The amplifying splitter 40 integrates a passive optical component, such as for example the splitter 42, with a high performance, compact fiber amplifier, such as for example the fiber amplifier 44. The fiber amplifier 44 is a doped phosphate glass fiber 50, inserted and epoxied to a groove, such as for example a V-groove 52, and coupled to an optical pump 54, such as for example a solid state laser emitting at 980 nm. The optical pump 54 propagates laser light in a direction opposite to a propagation direction of the split signals. The laser light is coupled into the phosphate glass fiber 50 by a 980/1550 fiber multiplexer 56. The fiber amplifier 44 and the splitter 42 are bonded to a substrate 58 to form a quasi-monolithic device. The amplifying splitter 40 is pigtailed with single mode fibers and packaged in a compact, rugged environmentally stable case (not shown). The amplifying splitter 40 exhibits high gain, high port-to-port uniformity, low insertion loss, low back reflection, and low polarization dependent loss.

Existing splitters are only 50% efficient for a single source, two output port (1x2) device. That is, the device divides the light intensity. In a more typical source, a sixteen output port (lxl6) splitter, the loss would be 94%. To counter this loss, current networks must employ expensive optical power boosting amplifiers.

The amplifying splitter 40 of the present invention with high gain compensates for losses in splitters. The amplifying splitter uses low cost erbium and ytterbium co-doped phosphate glass fiber amplifier technology. The amplifying splitter 40 is a device that can be used in a fiber optic network to split an optical fiber input into several fiber optic outputs, without any loss of output light intensity from each port. Optical splitter use is expected to grow strongly as fiber networks reach closer and closer to end users, such as in short haul terrestrial systems and metro optical networks. The amplifying splitter 40 finds application in fiber-to-the-curb and fiber-to-the-home applications.

Besides using a fiber multiplexer to couple laser light to a fiber amplifier, the fiber amplifier 44 is pumped, according to one embodiment of the present invention, with a low

cost multi-mode diode laser. The multi-mode laser emits light from 900 to 1000 nm. Figure 13 is a schematic illustrating pumping of a fiber amplifier with a multi-mode diode laser lasing near 980 nm. A silica fiber 60 introduces an optical signal to a single fiber amplifier 62. The single fiber amplifier 62 includes a doped phosphate single-mode glass fiber 64 attached to a substrate 66. A multi-mode diode laser 68 pumps the single-mode fiber 64. The beam diameter of the diode laser is focused to approximately 80 μm. The amplified signal is transmitted forward to an output silica fiber 70.

Being able to employ a mult-mode laser adds to the flexibility and reduces the cost of the optical amplifier design. Multi-mode laser diodes are less expensive than single mode diode lasers. However, to maximize coupling into less efficient conventional optical fibers, single mode lasers are typically used to pump single mode fibers; similarly, multi-mode laser diodes are used to pump multi-mode fibers. With the elevated gain achievable with the erbium doped fibers described herein, it is possible pump a single mode fiber with a low power multi-mode laser diode. Coupling losses to not preclude high gain. The length of the optical fiber can still remain reasonable short, e.g., between about 5 and 50 or 100 millimeters, yet high gain is achieved.

Further still, as shown in Figure 14, more than a single fiber can be pumped with a multi-mode laser. A fiber array amplifier 72 is utilized to amplify input optical signals. The fiber array amplifier 72 includes a multi-mode diode laser bar 74 which pumps a side of an array 76 of doped phosphate glass fibers. The array 76 of doped fibers exhibit high gain per unit length and are placed orthogonal to the multi-mode diode laser bar 74. The length of the rare-earth doped fibers is a few centimeters, such as for example 5 cm. The multi-mode diode laser bar 74 excite the array 76 from the side and/or the top of the substrate. As shown in Figure 14, the phosphate glass fibers are placed within two V-grooved substrates 78. Inside surfaces of two V-grooved substrates 78 are coated with a metallic coating 80 to reduce scattering of the pump laser, ensuring a high pumping efficiency. Less than 100 mW absorbed pump is needed to excite each fiber. With this approach, significant cost reduction is realized since the cost of multi-mode laser diode bar is significantly lower than the cost of a single mode diode laser.

The fiber array amplifier 72 could be used in an amplifying splitter by adding the fiber array amplifier 72 to the passive splitter 42 after the input signal has been split. The fiber amplifier 44 may optionally compensate for optical loss in the passive splitter 42.

Figure 15 is a schematic diagram illustrating the array of glass fibers placed on a surface of a substrate 78 (as shown in Figure 15a), between two substrates (as shown in Figure 15b), or in a fiber bundle 80 (as shown in Figure 15c). The multi-mode diode laser 74 is shown at several alternative positions by which the array 76 of phosphate glass fibers can be pumped. The optical transparency of the substrates 78 and the high absorption strength of the high gain doped phosphate fiber enables pumping of the fiber amplifier.

Amplifying Combiner

Figure 16 illustrates an amplifying combiner 82 of the present invention. Combiner 82 integrates a passive wavelength combiner 84 with a phosphate glass fiber amplifier 86. The combiner 84 and the amplifier 86 are separately designed and optimized before being assembled together into one package. The amplifying combiner 82 is a $n \times 1$ device with n multiple input ports 88 and one output port 90 for combining a variety of optical signal wavelengths around 1.54 μm, the optical fiber communication window. The amplifying combiner 82 combines the n multiple ports 88 without any intensity loss by employing the phosphate glass fiber amplifier 86 with extremely high gain per unit length. The fiber amplifier 86 is a co-doped phosphate glass fiber 92, inserted and fixed to a V-groove 94, coupled to an optical pump 96 such as for example a solid state laser emitting at 980 nm. The optical pump 96 propagates laser light in a direction opposite to a propagation direction of the combined signals. The laser light is coupled into the phosphate glass fiber 92 by a 980/1550 fiber multiplexer 98. The wavelength combiner 84 and fiber amplifier 86 are bonded to a substrate 100 to form a quasi-monolithic device. The amplifying combiner 82 is pigtailed with single mode fibers and packaged in a compact, rugged environmentally stable case (not shown). The amplifying combiner 82 exhibits high gain, low insertion loss, low back reflection, and low polarization dependent loss.

The amplifying combiner 82 is a device which could be used in a fiber optic network to combine and amplify optical signals. Use of the amplifying combiner 82 is expected to grow strongly as DWDM devices evolve and become more prevalent in optical networks.

As with the amplifying splitter 40, the fiber array amplifier 72 can be used in an amplifying combiner by adding the fiber array amplifier 72 to the combiner 84 before the input signals have been combined. The fiber amplifier 86 may or may not be utilized to compensate for optical loss in the combiner 84.

Amplifying Arrayed Waveguide Gratings

As shown in Figure 17, the present invention includes amplifying arrayed waveguide gratings 102 which integrate arrayed waveguide gratings (AWG) 104 with a compact phosphate glass fiber amplifier 106. The typical attenuation for AWG DWDM devices is 5 to 7 dB. The compact co-doped phosphate glass fiber amplifiers of the present invention can compensate this attenuation in order to simplify the system design. The amplifying arrayed waveguide gratings 102 is a device which resolves optical signal wavelengths around 1.54 μm, the optical fiber communication window, into specific frequency signals (i.e signals at 1.50 μm, 1.52 μm, 1.54 μm, 1,56 μm, etc.) . The fiber amplifier 106 is a doped phosphate glass fiber 108, inserted and fixed to a V-groove 110, coupled to an optical pump 112 such as for example a solid state laser emitting at 980 nm. Light from the solid state laser is coupled into the phosphate glass fiber 108 by a 980/1550 fiber multiplexer 114. The arrayed waveguide gratings 104 and the fiber amplifier 106 are bonded to a substrate 116 to form a quasi-monolithic device. The amplifying arrayed waveguide gratings 102 is packaged in a compact, rugged environmentally stable case (not shown). The amplifying arrayed waveguide gratings 102 exhibits high gain, low insertion loss, low back reflection, and low polarization dependent loss.

