

Description

The present invention relates to fiber amplifiers having means for selectively attenuating or removing unwanted wavelengths to modify or control the amplifier gain spectrum.

5 Doped optical fiber amplifiers consist of an optical fiber the core of which contains a dopant such as rare earth ions. Such an amplifier receives an optical signal of wavelength λ_s and a pump signal of wavelength λ_p which are combined by means such as one or more couplers located at one or both ends of the amplifier. The spectral gain of a fiber amplifier is not uniform through the entire emission band.

The ability to modify the gain spectrum of a fiber amplifier is useful. Three modifications are of interest: 10 (1) gain flattening, (2) changing the gain slope, and (3) gain narrowing. Gain flattening is of interest for such applications as wavelength division multiplexing. A change in the gain slope can be used to reduce harmonic distortion in AM modulated optical systems (see A. Lidgard et al. "Generation and Cancellation of Second-Order Harmonic Distortion in Analog Optical Systems by Interferometric FM-AM Conversion" IEEE Phot. Tech. Lett., vol. 2, 1990, pp. 519-521). Gain narrowing is of interest because although the amplifier can be operated at 15 wavelengths away from the peak gain without gain narrowing, disadvantages occur due to: increased spontaneous-spontaneous beat noise, a reduction in gain at the signal wavelength because of amplified spontaneous emission at a second wavelength (such as at 1050 nm in a Nd fiber amplifier designed to amplify at 1300 nm), and possible laser action at the peak gain wavelength.

Various techniques have been used for flattening the gain spectrum. An optical notch filter having a Lorentzian spectrum can be placed at the output of the erbium doped gain fiber to attenuate the narrow peak. A smooth gain spectrum can be obtained, but with no increase in gain at longer wavelengths.

Another filter arrangement is disclosed in the publication, M. Tachibana et al. "Gain-Shaped Erbium-Doped Fibre Amplifier (EDFA) with Broad Spectral Bandwidth", Topical Meeting on Amplifiers and Their Applications, Optical Society of America, 1990 Technical Digest Series, Vol. 13, Aug. 6-8, 1990, pp. 44-47. An optical notch 25 filter is incorporated in the middle of the amplifier by sandwiching a short length of amplifier fiber between a mechanical grating and a flat plate. This induces a resonant coupling at a particular wavelength between core mode and cladding leaky modes which are subsequently lost. Both the center wavelength and the strength of the filter can be tuned. The overall gain spectrum and saturation characteristics are modified to be nearly uniform over the entire 1530-1560 nm band. By incorporating the optical filter in the middle of the erbium doped fiber amplifier, the amplifier efficiency is improved for longer signal wavelengths.

International patent application No. WO 91/18434, which constitutes prior art falling within the terms of Article 54(3) EPC, discloses a fiber amplifier comprising a gain optical fiber having a single-mode core containing dopant ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of a wavelength λ_p . Means are provided for introducing a signal of wavelength λ_s and pump light of wavelength λ_p into the gain fiber. The amplifier includes 35 absorbing ion filtering means for attenuating light at least at some of the wavelengths within the predetermined band of wavelengths.

EP-A-426222 discloses a fiber amplifier comprising a gain fiber having a single-mode core containing erbium ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of a wavelength λ_p . Samarium ions contained in the gain fiber enable it to absorb spontaneous erbium emission which would constitute a noise source.

Summary of the Invention

45 An object of the present invention is to further improve the efficiency of a fiber amplifier and/or tailor the spectral output of a fiber amplifier.

The present invention relates to a fiber amplifier comprising a gain optical fiber having a single-mode core containing dopant ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p . Means introduces a signal of wavelength λ_s into the gain fiber input end, and 50

means introduces pump light of wavelength λ_p into the gain fiber. Absorbing ion filtering means attenuates light at at least some of the wavelengths within the predetermined band of wavelengths. The invention is characterized in that the absorbing ion filtering means comprises unpumped gain ions, and in that the amplifier further comprises means for preventing the excitation of the unpumped gain ions by light of wavelength λ_p .

55 In one embodiment, the invention is characterized in that the gain fiber means includes first and second gain optical fiber sections. The amplifier further includes first and second pump light-attenuating fiber sections, each having a core containing a dopant that attenuates optical power in at least one wavelength band including the wavelength λ_p , while optical power at the wavelength λ_s remains substantially unattenuated there-

by. The first end of each of the pump light-attenuating fiber sections is spliced to a respective one of the second ends of the gain fiber sections. The ends of the filtering fiber are respectively connected to the second ends of the pump light attenuating fiber sections, the filtering fiber being doped with the dopant gain ions for filtering the signal light. The pump light introducing means introduces pump light into the first end of each of the gain fiber sections, and the signal introducing means introduces a signal into the first end of one of the gain fiber sections, the gain ions of the filtering fiber remaining unexcited during operation because of the pump light filtering action of the pump light-attenuating fiber.

