A compact single frequency, single-mode 2 μm fiber laser with narrow linewidth, <100 kHz and preferably <100 kHz, is formed with a low phonon energy glass doped with triply ionized rare-earth thulium and/or holmium oxide and fiber gratings formed in sections of passive silica fiber and fused thereto. Formation of the gratings in passive silica fiber both facilitates splicing to other optical components and reduces noise thus improving linewidth. An increased doping concentration of 0.5 to 15 wt. % for thulium, holmium or mixtures thereof produces adequate gain, hence output power levels for fiber lengths less than 5 cm and preferably less than 3 cm to enable single-frequency operation.

27 Claims, 4 Drawing Sheets
U.S. PATENT DOCUMENTS

6,567,432 B1 5/2003 Kim et al.
6,570,893 B1 5/2003 Libatique et al.
6,603,779 B1 8/2003 Pedersen et al.

OTHER PUBLICATIONS


* cited by examiner
SINGLE-FREQUENCY NARROW LINewidth 2 µm FIBER LASER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of priority under 35 U.S.C. 120 and is a continuation in part of U.S. application Ser. No. 10/056,830 entitled “Rare-Earth Doped Phosphate-Glass Single-Mode Fiber Lasers” filed on Jan. 24, 2002, now U.S. Pat. No. 6,816,514, the entire contents of which are incorporated by reference.

GOVERNMENTAL RIGHTS

This invention was made with Government support under Contract NNL05AA94P awarded by NASA. The government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to fiber lasers and more specifically to a single frequency 2 µm fiber laser with narrow linewidth (<100 kHz and preferably <10 kHz) formed from glass fibers doped with Thulium and Holmium oxides and mixtures thereof.

2. Description of the Related Art

Rare-earth doped glass fiber lasers were first proposed in the 1960s and have received considerable attention in the 1980s for potential applications in optical communications. For laser emission to occur, the active fiber is placed inside a resonant cavity. The optical feedback can be provided simply by the reflectivity of the end facets, by mirrors, by distributed feedback Bragg (DBR) gratings, or by distributed Bragg reflectors (DBR), or by constructing a ring cavity structure. Laser emission occurs when the total gain overcomes the losses in the cavity. Hence, a minimum gain has to be achieved to reach the laser threshold condition. Typical fiber lasers lase in a great number of longitudinal modes in single transverse mode optic fibers, the so-called “single mode fibers”. A “single frequency” fiber laser lases at a single longitudinal mode.


2 µm lasers are important because of the high transmission property in air at that wavelength. Applications such as seeders lasers, LIDAR, optical heterodyne systems, nonlinear frequency conversion, coherent satellite communication, and distributed sensing require a robust 2 µm, e.g. typically 1.8–2.1 µm, single frequency narrow linewidth fiber laser. Single-frequency operation with a linewidth less than 100 kHz, preferably less than 10 kHz, provides both the resolution and long coherence needed by these applications. The 2 µm laser would preferably have sufficient output power without the need for a booster amplifier in order to maintain the high signal to noise ratio.

Current 2 µm single frequency laser technology is limited to solid state lasers, which are either configured to use an intracavity diode pumped etalon in conjunction with an external reference etalon (U.S. Pat. No. 5,457,706 to McGuckin) or as a non-planar ring oscillator (NPRO) in the presence of a sufficiently strong magnetic field (U.S. Pat. Nos. 4,578,793 and 5,043,996).