Utilization of the amplifying arrayed waveguide is expected to grow strongly as DWDM devices evolve and become more prevalent in optical networks.

As with the amplifying splitter 40, the fiber array amplifier 72 could be used in an amplifying arrayed waveguide gratings 102 by adding the fiber array amplifier 72 to the passive waveguide grating 104 after the input signals have been resolved. The fiber amplifier 106 may or may not be utilized to compensate for optical loss in the grating 104.

Amplifying Modulator

Lithium niobate modulators are known in the art and have the following advantages: compatibility with optical fiber, high frequency bandwidth (up to 40 GHz), low driving voltage, and rugged and all solid state construction. A further advantage of a lithium niobate modulator is that multiple optical components can be integrated into a single chip. In a similar approach to the above-mentioned splitter, combiner, and arrayed waveguide gratings, an amplifying modulator 118 of the present invention as shown in Figure 18 integrates a lithium niobate modulator 120 with a compact phosphate glass fiber amplifier 122. This integration provides a mechanism to compensate for insertion loss from the lithium niobate modulator 120. The amplifying modulator 118 compensates for intensity loss from the lithium niobate modulator 120 by employing the fiber amplifier 122 with extremely high gain per unit length. The fiber amplifier 122 is a doped phosphate glass fiber 124, inserted and fixed to a V-groove 126, coupled to an optical pump 128 such as for example a solid state laser emitting at 980 nm. The laser light is coupled into the phosphate glass fiber 124 by a 980/1550 fiber multiplexer 130. The amplifying modulator 118 and the fiber amplifier 122 are bonded to a substrate 132 to form a quasi-monolithic device. The amplifying modulator 118 is packaged in a compact, rugged environmentally stable case (not shown). The amplifying modulator 118 exhibits high gain, low insertion loss, low back reflection, and low polarization dependent loss.

Typical attenuation for a lithium niobate modulator can be between 0.5 to 3 dB. The low cost erbium and ytterbium co-doped phosphate glass fiber amplifier of the present invention allows for mated structures to the lithium niobate integrated optical component chip package and provides amplification before sending or receiving an optical signal. The amplifying modulator will help substantially in management of power losses in metro and local loop applications.

As with the amplifying splitter 40, the fiber array amplifier 72 could be used with an amplifying modulator 118. Adding the fiber array amplifier 72 to the modulator 118 enables amplification of multiple input signals before modulation.

Similarly, the optical fiber amplifier can be employed with an optical switch to minimize loss in the switch experienced by light passing therethrough. An optical switch is very similar to a modulator. In the optical switch, a beam of light switches between two or more optical paths. Like modulators, switches may have loss. Use of the optical amplifier in

combination with the switch can minimize affects of loss imparted on the signal that is transmitted through the switch.

Large Core Fiber Amplifier

Figure 19 is a schematic illustration of a large core fiber amplifier 160 of the present invention. The core diameter for such multi-mode fibers ranges from 50 μm to 300 μm. Typically in fiber amplifiers the light-guiding region (i.e., the core of the fiber) is only about 5 μm in diameter. Such a small core diameter allows only a single-mode propagation of the light at a signal wavelength around 1550 nm. According to the present invention, the high gain coefficient enables the use of short amplifying fibers that can be assembled in V-grooves without bending the fibers. This compactness enables the use of large core fibers that are not single-mode. Due to the short length and stable and rugged packaging, light that is coupled to the fundamental mode of the fiber, remains mostly in the fundamental mode with very little coupling to the other modes of the fiber. As shown in Figure 19, light is coupled, from input single-mode fiber 162, predominantly into the fundamental mode of a large core fiber 164 using conventional micro-optic techniques, such as for example a collimating lens 166. A key benefit of this embodiment is that high power 980 nm multi-mode light-emitting laser diodes 168 pump the core fiber 164 by introducing the laser light with a lens 170 through a split mirror 172 onto the core fiber 164. Light is coupled from the multi-mode laser diodes 168 into the fiber core with high efficiency, which is not possible with the small core diameter fiber amplifiers. The multi-mode laser diodes have an emitting cross-sectional area on the order of 1 μm x 100 μm. A second collimating lense 174 focuses the light onto an output fiber 176.

Accordingly, rare-earth doped phosphate glass is employed to fabricate optical fibers for amplifiers which may be pumped by diode or solid state laser sources. The rare-earth ions, erbium and ytterbium, may be co-doped at high levels to provide for extremely high gain. Erbium ion concentration is increased to provide very high active ion content. Ytterbium ion concentration is preferably increased to provide efficient absorption of pump power. The erbium concentration may range, for example, between about 1.5, 2.0, or 2.5 weight percent to as much as 12 weight percent. The ytterbium concentration may range from about zero to about 15 or 30 weight percent. The phosphate glass fiber provides for a

low-loss and stable fiber host. Phosphate glass fibers can be produced with a temperature coefficient of refractive index close to zero. Gains per unit length of at least about 1.0 dB/cm to about 6 dB/cm over a desired bandwidth, e.g., the telecomm C-band from 1530-1565 nanometers, are obtainable with a relatively compact amplifier. The length of the fiber may range for example between about 5 to 25, 50, or 100 millimeters.

Numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

WHAT IS CLAIMED IS:

1. An optical device comprising:

an optical fiber amplifier including,

at least one multi-component glass fiber co-doped with erbium and ytterbium, and

an optical pump arranged with respect to said multi-component glass fiber to direct light into said co-doped glass fiber to create a population inversion to produce, upon introduction of an optical signal into said glass fiber, stimulated emission and amplification of said optical signal.

2. The optical device of Claim 1, wherein said multi-component glass fiber comprises (i) a core co-doped with erbium and ytterbium and (ii) a cladding surrounding said core.

3. The optical device of Claim 2, wherein said cladding is undoped and thereby contains substantially no erbium and ytterbium.

4. The optical device of Claim 1, further comprising an optical component optically coupled to said multi-component glass fiber to enable communication of said optical signal between said optical component and said glass fiber.

5. The optical device of claim 4, wherein said optical component and said optical fiber are mounted on a substrate to form an integrated optics amplifier module.

6. The optical device of Claim 5, wherein said optical component is selected from the group consisting of a splitter, a combiner, a modulator, an optical switch, and an arrayed waveguide grating.

7. The optical device of Claim 1, wherein said multi-component glass fiber has a length between about 5 millimeters to about 100 millimeters.

8. The optical device of Claim 1, wherein the multi-component glass fiber includes by weight percentages Er_2O_3 of at least 1.5% and Yb_2O_3 up to 30 percent.

9. The optical device of Claim 8, wherein the optical pump comprises a multi-mode laser and said multi-component glass fiber includes by weight Yb_2O_3 from 5 to 30 percent.

10. The optical device of claim 9, wherein said optical fiber comprises a single-mode fiber that is pumped by the multi-mode laser.

11. The optical device of Claim 1, wherein the multi-component glass fiber further includes by weight percentages P_2O_5 from 30 to 80 percent,L_2O_3 from 5 to 30 percent, MO from 5 to 30 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof.

12. The optical device of Claim 11, wherein said active optical fiber has a temperature coefficient of refractive index from about -2.0×10^{-6} to 2.0×10^{-6}.

13. The optical device of Claim 12, wherein MO is a mixture of BaO, which exhibits a negative temperature coefficient, and ZnO, which exhibits a positive temperature coefficient.

14. The optical device of Claim 1, wherein said active optical fiber has a temperature coefficient of refractive index from about -2.0×10^{-6} to 2.0×10^{-6}.

15. The optical device of Claim 1, wherein said concentration of erbium and ytterbium dopants is sufficient to impart said active optical fiber with a gain per unit length of at least 1.0 dB/cm to about 6 dB/cm for an optical signal traveling therethrough.