Brief Description of the Drawings

Fig. 1 is a schematic illustration of a fiber amplifier in accordance with the present invention.
 Fig. 2 is a graph showing the gain spectra of an erbium-aluminum-doped germania silicate fiber amplifier.
 Fig. 3 is a schematic illustration showing a fiber amplifier in accordance with the invention.
 Fig. 4 is a schematic illustration of an embodiment wherein pump light attenuating means is in series with the gain fiber.
 Fig. 5 is a graph illustrating the spectral transmission characteristic of an unpumped erbium-aluminum-doped germania silicate fiber that can be employed in the embodiment of Fig. 4.
 Figs. 6 and 7 are graphs showing gain spectra and spectral transmission for a further mode of operation of Fig. 4.
 Fig. 8 illustrates a fiber amplifier in which the pump light attenuating means is an optical fiber.
 Fig. 9 is a schematic illustration of a reverse pumped fiber amplifier.
 Fig. 10 is a schematic illustration of a dual ended device.
 Figs. 11, 12, and 13 are schematic illustrations of fiber amplifier embodiments in which the gain ion-doped signal filtering means is in series with the gain fiber.
 Fig. 14 is a schematic illustration of a fiber amplifier embodiment in which the gain ion-doped signal filtering means is distributed along the gain fiber.
 Fig. 15 is a graph illustrating the radial distribution of signal and pump power within the gain fiber of Fig. 14.
 Fig. 16 is a schematic illustration of a fiber amplifier embodiment in which the gain ion-doped signal filtering means is contained within a fiber that extends along the gain fiber.
 Fig. 17 is a graph illustrating the radial distribution of signal and pump power within coupler 83 of Fig. 16.
 Figs. 18 and 19 are schematic illustrations of fiber amplifiers not in accordance with the present invention in which the absorbing ions of the signal filtering means are different from the gain ions.

Description of the Preferred Embodiments

Fiber amplifiers typically include a gain fiber 10 (Fig. 1), the core of which is doped with gain ions that are capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p that is outside the predetermined band. A wavelength division multiplexer (WDM) fiber optic coupler 11 can be used for coupling pump energy of wavelength λ_p from laser diode 15 and the signal of wavelength λ_s from input telecommunication fiber 14 to gain fiber 10. Such devices are disclosed in U.S. Patents Nos. 4,938,556, 4,941,726, 4,955,025 and 4,959,837. Fusion splices are represented by large dots in the drawings. Input fiber 14 is spliced to coupler fiber 13, and gain fiber 10 is spliced to coupler fiber 12. Splice losses are minimized when coupler 11 is formed in accordance with the teachings of copending U.S. Patent Application S.N. 671,075 (Hall 4-6-2-4) filed March 18, 1991.

Various fiber fabrication techniques have been employed in the formation of rare earth-doped amplifying and absorbing optical fibers. A preferred process, which is described in copending U.S. Patent Application S.N. 07/715,348 (R.F. Bartholomew et al. 18-1) filed June 14, 1991, is a modification of a process for forming standard telecommunication fiber preforms. In accordance with the teachings of that patent application, a porous core preform is immersed in a solution of a salt of the dopant dissolved in an organic solvent having no OH groups. The solvent is removed, and the porous glass preform is heat treated to consolidate it into a non-porous glassy body containing the dopant. The glassy body is provided with cladding glass to form a draw preform or blank that is drawn into an optical fiber. The process can be tailored so that it results in the formation of a fiber having the desired MFD. The porous core preform could consist solely of core glass, or it could consist of core glass to which some cladding glass has been added. By core glass is meant a relatively high refractive index glass, e.g. germania silicate glass, that will form the core of the resultant optical fiber.

If the rare earth ions are to extend to a region of the resultant fiber beyond the core, then the porous core preform that is immersed in dopant containing solvent must contain a central core glass region and a suffi-

ciently thick layer of cladding glass. After the resultant doped, cladding-covered core preform has been consolidated, it is provided with additional cladding glass and drawn into a fiber.

If too much rare earth dopant is added to a GeO_2 -doped silica core, the core can crystallize. Such higher rare earth dopant levels can be achieved without crystallization of the core glass by adding Al_2O_3 to the core.

5 As indicated above, it is sometimes desirable to modify the gain spectrum of a fiber amplifier. Since the erbium-doped fiber amplifier has utility in communication systems operating at 1550 nm, that fiber amplifier is specifically discussed herein by way of example. The invention also applies to fiber amplifiers containing gain ions other than erbium, since the gain spectrum of such other fiber amplifiers can also be advantageously modified. As shown by curve 23 of Fig. 2, the gain spectra of an erbium-aluminum-doped germania silicate
10 fiber amplifier has a peak around 1532 nm and a broad band with reduced gain to about 1560 nm. It is sometimes desirable to reduce the 1532 nm peak to prevent the occurrence of such disadvantageous operation as wavelength dependent gain or gain (with concomitant noise) at unwanted wavelengths. Alternatively, it may be desirable to provide the fiber amplifier gain spectrum with a plurality of peaks so the amplifier can operate at a plurality of discrete wavelengths.