SUMMARY OF THE INVENTION

The present invention provides a compact single frequency, single-mode 2 µm fiber laser with narrow linewidth. The 2 µm fiber laser includes a gain fiber formed of a low phonon energy glass host, either fluoride based or an oxide-based multi-component glass such as germanate or tellurite, that is doped with triply ionized rare-earth thulium or holmium oxide or mixtures thereof. Erbium and ytterbium may be used to absorb and transfer pump energy to the active ions. Fiber gratings are formed in sections of passive silica fiber and fused to the gain fiber to form the resonant cavity. A doping concentration of 0.5 to 15 wt. % for either thulium or holmium oxides or mixtures thereof produces adequate gain, hence output power levels for fiber lengths less than 5 cm and preferably less than 3 cm to enable stable single-frequency operation. Formation of the gratings in passive silica fiber both facilitates splicing to other optical components and reduces noise thus improving linewidth. The pump can be a multimode or single mode laser. In the case of a single mode laser, the use of a polarization maintaining (PM) fiber in the pump source further improves wavelength stability, linewidth and vibration/RF sensitivity.

In another embodiment, the gain fiber is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active ions experience an anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization fluctuations inside the laser cavity.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:
BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a single-frequency fiber laser in accordance with the present invention; FIG. 2 is a plot of the absorption spectra of thulium and holmium doped glasses; FIG. 3 is a diagram of the longitudinal mode spacing and grating bandwidth that produce a single-frequency output; FIG. 4 is a sectional view of the gain fiber; FIGS. 5a and 5b are diagrams of a packaged single-frequency fiber laser including temperature control and vibration isolation; and FIG. 6 is a diagram of a pump source with a PM fiber.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a compact single frequency, single-mode 2 μm fiber laser with narrow linewidth, less than 100 kHz and preferably less than 10 kHz. As shown in FIGS. 1 through 4, a 2 μm fiber laser 10 includes a single mode gain fiber 12 formed of a low phonon energy glass host doped with triply ionized rare-earth thulium or holmium oxide or mixtures thereof. Erbium or ytterbium dopants may also be used to absorb and then transfer pump energy to the active ions. The low phonon energy glass host is selected from either an oxide-based multi-component germanate or tellurite glasses or a fluoride based glass. These host glasses have sufficiently low phonon energy to slow down the multi-phonon relaxation process. Narrowband and broadband fiber gratings 14 and 16, respectively, are formed in sections of passive silica fiber 18 and 20 and fused to the ends of gain fiber 12 to form a resonant cavity that provides the feedback necessary to sustain laser operation. The reflectivity of the broadband grating 16 should be as close to 100% as possible. The reflectivity of the narrowband grating 14 is less than 100%, suitably 30-90% depending upon the pump power and target output power, such that power can be removed from the cavity. Alternately, the broadband grating could be used to output couple the laser energy.

The low phonon energy glasses (germanate, tellurite and fluoride) exhibit high quantum efficiency for the 2 μm transition. These glasses also support the high doping concentrations required to provide sufficient gain in short fiber lengths to achieve both single frequency operation and narrow linewidths. The holmium oxide (Ho₂O₃) or thulium oxide (Tm₂O₃) doping concentration is 0.5-15 wt. %. If co-doped, the thulium/holmium concentration can range from 0.5 to 15 wt. %. The formation of the gratings in passive silica fiber rather than the gain fiber reduces ASE noise, which improves linewidth. As will be described with reference to FIGS. 5a and 5b, thermal stabilization and vibration isolation of the gain fiber and gratings and the use of a polarization maintaining (PM) fiber in the pump source further improve and maintain linewidth in commercial applications.

A source of pump radiation 22, e.g. a single-mode or multi-mode laser diode, illuminates gain fiber 12 at a wavelength, typically 800 nm, within the absorption band. As shown in FIG. 2, the absorption band 24a of triply ionized thulium occurs from 750 to 820 nm. The pump wavelength can be around 1.2 μm and 1.7 μm to excite Thulium from ⁴H₅ state to ⁴F₇ and ⁴F₅ levels. The absorption band 24b of triply ionized holmium occurs from 1800 to 2100 nm. The pump wavelength can be around 1800 μm and 2100 μm to excite Holmium from ¹I₉ to ¹I₇ levels. Typically one excites thulium ions, which in turn transfers energy to the holmium ions. The pump wavelength can also be shifted to other wavelengths to excite Yb and Er when these ions are doped into the host. Pumping of the doped glass populates the thulium upper level creating a population inversion. Synchronous emission catalyzes the stimulated emission of the thulium (holmium) ions in the upper level over a range of 1800 to 2000 nm (1900 to 2200 nm). The emission peak of thulium (holmium) occurs at a wavelength of approximately 1800 nm (2080 nm).