16. The optical device of Claim 1, wherein said active optical fiber exhibits gain per unit length of at least 1.0 dB/cm over a range of 1530 nm to 1565 nm.

17. The optical device of Claim 1, wherein said multi-component glass fiber comprises a phosphate glass fiber, and said optical device further comprises:

a substrate configured to hold said phosphate glass fiber; and

an optical component mounted to the substrate,

wherein said phosphate glass fiber contains at least erbium dopants, said optical pump is configured to excite erbium ionic energy levels in said multi-component glass fiber to produce said stimulated emission and amplification of said optical signal.

18. The optical device of Claim 17, wherein the phosphate glass fiber comprises both erbium and ytterbium concentrations of at least 1.5 weight %.

19. The optical device of Claim 17, wherein the phosphate glass fiber contains greater than 2.5 wt. % of at least one of erbium and ytterbium.

20. The optical device of Claim 17, wherein the phosphate glass fiber includes concentrations of BaO and ZnO and the glass fiber has a temperature coefficient of refractive index from -2.0×10^{-6} to 2.0×10^{-6}.

21. The optical device of Claim 20, wherein said concentration of BaO ranges up to 26 mole % and said concentration of ZnO ranges up to 26 mole %.

22. The optical device of Claim 21, wherein the phosphate glass fiber contains Al_2O_3 with a concentration from 6 to 11 mole %.

23. An optical fiber amplifier, comprising:

a glass fiber comprising a phosphate glass including by weight percentages,

P_2O_5 from 30 to 80 percent,

Yb_2O_3 up to 30 percent and more than zero percent,

Er_2O_3 from 1.5 to 12 percent,

L_2O_3 from 5 to 30 percent,

MO from 5 to 30 percent,

wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof; and

an optical pump that outputs pump radiation, said pump being configured to direct said pump radiation into said fiber and thereby populate excited energy states therein,

wherein introduction of an input optical signal into said glass fiber produces stimulated emission and amplification of said input signal.

24. The optical fiber amplifier of Claim 23, wherein the optical pump comprises a multi-mode laser and said optical fiber comprises a single-mode fiber.

25. The optical fiber amplifier of Claim 24, wherein the weight percentage of Yb_2O_3 is greater than 5 percent.

26. The optical fiber amplifier of Claim 23, wherein MO includes a mixture of BaO and ZnO such that said active optical fiber has a temperature coefficient of refractive index from about -2.0×10^{-6} to 2.0×10^{-6}.

27. The optical fiber amplifier of Claim 26, wherein said BaO concentration and said ZnO concentration are as large as 26 mole %.

28. The optical fiber amplifier of Claim 23, wherein L_2O_3 comprises Al_2O_3 in a concentration from about 6 to about 11 mole %.

29. The optical fiber amplifier of Claim 23, wherein said phosphate glass further includes by weight percentages:

R_2O from 0 to 5 percent,

wherein R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof, the Yb_2O_3 concentration ranges from 0 to 12 weight percentages, the Er_2O_3 concentration ranges from 2.5 to 12 weight percentages, the sum of the weight percentages of Yb_2O_3 and Er_2O_3 is 2.5 % or greater; and

said optical pump is configured to pump at least erbium ionic energy levels in said glass fiber.

30. The optical fiber amplifier of Claim 29, wherein said phosphate glass has both ytterbium and erbium concentrations greater than 2.5 wt. %.

31. The optical fiber amplifier of Claim 29, wherein MO in said phosphate glass includes BaO and ZnO and the phosphate glass has a temperature coefficient of refractive index from -2.0×10^{-6} to 2.0×10^{-6}.

32. The optical fiber amplifier of Claim 31, wherein said phosphate glass has a concentration of BaO up 26 mole % and a concentration of ZnO up to 26 mole %.

33. The optical fiber amplifier of Claim 31, wherein L_2O_3 comprises Al_2O_3 in a concentration from 6 to 11 mole %.

34. A phosphate glass comprising the following ingredients by weight percentages,

P_2O_5, from 30 to 80 percent,

Yb_2O_3, up to 30 percent,

Er_2O_3, from 1.5 to 12 percent,

L_2O_3, from 5 to 30 percent, and

MO, from 5 to 30 percent,

wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof.

35. The phosphate glass of Claim 34, wherein Yb_2O_3 comprises 5% or greater by

weight percentage.

36. The phosphate glass of Claim 34, wherein said phosphate glass comprises 3.5 weight % erbium.

37. The phosphate glass of Claim 34, further comprising R_2O, wherein R_2O is selected from the alkali metal oxide group consisting of Li_2O, K_2O, Na_2O, Rb_2O, and mixtures thereof.

38. The phosphate glass of Claim 37, wherein the R_2O concentration ranges from 0 to 5 weight percentages, the Yb_2O_3 concentration ranges from 0 to 12 weight percentages, the Er_2O_3 concentration ranges from 2.5 to 12 weight percentages, the sum of the weight percentages of Yb_2O_3 and Er_2O_3 is 2.5 % or greater, and the glass composition has a temperature coefficient of refractive index from -2.0×10^{-6} to 2.0×10^{-6}.

39. The phosphate glass of Claim 37 comprising by mole %: 63 P_2O_5· 8.5 Al_2O_3 · 3 (Er_2O_3 + La_2O_3 + Yb_2O_3) · 9.5 BaO · 16 Li_2O.

40. The phosphate glass of Claim 34, wherein said concentration of Yb_2O_3 and Er_2O_3 are sufficient to provide a gain per unit length of glass of at least 1.0 dB/cm to about 6 dB/cm for an optical signal traveling therethrough.

41. The phosphate glass of Claim 34, wherein MO includes a mixture of BaO and ZnO such that said active optical fiber has a temperature coefficient of refractive index from about -2.0×10^{-6} to 2.0×10^{-6}.

42. An optical device comprising:

an optical fiber amplifier including,

at least one multi-component glass single-mode fiber co-doped with erbium and ytterbium, and

a multi-mode optical pump arranged with respect to said multi-component glass fiber to direct light into said co-doped glass fiber to create a population inversion to produce, upon introduction of an optical signal into said glass fiber, stimulated emission and amplification of said optical signal.

43. The optical device of Claim 42, wherein the multi-component glass includes by weight percentages Er_2O_3 from 1.5 to 12 percent and Yb_2O_3 from 5 to 30 percent.

44. The optical device of Claim 43, wherein said multi-component glass fiber has a length between about 5 millimeters to about 100 millimeters.

45. The optical device of Claim 43, wherein the multi-component glass further

includes by weight percentages P_2O_5 from 30 to 80 percent, L_2O_3 from 5 to 30 percent, MO from 5 to 30 percent, wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof.

46. The optical device of claim 43, wherein MO is a mixture of BaO, which exhibits a negative temperature coefficient, and ZnO, which exhibits a positive temperature coefficient such that the fiber's temperature coefficient of refractive index lies between about -2.0×10^{-6} to 2.0×10^{-6}.

47. The optical device of claim 43, wherein said concentration of erbium and ytterbium dopants is sufficient to impart said active optical fiber with a gain per unit length of at least 1.0 dB/cm to about 6 dB/cm for an optical signal traveling therethrough over a range of 1530 nm to 1565 nm.

48. The optical device of Claim 43, further comprising an optical component optically coupled to said multi-component glass fiber to enable communication of said optical signal between said optical component and said glass fiber.

49. The optical device of claim 48, wherein said optical component and said optical fiber are mounted on a substrate to form an integrated optics amplifier module.

50. The optical device of claim 48, wherein said optical component is selected from the group comprising a splitter, a combiner, a modulator, an optical switch, and an arrayed waveguide grating.