15 In accordance with the present invention, the amplifier spectral gain curve is altered by providing the fiber amplifier with filtering means 17 which includes absorbing ions that modify the gain spectrum by attenuating the amplified signal at various wavelengths in the gain spectrum. In accordance with the invention the absorbing ions are the same rare earth "gain ions" as the active gain ions in gain fiber 10; however, these absorbing gain ions must remain unpumped by light at wavelength λ_p . Such unpumped "gain ions" can be located in a
20 fiber that is in series with gain fiber 10, or they can be distributed along the pumped gain fiber ions of gain fiber 10 but be located at a radius that is sufficiently greater than that of the pumped gain ions that they are substantially unpumped and yet influence the propagation of light of wavelength λ_s . The invention is further discussed in conjunction with Figs. 2 through 17.

In accordance with a fiber amplifier not in accordance with the invention, the absorbing ions are different
25 from the rare earth gain ions of gain fiber 10; such absorbing ions remain unexcited when subjected to light at wavelength λ_p . The absorbing ions can be positioned as follows: (a) they can be used to co-dope the gain fiber such that they are distributed along with the gain ions (optionally at the same radius as the gain ions), or (b) they can be incorporated into the core of a fiber that is connected in series with gain fiber 10. This further aspect which is not in accordance with the invention is further discussed in conjunction with Figs. 18 and 19.

30 In the figures discussed below, elements similar to those of Fig. 1 are represented by primed reference numerals.

Fig. 3 generally illustrates the invention wherein the absorbing ions are the same rare earth "gain ions" as the active dopant ions in the gain fiber. The fiber amplifier system includes unpumped gain ion filtering means 27 for altering the amplifier spectral gain curve. The unpumped gain ions can be located in series with
35 the pumped gain fiber ions of gain fiber 10', or they can be distributed along the pumped gain fiber ions as discussed below in conjunction with Figs. 14 and 15.

Fig. 4 shows that the unpumped gain ion filtering means can be located in series with the pumped gain fiber ions of fiber 10'. In the absence of an input signal at fiber 14', high levels of pump light can emanate from gain fiber 10'. Furthermore, some fiber amplifiers, especially those based on a three level laser system, are
40 pumped at a power level that is sufficiently high that some remnant pump light emanates from the output end of gain fiber 10'. The presence of pump light along with the amplified signal at output end 30 of gain fiber 10' is indicated by the arrow labeled $\lambda_s + \lambda_p$. Means 31 substantially attenuates the remnant pump light, i.e. only an insignificant level of pump light, if any, remains. However, means 31 leaves the signal light at wavelength λ_s substantially unattenuated, i.e. it attenuates signal light less than about 0.5 dB. The arrow at the output of
45 means 31 is therefore labelled λ_s . A length 32 of fiber doped with gain ions is spliced to the output end of attenuating means 31.

If fiber 10' of Fig. 4 has a germania silicate core doped with erbium and aluminum, for example, fiber 32 can also be doped with erbium or a combination of dopants including erbium. Fig. 5 shows the spectral transmission characteristic of an optical fiber having a germania silicate core doped with aluminum and unpumped
50 erbium ions. The reduced transmission between about 1525 and 1560 nm is caused by the absorption of light at those wavelengths by erbium ions. The depression in transmission curve 34 at 1532 nm corresponds to the gain peak in curve 23 of Fig. 2. If fibers 10' and 32 of Fig. 4 are both co-doped with aluminum and erbium ions, the effect of absorbing fiber 32 will be to flatten the spectral gain curve of the resultant fiber amplifier (see curve 24 of Fig. 2).

55 If gain ion-doped fiber 32 of Fig. 4 had a germania silicate core doped with unpumped erbium ions, its absorption spectra would be represented by curve 35 of Fig. 6. If fiber 10' had the previously described core whereby its gain spectra was represented by curve 23 of Fig. 2, the net gain spectra of the resultant fiber amplifier would be that of Fig. 7. Such an amplifier can operate at three discrete wavelengths along curve 36 where

peaks a, b and c are located.

The performance of the gain-ion doped filtering fiber may be improved by quenching the Er fluorescence to minimize signal induced bleaching of the absorption. The Er fluorescence can be quenched by adding dopants such as B or OH to the fiber or by increasing the doping density of Er in the absorbing fiber, for example, to levels above 500 ppm in $\text{SiO}_2\text{-GeO}_2$ fibers.