Laser emission occurs when the total gain produced by stimulated emission overcomes the losses in the cavity. The gain profile of thulium and holmium and the geometry of the resonant cavity create preferential feedback so that laser emission only occurs at one or more discrete wavelengths. As shown in FIG. 3, an ultra-short cavity, less than 5 cm and preferably less than 3 cm, produces a mode spacing 4 Av that is at least comparable to and preferably larger than the linewidth 30 (full-width half-max of the peak) of the narrowband grating (less than 0.07 nm), which together with the gain spectrum 31 limits laser emission to a single longitudinal mode 32. Therefore, a very high gain per unit length is needed in order to achieve single frequency fiber laser operation if a linear cavity is used. The gain per unit length required here typically exceeds normally achievable value. Glasses with high doping concentration and fibers with high gain per unit length are required. In addition, a fusion splicing technique with a short working distance between the active fiber and the gratings is needed.

To achieve single-frequency performance the glass host must support high Thulium and Holmium doping concentrations to realize the necessary gain per unit length. The doping concentrations are at least 0.5 wt. % and typically about 1-8 wt. %. Therefore, glasses with good rare-earth ion solubility must be selected.

Suitable oxide-based multi-component laser glasses contain either a germanate-oxide (GeO₂) or tellurite-oxide (TeO₂) network former, one or more glass network modifiers including alkaline-earth oxides and transition metal oxides MO such as BaO, CaO, MgO, SrO, ZnO, PbO and mixtures thereof and/or alkali metal oxides RO such as Na₂O, Li₂O and K₂O and mixtures thereof, and one or more glass network intermediaries L₂O, such as Y₂O₃, La₂O₃, Al₂O₃, B₂O₃, WO and mixtures thereof. The modifier modifies the glass network, thereby reducing its melting temperature and creating additional dopant sites. The intermediate bridges some of the bonds in the network thereby increasing the network’s strength and chemical durability without raising the melting temperature appreciably. The glass host composition by weight percent is 30 to 85% network former, 2 to 50% modifier including 0-10% MO and 0-20% RO, and 0.2 to 50% intermediate. Typically, the intermediate is at least 2 wt. % and suitably 10 wt. % and the total modifier is at least 2 wt. % and suitably 25 wt. %.

As shown in FIG. 4, the fiber core 40 is made up of the glass host doped with high concentrations of thulium or holmium oxide or mixtures thereof. The cladding layer(s) 42 are formed from the same glass host, although the exact composition may vary somewhat from the core glass, and are typically undoped. Numerous glass compositions were characterized for thermal properties (crystallization, expansion coefficient, transition and softening temperatures, core-to-clad similarity), chemical durability, ability to host high Tm (Ho) doping concentrations without quenching, spectroscopic properties (maximum emission cross-section at 2.0 microns), linewidth (maximum breadth at 2.0 microns) and refractive index to determine a range of wt. % for each
ingredient that are acceptable. Suitable glass compositions for germinate host glasses are illustrated in Tables 1 and 2 and tellurite host glasses are illustrated in Table 3, respectively.

### TABLE 1

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<tr>
<th>Composition</th>
<th>Wt %</th>
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### TABLE 3

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<th>Composition</th>
<th>Wt %</th>
<th>Na₂O</th>
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<th>B₂O₃</th>
<th>TeO₂</th>
<th>TmO₂</th>
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<td>100</td>
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Based on this empirical data, a first exemplary embodiment of a suitable core laser glass may comprise by weight percent:

- 45 to 70 GeO₂;
- 0.5 to 20 L₂O₃ selected from Al₂O₃, B₂O₃ and La₂O₃ and mixtures thereof;
- 2 to 20 MO selected from BaO, CaO and MgO and mixtures thereof;
- 2 to 30 R₂O selected from Na₂O, Li₂O, and K₂O and mixtures thereof; and
- 0.5–15 Ho₂O₃, Tm₂O₃ and mixtures thereof.