51. An optical fiber amplifier, comprising:

a glass fiber comprising a phosphate glass including by weight percentages,

P_2O_5 from 30 to 80 percent,

Er_2O_3 from 1.5 to 12 percent,

L_2O_3 from 5 to 30 percent,

MO from 5 to 30 percent,

wherein L_2O_3 is selected from the transition metal oxide group consisting of Al_2O_3, B_2O_3, Y_2O_3, La_2O_3, and mixtures thereof, and MO is selected from the alkaline earth oxide group consisting of BaO, BeO, MgO, SrO, CaO, ZnO, PbO and mixtures thereof; and

an optical pump that outputs pump radiation, said pump being configured to direct said pump radiation into said fiber and thereby populate excited energy states therein,

wherein introduction of an input optical signal into said glass fiber produces stimulated emission and amplification of said input signal.

52. The optical device of Claim 51, wherein said active optical fiber has a temperature coefficient of refractive index from about -2.0×10^{-6} to 2.0×10^{-6}.

53. The optical device of Claim 52, wherein MO is a mixture of BaO, which exhibits a negative temperature coefficient, and ZnO, which exhibits a positive temperature coefficient.

54. The optical device of Claim 51, further comprising an optical component optically coupled to said phosphate glass fiber on a substrate to form an integrated optics amplifier module.

55. The optical device of Claim 54, wherein said optical component is selected from the group consisting of a splitter, a combiner, a modulator, an optical switch, and an arrayed waveguide grating.

FIG. 1

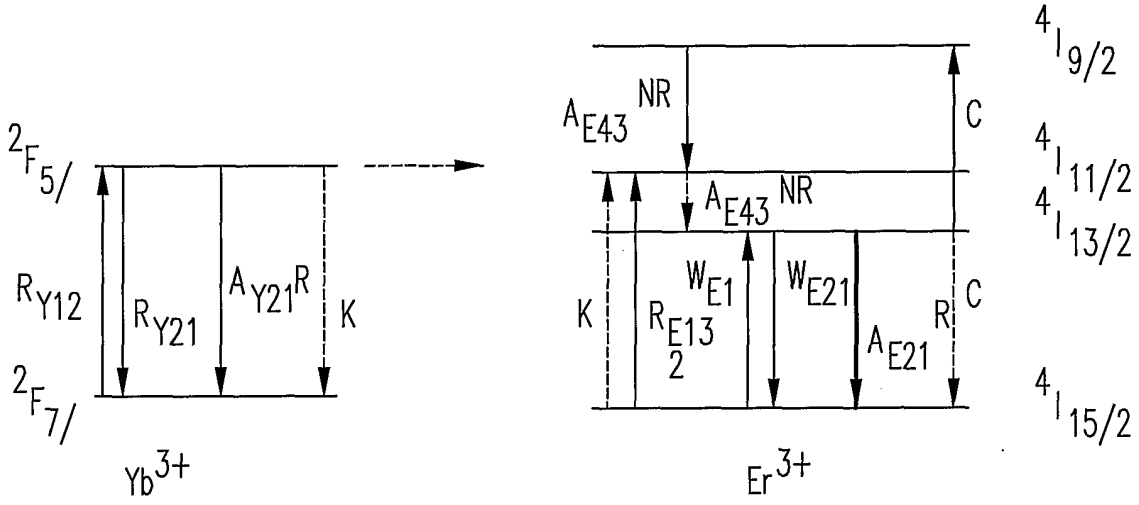
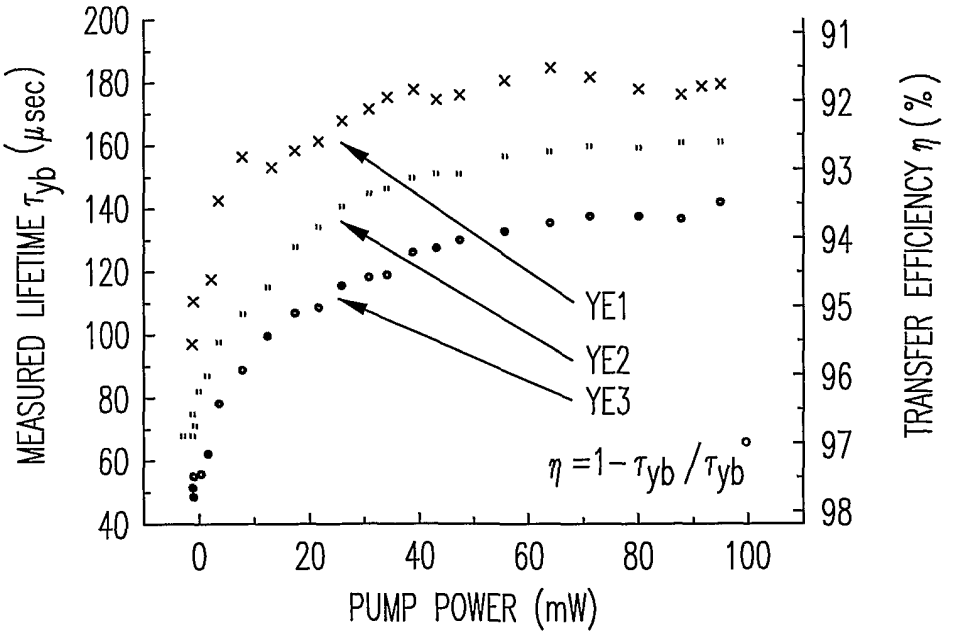


FIG. 2



YE 1: 2wt% Yb_2O_3+2wt% Er_2O_3;

YE 2: 4wt% Yb_2O_3+2wt% Er_2O_3;

YE 3: 6wt% Yb_2O_3+2wt% Er_2O_3;

FIG. 3

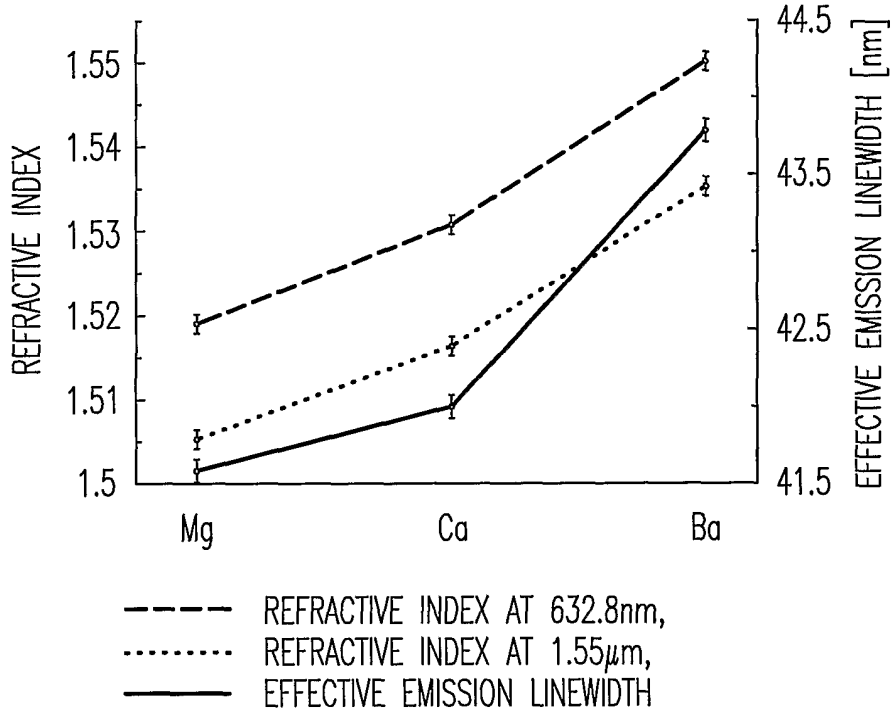
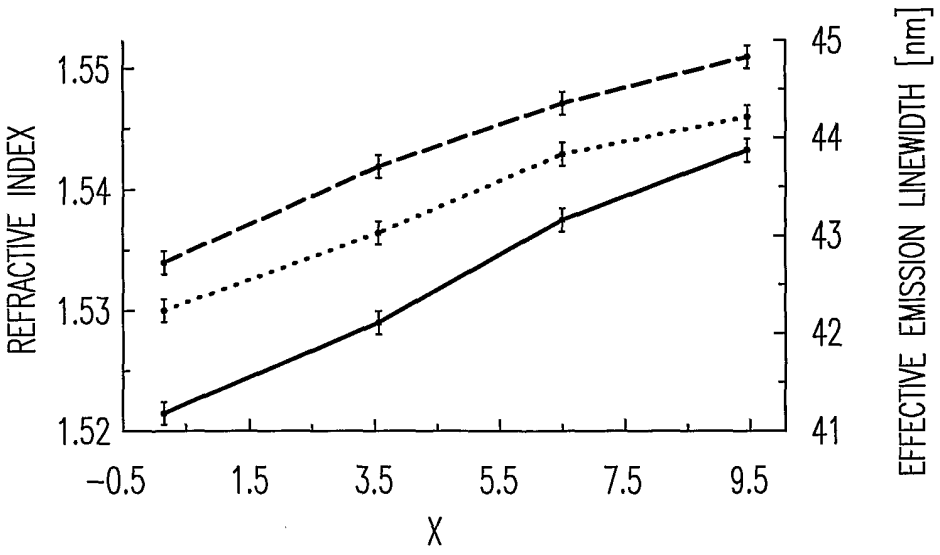