Attenuating means 31 of Fig. 4 could consist of a pump light reflector such as a fiber-type grating reflector of the type disclosed in the publication: K.O. Hill et al. "Photosensitivity in Optical Fiber Waveguides: Application to Reflection Filter Fabrication" Applied Physics Letters, vol. 32, pp. 647-649, (1978).

In the embodiment of Fig. 8, the pump light attenuating means is a fiber 38 that is spliced between gain fiber 10' and gain ion-doped fiber 32'. Fiber 38 must sufficiently attenuate light of wavelength λ_p that within a relatively short length, e.g. less than 20 m, the pump power at its output end 39 is attenuated to an insignificant level while signal light at wavelength λ_s is not unduly attenuated. Attenuating fiber 38 must be tailored to the specific gain fiber and pump wavelength. If the gain fiber 10' is an erbium-doped optical fiber that is pumped at a wavelength of 980 nm, fiber 38 can be doped with ytterbium, for example. Table 1 lists dopant candidates for use in pump light-absorbing fibers to be employed in conjunction with gain fibers doped with Er, Nd and Pr.

Table 1

Gain Ion	Wavelength		Absorbing Ion or Center
	Signal	Pump	
Er	1.52-1.6 μm	980 nm	Yb, Dy, Pr, V, CdSe
Er	1.52-1.6 μm	1480 nm	Pr, Sm
Er	1.52-1.6 μm	800 nm	Nd, Dy, Tm, V, CdSe
Nd	1.25-1.35 μm	800 nm	Dy, Er, Tm, V, CdSe
Pr	1.25-1.35 μm	1000 nm	Dy, Er, Yb, V,

Curves of absorptivity v. wavelength were used in selecting the rare earth ions and the transition metal (vanadium) ion. The CdSe should be present in the absorbing fiber in the form of micro crystallites.

The light attenuating fiber means of this invention is also useful in fiber amplifiers employing alternate pumping schemes. In the counter-pumping device of Fig. 9, wherein elements similar to those of Fig. 8 are represented by primed reference numerals, gain fiber 10' is connected to input fiber 14' by attenuating fiber 38' and gain ion-doped fiber 32'. Pumping light of wavelength λ_p is coupled to gain fiber 10' by coupler 41 which also couples the amplified signal to output fiber 20'. Attenuating fiber 38' removes pump light that would have excited the gain ions in fiber 32'. Since the gain ions in fiber 32' remain unexcited by pump light, fiber 32' filters the incoming signal.

In the dual-ended device of Fig. 10, coupler 43 couples the signal from input telecommunication fiber 45 and pumping power from first pump source 44 to gain fiber section 46a, as described in conjunction with Fig. 4. Coupler 47 couples pumping power from second pump source 48 to gain fiber section 46b. The output signal of wavelength λ_s is coupled by coupler 47 from gain fiber section 46b to outgoing telecommunication fiber 50. Pump light attenuating fibers 52a and 52b are spliced to gain fiber sections 46a and 46b. A length 53 of fiber doped with gain ions is spliced between attenuating fiber sections 52a and 52b. In the absence of the attenuating fiber sections, remnant pump light from sources 44 and 48 would be coupled from the gain fiber sections 46a and 46b, respectively, to gain ion-doped fiber 53, thereby negating its filtering ability. Since the characteristics of fiber 53 are similar to those of fiber 32' of Fig. 8, the fiber amplifier is provided with a modified spectral gain.

The signal is first introduced into section 46a where it gradually increases in amplitude due to amplification in that section. The amplitude of the signal that is introduced into section 46b is therefore much greater than that which was introduced into section 46a. The pump power is therefore absorbed at a greater rate per unit length in section 46b, and section 46b can be shorter than section 46a.

In the embodiment of Fig. 11 the length of gain fiber 57 is sufficient to dissipate all of the pump light from source 15' so that essentially no pump light reaches end 58 thereof. Gain ion-doped fiber 32' can therefore filter the amplified signal. However, for lowest noise amplification, an adequate pump light intensity should exist throughout the amplifier medium. The amplifier of Fig. 11 therefore generates more noise than previously described embodiments.

Gain fiber 62 of Fig. 12 can be provided with pump power from either or both of the couplers 60 and 61. This embodiment pertains to forward pumped, reverse pumped and double pumped fiber amplifiers. In the reverse pumped embodiment, coupler 60 is unnecessary. In all cases, the signal is amplified by gain fiber 62 and coupled to outgoing telecommunication fiber by coupler 61. In the reverse pumping mode, pump light propagates from coupler 61 into end 65 of gain fiber 62. In the forward and double pump situations, only a small fraction of the remnant pump light exiting output end 65 of fiber 62 is coupled to coupler fiber 66. Since gain ion-doped fiber 64 remains essentially unpumped, it filters the amplified signal light that is coupled to outgoing telecommunication fiber 63.