Based on this empirical data, a second exemplary embodiment of a suitable core laser glass may comprise by weight percent:

- 45 to 85 TeO₂;
- 0.5 to 15 L₂O₃ selected from Al₂O₃, B₂O₃ and La₂O₃ and mixtures thereof;
In another embodiment, the gain fiber 12 is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active ions experience an anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization fluctuations inside the laser cavity.

The subclass of multi-component glasses has a much lower softening temperature (<600°C) than silica (>1200°C), which greatly simplifies the fiber drawing process and supports higher doping concentrations but complicates the process of fusion splicing to silica fiber. A quality fusion splice should exhibit low optical loss (<0.3 dB), low back reflection loss (<50 dB) and good tensile strength (>100 g).

A standard silica-to-silica fusion splice degrades the multi-component fiber. Instead an asymmetric process that softens vibrations or acoustic pressure waves. The polarization anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization fluctuations inside the laser cavity.

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A standard silica-to-silica fusion splice degrades the multi-component fiber. Instead an asymmetric process that softens vibrations or acoustic pressure waves. The polarization anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization fluctuations inside the laser cavity.

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a glass modifier of 2 to 50 percent including (a) MO of 0 to 20 percent, where MO is selected from BaO, BeO, MgO, SrO, CaO, ZnO, PbO, and mixtures thereof, and (b) R,O of 0 to 20 percent, where R,O is selected from Na,O, Li,O and K,O and mixtures thereof.

7. The fiber laser of claim 6, wherein the glass includes by weight percentages,
   45 to 70 GeO,;
   0.5 to 20 Li,O;
   2 to 20 MO; and
   2 to 30 R,O,
   wherein L,O, is selected from Al,O,, B,O,, La,O, and MO is selected from BaO, CaO and MgO.

8. The fiber laser of claim 6, wherein the glass includes by weight percentages,
   45 to 85 TeO,;
   0.5 to 15 Li,O,; and
   0.5 to 20 R,O,
   wherein L,O, is selected from Al,O,, B,O,, and La,O,.

9. The fiber laser of claim 6, wherein the glass includes by weight percentages,
   45 to 85 TeO,;
   10 to 45 WO,; and
   0.5 to 20 R,O,
   wherein L,O, is selected from Al,O,, B,O,, and La,O,.

10. The fiber laser of claim 1, wherein the gain fiber is less than 5 cm in length.

11. The fiber laser of claim 1, wherein the gain fiber is a polarization maintaining (PM) fiber.

12. The fiber laser of claim 11, wherein the polarization whose stimulated emission cross section of the gain fiber is higher is aligned to the orientation of the operating polarization of the narrow-band fiber Bragg grating.

13. The fiber laser of claim 11, wherein the mode spacing is greater than 0.07 nm.

14. The fiber laser of claim 1, wherein the narrowband grating has a linewidth less than 0.07 nm and the broadband grating has a linewidth between 0.07 nm and 0.4 nm.

15. A fiber laser, comprising:
   A gain fiber less than 5 cm in length including,
   A cladding formed from fluoride, germanate or tellurite glass host; and
   A single mode core formed from the same glass host doped with 0.5–15% thulium or holmium oxide or mixtures thereof;
   A passive silica fiber having a narrowband grating formed therein and fused at one end of the gain fiber;
   A passive silica fiber having a broadband grating formed therein and fused at the other end of the gain fiber, and
   A source of pump radiation that illuminates the fiber so that said fiber outputs a single-frequency signal having a center wavelength at approximately 2 μm.