FIG. 4



REFRACTIVE INDEX AT 632.8nm,
REFRACTIVE INDEX AT 1.55μm,
EFFECTIVE EMISSION LINEWIDTH (LINES ARE DRAWN AS GUIDES FOR THE EYES)

FIG. 5

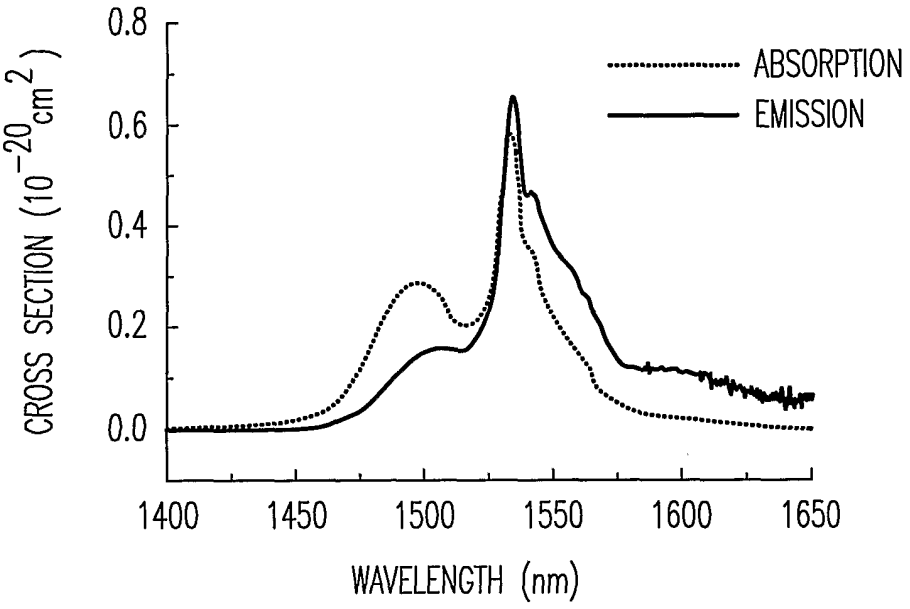

0.8
0.6
0.4
0.2
0.0
CROSS SECTION (10^{-20} cm^2)
ABSORPTION
EMISSION
1400
1450
1500
1550
1600
1650
WAVELENGTH (nm)

FIG. 6

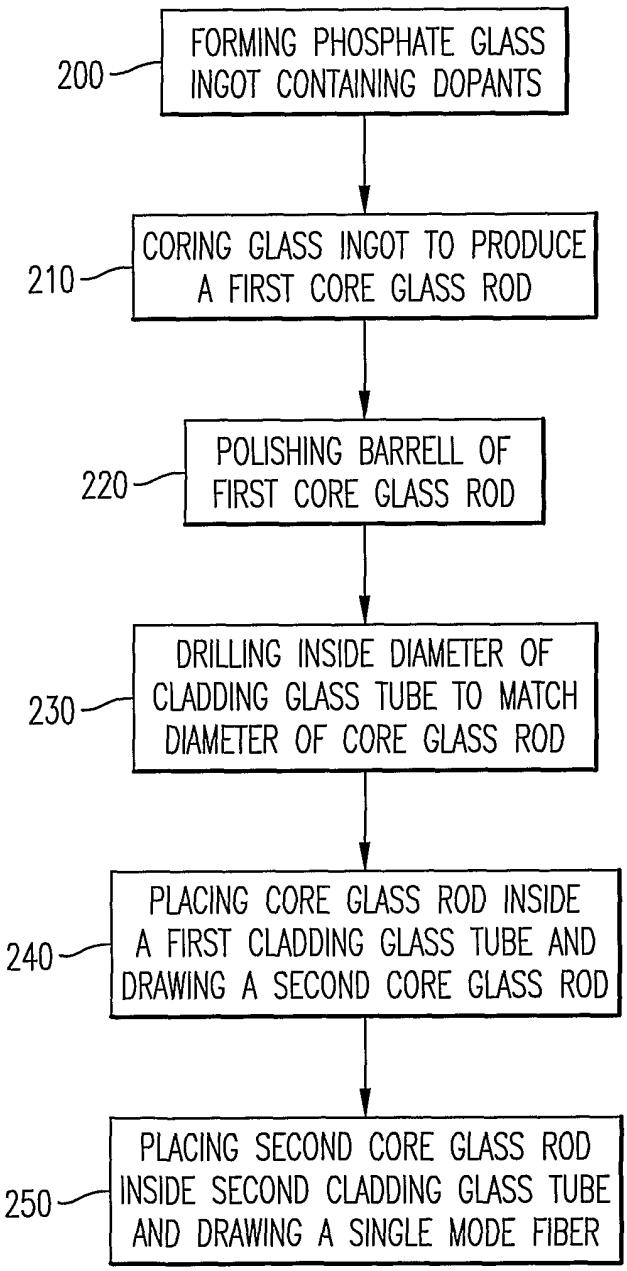

200
FORMING PHOSPHATE GLASS INGOT CONTAINING DOPANTS
210
CORING GLASS INGOT TO PRODUCE A FIRST CORE GLASS ROD
220
POLISHING BARRELL OF FIRST CORE GLASS ROD
230
DRILLING INSIDE DIAMETER OF CLADDING GLASS TUBE TO MATCH DIAMETER OF CORE GLASS ROD
240
PLACING CORE GLASS ROD INSIDE A FIRST CLADDING GLASS TUBE AND DRAWING A SECOND CORE GLASS ROD
250
PLACING SECOND CORE GLASS ROD INSIDE SECOND CLADDING GLASS TUBE AND DRAWING A SINGLE MODE FIBER