Fig. 13 shows a simplified embodiment wherein filtering fiber 74 contains a dopant that absorbs pump light; it also contains gain ions for altering the amplifier spectral gain curve. The concentration of the pump light attenuating ions is such that their absorption is much greater than that of the gain ions in fiber 74. For example, the absorption of pump light might be ten times the absorption of signal light. Thus, the remnant pump light is absorbed within a short distance of the input end 75 of fiber 74. The remainder of fiber 74 filters the amplified signal from fiber 10'.

In the embodiment of Fig. 14, gain fiber 79 itself is designed such that it contains dopant ions at a sufficiently large radius that only the relatively large mode field of the signal light reaches the large radii dopant ions. As shown in Fig. 15, the signal field extends to a greater radius in gain fiber 79 than the pump field. If the signal field extends to radius r_2 , the erbium ions, for example, should also extend to a radius of about r_2 . Since Er ions having radii larger than about r_1 remain unpumped, those large radii Er ions are available for filtering the signal.

The embodiment of Fig. 16 employs a fiber optic coupler-type device 83 that is formed by fusing together a gain fiber 81 and a gain ion doped signal attenuating fiber 82. Device 83 can be similar to the overlaid coupler of the type disclosed in U.S. patent 4,931,076 or the fused fiber coupler of the type disclosed in T. Bricheno et al. "stable Low-Loss single-Mode Couplers" Electronics Letters, vol. 20, pp. 230-232 (1984). Pump light and signal light are coupled to gain fiber 81 from input coupler fiber 12'. The fibers 81 and 82 of coupler 83 have sufficiently different propagation constants that, because of the resultant $\Delta\beta$, no coupling occurs. However, the large radius signal field from gain fiber 81 significantly overlaps the absorbing region of fiber 82 in that portion of the coupler where fibers 81 and 82 are fused together and stretched to decrease the distance between cores. Since there is a negligible overlap of the smaller radius pump field into the gain ion-doped region of fiber 82 (see Fig. 17), the gain ions remain unexcited and can filter the signal light.

Fiber amplifiers not in accordance with the invention wherein the signal absorbing ions are different from the rare earth gain ions of the gain fiber are illustrated in Figs. 18 and 19. The fiber amplifier of Fig. 18 includes gain fiber 90, the core of which is doped with gain ions that are capable of producing stimulated emission of light within a band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p . The signal and pump light are coupled to gain fiber 90 via coupler fiber 12'. Gain fiber 90 is co-doped with absorbing ions that are different from the gain ions; therefore, the pump light attenuating means of the previous embodiments can be eliminated. Table 2 lists dopant candidates for use as absorbing ions to be employed in conjunction with gain fibers in which Er, Nd and Pr are the gain ions.

Table 2

<u>Gain Ion</u>	<u>Gain Wavelength Range</u>	<u>Absorbing Ion</u>
Er	1.52-1.61 μm	Pr, Sm
Nd	1.25-1.35 μm (undesired gain at 1050 nm)	Sm, Dy, Pr
Pr	1.25-1.35 μm	Sm, Dy, Nd

Curves of absorptivity v. wavelength were used in selecting the absorbing ions of Table 2.

During the fabrication of a preform for drawing a gain fiber that is co-doped with absorbing ions as well as active gain ions, the central region of the fiber is provided with a sufficient concentration of active gain ions to provide the desired amplification; it is also provided with a sufficient concentration of absorbing ions to attenuate the undesired portion or modify the gain spectrum. Such a fiber could be formed in accordance with the aforementioned U.S. Patent Application S.N. 07/715,348 by immersing the porous core preform in a dopant solution containing salts of both the active dopant ion and the absorbing ion.

A fiber amplifier not in accordance with the invention wherein the absorbing ions are incorporated into the core of a fiber that is connected in series with gain fiber is shown in Fig. 19 wherein absorbing fiber 93 is spliced between two sections 92a and 92b of gain fiber. Alternatively, the absorbing fiber could be spliced to the output end or input end of a single section of gain fiber.