16. The fiber laser of claim 15, wherein the glass is doped with 1–8 wt. % thulium or holmium oxide.

17. The fiber laser of claim 15, wherein the glass includes by weight percentages,
   a network former of 30 to 85 percent, where the network former is selected from germanate-oxide (GeO,) or tellurite-oxide (TeO,);
   a glass intermediately L,O, of 0.5 to 50 percent, where L,O, is selected from Al,O,, B,O,, Y,O,, La,O, and WO, and mixtures thereof, and
   a glass modifier of 2 to 50 percent including (a) MO of 0 to 20 percent, where MO is selected from BaO, BeO, MgO, SrO, CaO, ZnO, PbO, K,O, Li,O and K,O and mixtures thereof, and
   (b) R,O of 0 to 20 percent, where R,O is selected from Na,O, Li,O and K,O and mixtures thereof.

18. The fiber laser of claim 15, wherein the source of pump radiation and/or the gain fiber includes a polarization maintaining (PM) fiber.

19. The fiber laser of claim 15, wherein the narrowband grating has a linewidth less than 0.07 nm and the broadband grating has a linewidth between 0.07 nm and 0.4 nm, said narrowband and broadband gratings forming a resonant cavity less than 5 cm in length with a mode spacing that is greater than 0.07 nm so that said single-frequency signal has a linewidth less than 10 kHz.

20. A fiber laser, comprising:
   A gain fiber less than 5 cm in length including,
   A core formed from an oxide-based multi-component glass host including by weight percentage a network former of 30 to 85 percent selected from germanate-oxide (GeO,) or tellurite-oxide (TeO,), a glass intermedium L,O, of 0.5 to 50 percent selected from Al,O,, B,O,, Y,O,, La,O,, WO, and mixtures thereof, and a glass modifier of 2 to 50 percent including (a) MO of 0 to 20 percent selected from BaO, BeO, MgO, SrO, CaO, ZnO, PbO, K,O, Li,O and K,O and mixtures thereof, and (b) R,O of 0 to 20 percent selected from Na,O, Li,O and K,O and mixtures thereof, said glass host being doped with 0.5–15 weight percent thulium or holmium oxide or mixtures thereof; and
   A cladding formed from the same glass host;
   A narrowband grating at one end of the fiber;
   A broadband grating at the other end of the fiber; and
   A source of pump radiation that illuminates the fiber so that the dopant oxide ions lase at a single longitudinal mode and said fiber outputs a single-frequency signal having a center wavelength at approximately 2 μm.

21. The fiber laser of claim 20, wherein the narrowband and broadband gratings are formed in sections of passive silica fiber that are fusion spliced to the ends of the gain fiber.

22. The fiber laser of claim 21, wherein the narrowband grating has a linewidth less than 0.07 nm and the broadband grating has a linewidth between 0.07 nm and 0.4 nm, said narrowband and broadband gratings forming a resonant cavity less than 5 cm in length with a mode spacing that is greater than 0.07 nm so that said single-frequency signal has a linewidth less than 10 kHz.

23. The fiber laser of claim 20, wherein the single-mode signal has a linewidth of less than 10 kHz.

24. The fiber laser of claim 20, wherein the glass is doped with 1–8 wt. % thulium or holmium oxide.

25. The fiber laser of claim 20, wherein the glass includes by weight percentages,
   45 to 70 GeO,;
   0.5 to 20 Li,O,; and
   2 to 30 R,O,
   wherein L,O, is selected from Al,O,, B,O,, La,O, and MO is selected from BaO, CaO and MgO.

26. The fiber laser of claim 20, wherein the glass includes by weight percentages,
   45 to 85 TeO,;
   0.5 to 15 Li,O,; and
   0.5 to 20 R,O,
   wherein L,O, is selected from Al,O,, B,O,, La,O, and MO is selected from BaO, CaO and MgO.

27. The fiber laser of claim 20, wherein the glass includes by weight percentages,
   45 to 85 TeO,;
   10 to 45 WO,; and
   0.5 to 20 R,O.