FIG. 7

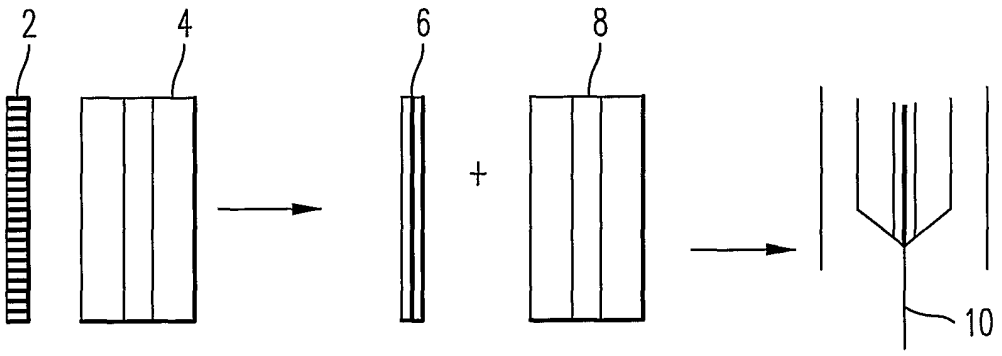

2
4
6
8
+
10

FIG. 8

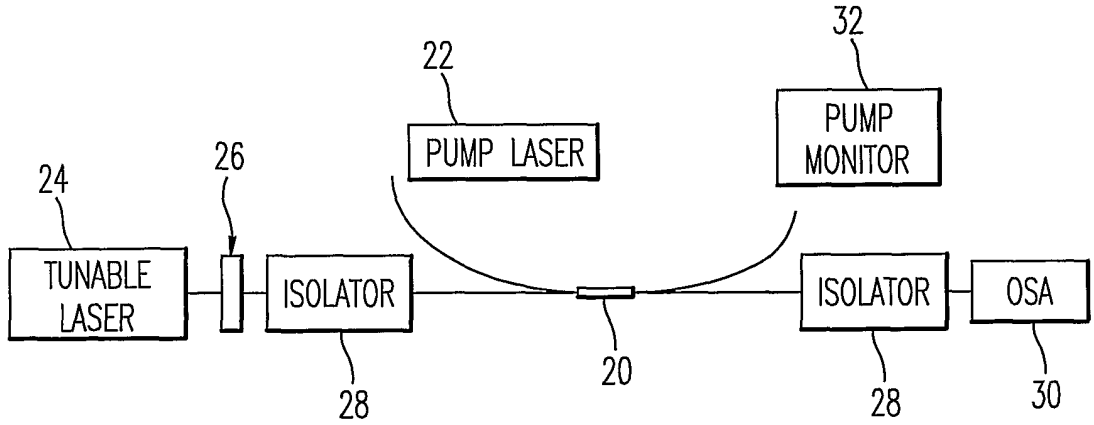

32
22
PUMP MONITOR
PUMP LASER
24
26
TUNABLE LASER
ISOLATOR
ISOLATOR
OSA
20
28
28
30

FIG. 9

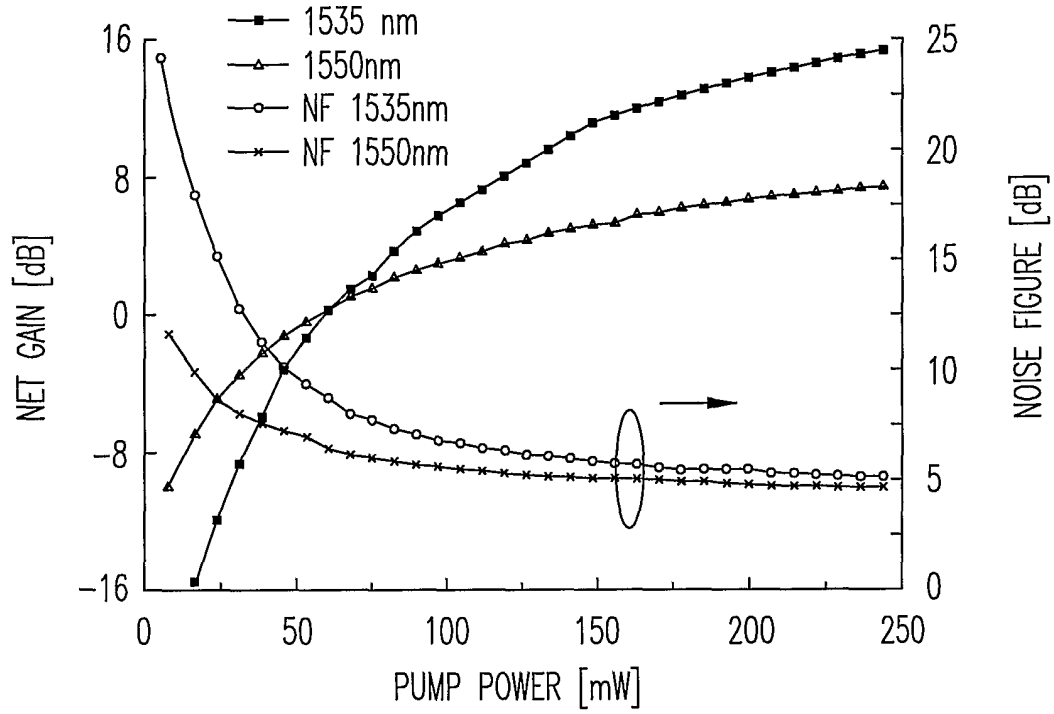

1535 nm
1550nm
NF 1535nm
NF 1550nm
NET GAIN [dB]
NOISE FIGURE [dB]
PUMP POWER [mW]
16
8
0
-8
-16
25
20
15
10
5
0
0
50
100
150
200
250

FIG. 10

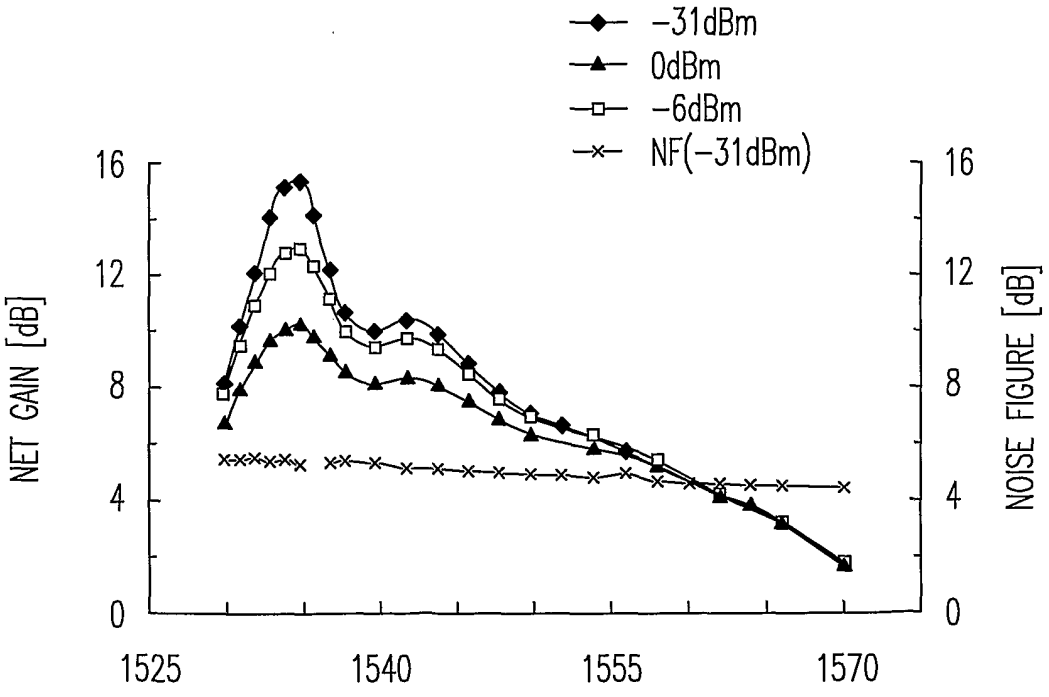

-31dBm
0dBm
-6dBm
NF(-31dBm)
NET GAIN [dB]
NOISE FIGURE [dB]
16
12
8
4
0
1525
1540
1555
1570