Claims

1. A fiber amplifier comprising
 - a gain optical fiber (10, 10', 46a, 46b, 57, 62, 78, 81) having a single-mode core containing dopant gain ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p , said gain fiber having input and output ends,
 - means (11, 11', 14, 14', 43, 45) for introducing a signal of wavelength λ_s into said gain fiber input end,
 - means (11, 11', 15, 15', 41, 43, 44, 47, 48) for introducing pump light of wavelength λ_p into said gain fiber, and
 - absorbing ion filtering means (17, 27, 32, 32', 53, 64, 74, 79, 82) for attenuating light at at least some of the wavelengths within said predetermined band of wavelengths, characterized in that said absorbing ion filtering means comprises unpumped gain ions which are the same as said dopant gain ions, and said amplifier further comprises means (31, 38, 38', 52a, 52b, 57, 61, 74, 79, 83) for preventing the excitation of said unpumped gain ions by light of wavelength λ_p .
2. A fiber amplifier in accordance with claim 1 wherein said unpumped gain ions are situated in a signal filtering optical fiber (32, 32', 53, 64, 74) that is connected in series with said gain fiber (10', 46a, 46b, 57, 62).
3. A fiber amplifier in accordance with claim 2 wherein said means (31, 38, 38', 52a, 52b, 61) for preventing excitation is connected in series between said gain fiber (10', 46a, 46b, 62) and said signal filtering optical fiber (32, 32', 53, 64), and/or comprises a fiber-type grating reflector (31) for reflecting pump light, and/or comprises interference filter means (31) for reflecting pump light, and/or comprises an optical fiber (38, 38', 52a, 52b, 74) containing a dopant that substantially attenuates light at wavelength λ_p .
4. A fiber amplifier in accordance with claim 3, wherein said pump light attenuating optical fiber (38') connects said signal filtering optical fiber (32') to the input end of said gain fiber (10'), or wherein said gain fiber comprises first and second sections (46a, 46b), and said pump light attenuating fiber comprises first and second sections (52a, 52b), and said fiber amplifier comprises the serially connected arrangement of the first section (46a) of said gain fiber, said first section (52a) of said pump light attenuating fiber, said unpumped gain ion-doped signal filtering optical fiber (53), the second section (52b) of said pump light attenuating fiber and the second section (46b) of said gain fiber, said means for introducing pump light comprising means (43, 44, 47, 48) for introducing pump light into said first and second gain fiber sections.
5. A fiber amplifier in accordance with claim 2, 3 or 4 wherein said means for preventing excitation of said unpumped gain ions by pump light comprises a sufficient length of said gain fiber (57) to dissipate all of the pump light introduced therein, and/or an optical fiber coupler (61) which couples essentially no pump light from said gain fiber to said signal filtering optical fiber.
6. A fiber amplifier in accordance with any one of claims 1-5, wherein said absorbing ion filtering means comprises an optical fiber (74) containing unpumped gain ions and a dopant for absorbing pump light, the concentration of said dopant being much greater than unpumped gain ions.
7. A fiber amplifier in accordance with any of claims 1-5, wherein the radial distribution of said gain ions in said gain fiber (79) extends beyond the mode field radius of light of wavelength λ_p , whereby those gain ions at radii greater than said mode field radius are unexcited by pump light and are free to absorb signal light.
8. A fiber amplifier in accordance with any one of the preceding claims wherein a section of said gain fiber (81) is fused in side-by-side arrangement to a further section of optical fiber (82) doped with said gain ions to form a fused region into which signal light but not pump light can extend from said gain fiber into



A fiber amplifier not in accordance with the invention wherein the absorbing ions are incorporated into the core of a fiber that is connected in series with gain fiber is shown in Fig. 19 wherein absorbing fiber 93 is spliced between two sections 92a and 92b of gain fiber. Alternatively, the absorbing fiber could be spliced to the output end or input end of a single section of gain fiber.

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Claims

1. A fiber amplifier comprising
 - 10 a gain optical fiber (10, 10', 46a, 46b, 57, 62, 78, 81) having a single-mode core containing dopant gain ions capable of producing stimulated emission of light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p , said gain fiber having input and output ends,
 - means (11, 11', 14, 14', 43, 45) for introducing a signal of wavelength λ_s into said gain fiber input end,
 - 15 means (11, 11', 15, 15', 41, 43, 44, 47, 48) for introducing pump light of wavelength λ_p into said gain fiber, and
 - absorbing ion filtering means (17, 27, 32, 32', 53, 64, 74, 79, 82) for attenuating light at at least some of the wavelengths within said predetermined band of wavelengths, characterized in that said absorbing ion filtering means comprises unpumped gain ions which are the same as said dopant gain ions,
 - 20 and said amplifier further comprises means (31, 38, 38', 52a, 52b, 57, 61, 74, 79, 83) for preventing the excitation of said unpumped gain ions by light of wavelength λ_p .
2. A fiber amplifier in accordance with claim 1 wherein said unpumped gain ions are situated in a signal filtering optical fiber (32, 32', 53, 64, 74) that is connected in series with said gain fiber (10', 46a, 46b, 57, 62).
- 25 3. A fiber amplifier in accordance with claim 2 wherein said means (31, 38, 38', 52a, 52b, 61) for preventing excitation is connected in series between said gain fiber (10', 46a, 46b, 62) and said signal filtering optical fiber (32, 32', 53, 64), and/or comprises a fiber-type grating reflector (31) for reflecting pump light, and/or comprises interference filter means (31) for reflecting pump light, and/or comprises an optical fiber (38, 38', 52a, 52b, 74) containing a dopant that substantially attenuates light at wavelength λ_p .
- 30 4. A fiber amplifier in accordance with claim 3, wherein said pump light attenuating optical fiber (38') connects said signal filtering optical fiber (32') to the input end of said gain fiber (10'), or wherein said gain fiber comprises first and second sections (46a, 46b), and said pump light attenuating fiber comprises first and second sections (52a, 52b), and said fiber amplifier comprises the serially connected arrangement of the first section (46a) of said gain fiber, said first section (52a) of said pump light attenuating fiber, said unpumped gain ion-doped signal filtering optical fiber (53), the second section (52b) of said pump light attenuating fiber and the second section (46b) of said gain fiber, said means for introducing pump light comprising means (43, 44, 47, 48) for introducing pump light into said first and second gain fiber sections.
- 35 40 5. A fiber amplifier in accordance with claim 2, 3 or 4 wherein said means for preventing excitation of said unpumped gain ions by pump light comprises a sufficient length of said gain fiber (57) to dissipate all of the pump light introduced therein, and/or an optical fiber coupler (61) which couples essentially no pump light from said gain fiber to said signal filtering optical fiber.
- 45 6. A fiber amplifier in accordance with any one of claims 1-5, wherein said absorbing ion filtering means comprises an optical fiber (74) containing unpumped gain ions and a dopant for absorbing pump light, the concentration of said dopant being much greater than unpumped gain ions.
- 50 7. A fiber amplifier in accordance with any of claims 1-5, wherein the radial distribution of said gain ions in said gain fiber (79) extends beyond the mode field radius of light of wavelength λ_p , whereby those gain ions at radii greater than said mode field radius are unexcited by pump light and are free to absorb signal light.
- 55 8. A fiber amplifier in accordance with any one of the preceding claims wherein a section of said gain fiber (81) is fused in side-by-side arrangement to a further section of optical fiber (82) doped with said gain ions to form a fused region into which signal light but not pump light can extend from said gain fiber into