FIG. 11

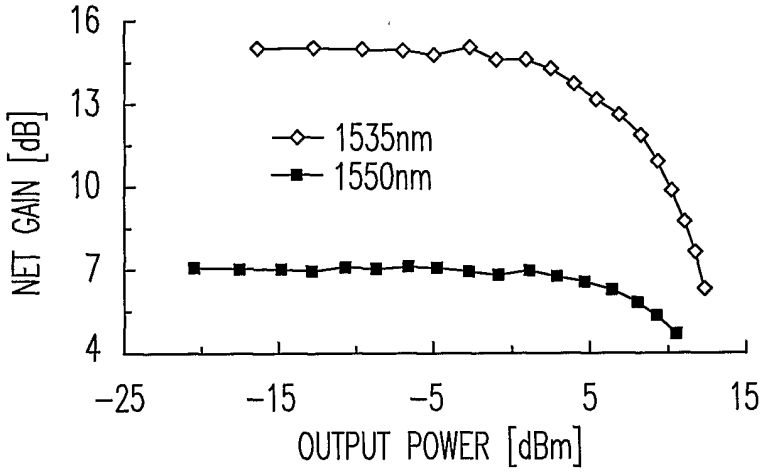

16
13
10
7
4
NET GAIN [dB]
1535nm
1550nm
-25
-15
-5
5
15
OUTPUT POWER [dBm]

FIG. 12

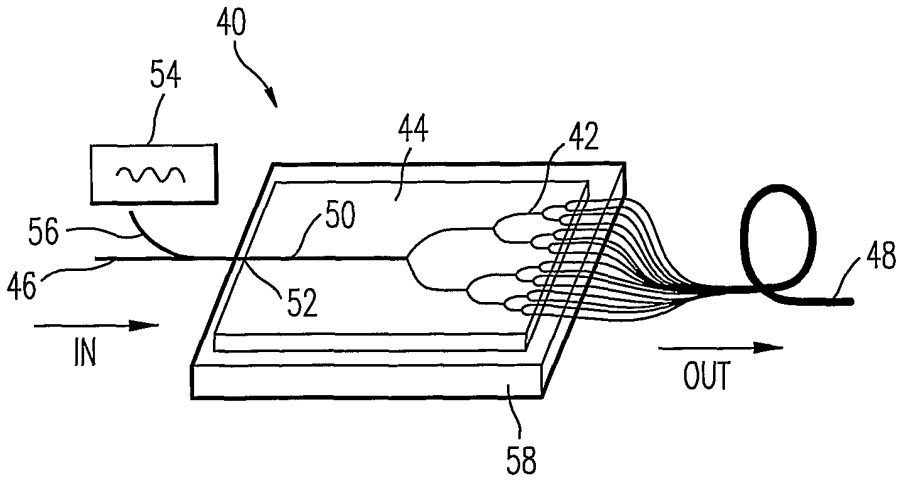

40
54
44
42
56
50
48
46
52
IN
OUT
58

FIG. 13

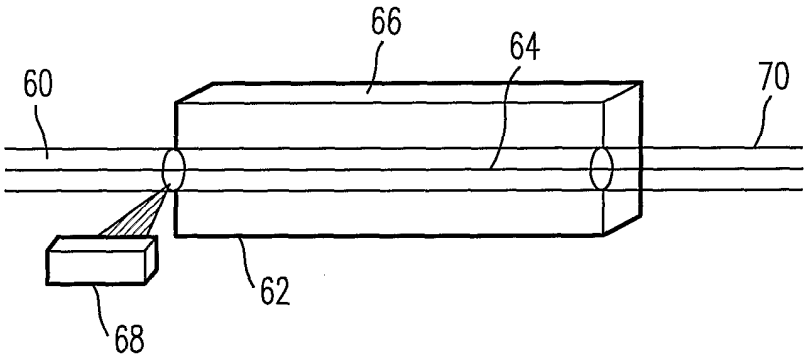


FIG. 14

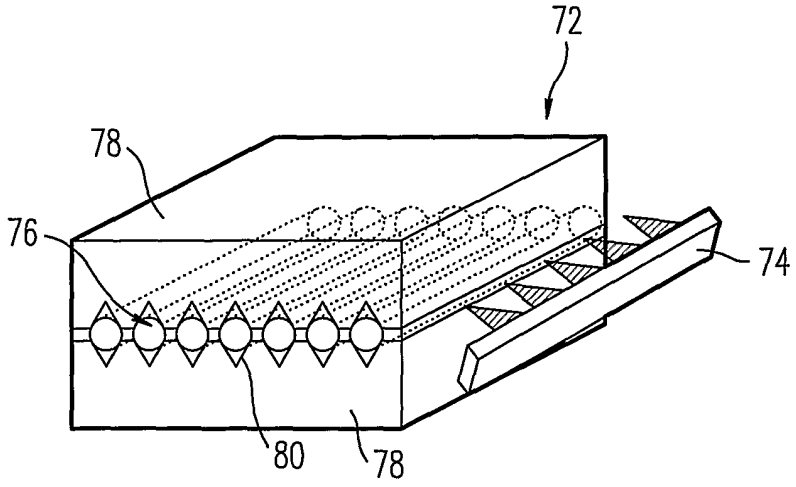


FIG. 15a

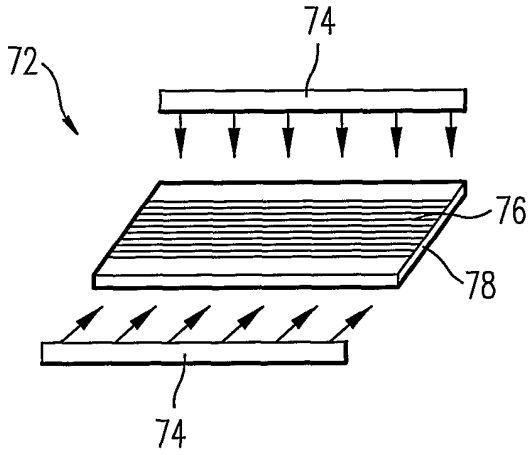


FIG. 15b

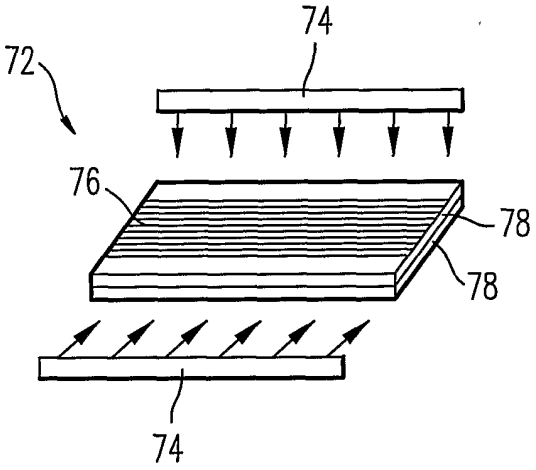


FIG. 15c

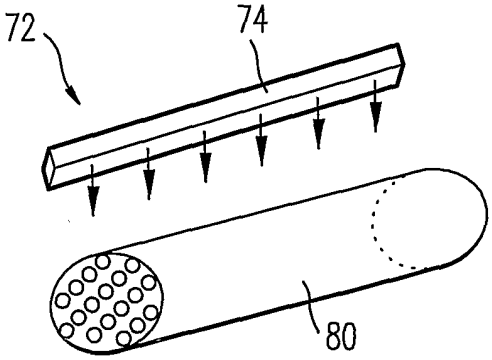


FIG. 16

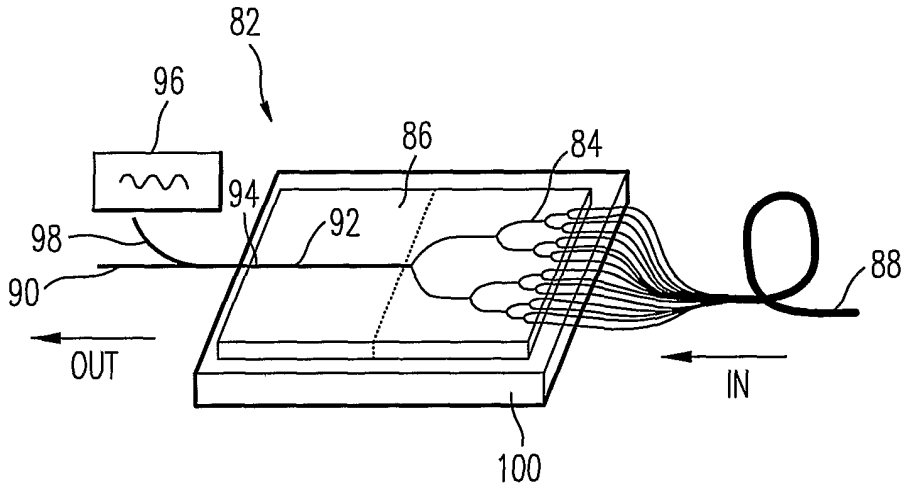


FIG. 17

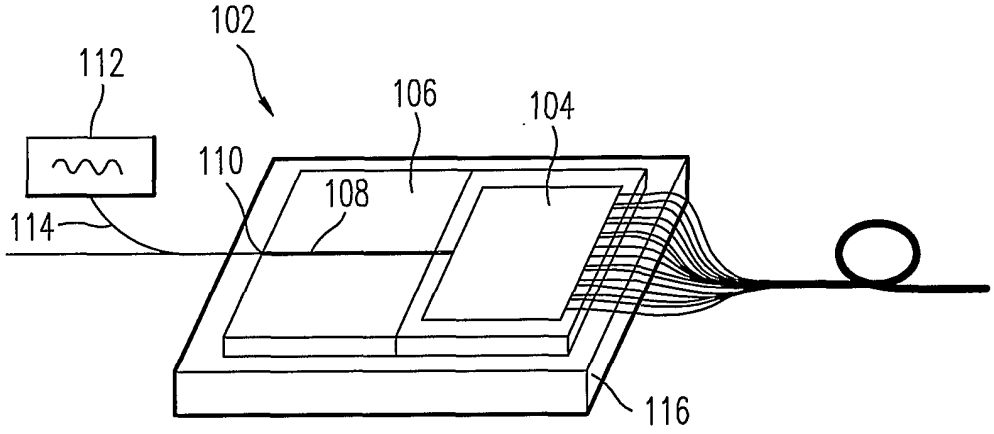


FIG. 18

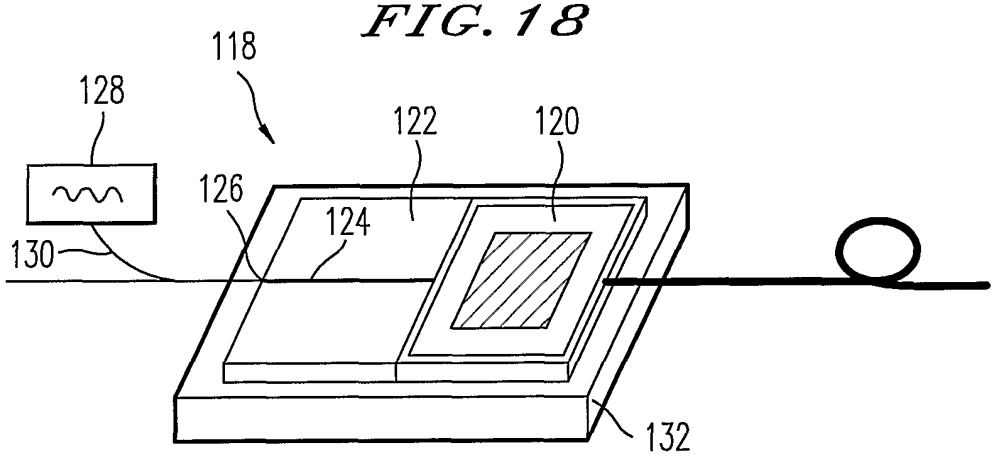
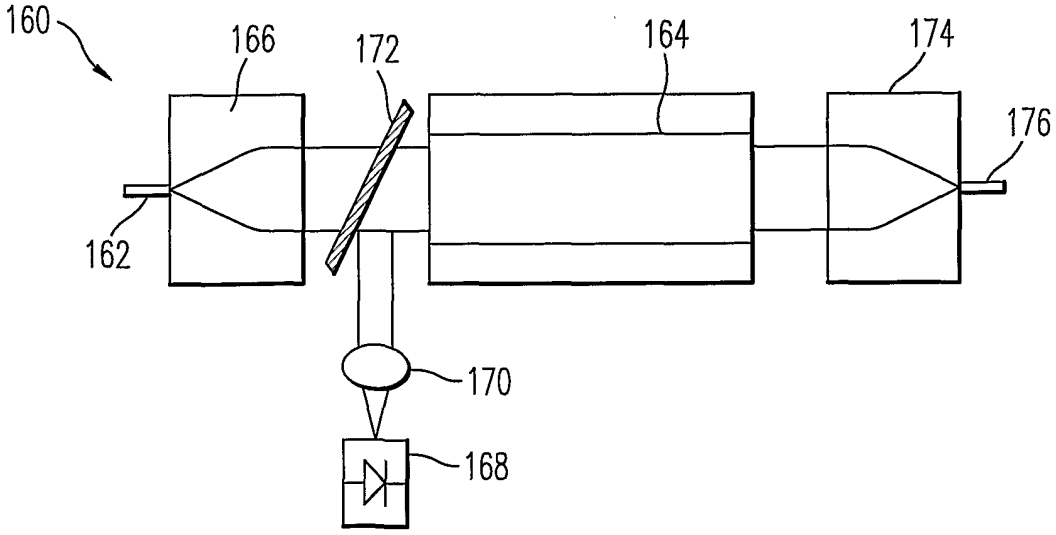


FIG. 19



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/14849

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H01S 3/00
US CL :372/68; 359/341.5
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)

U.S. : 372/68; 359/341.5, 341.1; 385/141; 65/390, 412

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

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

IEEE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US 5,982,973 A (YAN al) 09 November 1999, see entire document.	1-22, 42-44, 46-50 ---------- 24-25, 45, 51-55
X ---- Y	US 5,491,708 A (MALONE et al.) 13 February 1996, see entire document.	23-38, 40-41, 45, 51-55 ---------- 11-13
Y	US 5,032,315 A (HAYDEN et al.) 16 July 1991, see entire document.	14, 20-22, 26-27, 41, 46, 52-53

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

*	Special categories of cited documents:	"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
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"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		

Date of the actual completion of the international search 28 AUGUST 2001	Date of mailing of the international search report 21 SEP 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer DEANDRA M. HUGHES Telephone No. (703) 308-4357

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/14849

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,555,127 A (ABDELKADER et al) 10 September 1996, see entire document.	4-6, 17-22, 48-50, 54-55
A	US 5,032,315 A (HAYDEN et al.) 16 July 1991	1-55
A	US 5,334,559 A (HAYDEN) 2 August 1994	1-55
A, P	US 6,192,713 B1 (ZHANG et al.) 27 February 2001	1-55
A	Park et al. High_power Er-Yb-Doped Fiber Amplifier with Multichannel Gain Flatness within 0.2 dB over 14 nm. IEEE Photnonics Technology Letters. Vol. 8, No. 9. September 1996. pgs. 1148-1150	1-55
A	Vienne et al. Fabrication and Characterization of Yb3+: Er3+ Phosphosilicate Fibers for Lasers, Journal of Lightwave Technology. November 1998. Vol. 10, No. 9. pgs. 1990-2001	1-55
A	Hofer et al. High-Power Side-Pumped Passively Mode-Locked Er-Yb Fiber Laser. IEEE Photonics Technology Letters, Vol. 10, No. 9. September 1998. Pgs. 1247-1249.	1-55