said further section, whereby those gain ions of said further section are unexcited by pump light and are free to absorb signal light.

- 5 9. A fiber amplifier comprising gain fiber means having a single-mode core containing dopant gain ions capable of producing stimulated emission of signal light within a predetermined band of wavelengths including a wavelength λ_s when pumped with light of wavelength λ_p into said gain fiber, means for introducing pump light of wavelength λ_p and a signal of wavelength λ_s into said gain fiber means, and a filtering fiber for filtering signal light, characterized in that
- 10 said gain fiber means includes first and second gain optical fiber sections (46a, 46b), each gain fiber section having first and second ends,
- said amplifier includes first and second pump light-attenuating fiber sections (52a, 52b), each having a core containing a dopant that attenuates optical power in at least one wavelength band including said wavelength λ_p , while optical power at said wavelength λ_p remains substantially unattenuated thereby,
- 15 each pump light-attenuating fiber section having first and second ends, the first end of each of said pump light-attenuating fiber sections being spliced to a respective one of the second ends of said gain fiber sections,
- the ends of said filtering fiber (53) are respectively connected to the second ends of said pump light attenuating fiber sections, said filtering fiber being doped with said dopant gain ions for filtering said signal light,
- 20 said pump light introducing means (43, 44, 47, 48) introduces pump light into the first end of each of said gain fiber sections, and
- said signal introducing means (43) introduces a signal into the first end of one of said gain fiber sections, the gain ions of said filtering fiber remaining unexcited during operation because of the pump light filtering action of said pump light-attenuating fiber.
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Patentansprüche

- 30 1. Faserverstärker mit einer optischen Verstärkungsfasern (10, 10', 46a, 46b, 57, 62, 78, 81), die einen Einzelmodenkern hat, der Dotierstoffverstärkungsionen hat, die eine stimulierte Lichtemission innerhalb eines vorbestimmten Wellenlängenbands erzeugen können, das eine Wellenlänge λ_s umfaßt, wenn sie mit Licht der Wellenlänge λ_p gepumpt werden, wobei die Verstärkungsfasern Eingabe- und Ausgabeenden hat,
- 35 eine Einrichtung (11, 11', 14, 14', 43, 45) zum Einleiten eines Signals der Wellenlänge λ_s in das Verstärkungsfasereingabeende,
- eine Einrichtung (11, 11', 15, 15', 41, 43, 44, 47, 48) zum Einleiten von Pumplicht der Wellenlänge λ_p in die Verstärkungsfasern, und
- 40 eine Absorptionsionenfiltereinrichtung (17, 27, 32, 32', 53, 64, 74, 79, 82) zum Abschwächen von Licht bei zumindest einigen der Wellenlängen innerhalb des vorbestimmten Wellenlängenbands, dadurch gekennzeichnet, daß die Absorptionsionenfiltereinrichtung ungepumpte Verstärkungsionen umfaßt, bei denen es sich um dieselben handelt, wie die Dotierstoffverstärkungsionen, und der Verstärker ferner eine Einrichtung (31, 38, 38', 52a, 52b, 57, 61, 74, 79, 83) zum Verhindern der Erregung der ungepumpten Verstärkungsionen durch Licht der Wellenlänge λ_p umfaßt.
- 45 2. Faserverstärker nach Anspruch 1, wobei die ungepumpten Verstärkungsionen in einer optischen Signalfilterfasern (32, 32', 53, 64, 74) angeordnet sind, die in Reihe mit der Verstärkungsfasern (10', 46a, 46b, 57, 62) geschaltet ist.
- 50 3. Faserverstärker nach Anspruch 2, wobei die Einrichtung (31, 38, 38', 52a, 52b, 61) zum Verhindern der Erregung in Reihe zwischen die Verstärkungsfasern (10', 46a, 46b, 62) und die optische Signalfilterfasern (32, 32', 53, 64) geschaltet ist und/oder einen Fasergitterreflektor (31) zum Reflektieren von Pumplicht umfaßt, und/oder eine Interferenzfiltereinrichtung (31) zum Reflektieren von Pumplicht umfaßt und/oder eine optische Fasern (38, 38', 52a, 52b, 74) umfaßt, die einen Dotierstoff enthält, der das Licht bei der Wellenlänge λ_p deutlich abschwächt.
- 55 4. Faserverstärker nach Anspruch 3, wobei die optische Pumplichtabschwächungsfasern (38') die optische Signalfilterfasern (32') mit dem Eingabeende der Verstärkungsfasern (10') verbindet, oder wobei die Ver-



- stärkungsfaser erste und zweite Abschnitte (46a, 46b) umfaßt und die Pumplichtabschwächungsfaser erste und zweite Abschnitte (52a, 52b) umfaßt und der Faserverstärker die Reihenschaltungsanordnung des ersten Abschnitts (46a) der Verstärkungsfaser, den ersten Abschnitt (52a) der Pumplichtabschwächungsfaser, die optische ungepumpte Verstärkungsionen-dotierte Signalfilterfaser (53), den zweiten Abschnitt (52b) der Pumplichtabschwächungsfaser und den zweiten Abschnitt (46b) der Verstärkungsfaser umfaßt, wobei die Einrichtung zum Einleiten von Pumplicht eine Einrichtung (43, 44, 47, 48) zum Einleiten von Pumplicht in die ersten und zweiten Verstärkungsfaserabschnitte umfaßt.
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5. Faserverstärker nach Anspruch 2, 3 oder 4, wobei die Einrichtung zum Verhindern der Erregung der Ionen durch Pumplicht eine ausreichende Länge der Faser (57) umfaßt, um das gesamte Pumplicht zu zerstreuen, das in sie eingeleitet wird, und/oder einen optischen Faserkoppler (61), der im wesentlichen kein Pumplicht aus der Verstärkungsfaser an die optische Signalfilterfaser koppelt.
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6. Faserverstärker nach einem der Ansprüche 1 bis 5, wobei die Absorptionsionenfiltereinrichtung eine optische Faser (74) umfaßt, die ungepumpte Verstärkungsionen und einen Dotierstoff zum Absorbieren von Pumplicht enthält, wobei die Konzentration des Dotierstoffs viel größer ist als diejenige der ungepumpten Verstärkungsionen.
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7. Faserverstärker nach einem der Ansprüche 1 bis 5, wobei die radiale Verteilung der Verstärkungsionen in der Verstärkungsfaser (79) sich über den Modenfeldradius des Lichts der Wellenlänge λ_p hinaus erstreckt, wobei diejenigen Ionen mit Radien größer als der Modenfeldradius durch Pumplicht unerregt und frei von Absorptionssignallicht sind.
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8. Faserverstärker nach einem der vorangehenden Ansprüche, wobei ein Abschnitt der Verstärkungsfaser (81) in Nebeneinanderanordnung an einen weiteren Abschnitt der optischen Faser (62) angeschmolzen ist, die mit den Verstärkungsionen dotiert ist, um einen geschmolzenen Bereich auszubilden, in den hinein sich Signallicht, jedoch kein Pumplicht aus der Verstärkungsfaser in diesen weiteren Abschnitt ausbreiten kann, wobei diese Verstärkungsionen des weiteren Abschnitts durch Pumplicht unerregt und in der Lage sind, Signallicht zu absorbieren.
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9. Faserverstärker mit einer Verstärkungsfasereinrichtung, die einen Einzelmodenkern hat, der Dotierstoffverstärkungsionen enthält, die eine stimulierte Emission eines Signallichts in einem vorbestimmten Wellenlängenband erzeugen können, das eine Wellenlänge λ_s einschließt, wenn sie mit Licht einer Wellenlänge λ_p in die Verstärkungsfaser hineingepumpt werden, einer Einrichtung zum Einleiten von Pumplicht der Wellenlänge λ_p und eines Signals der Wellenlänge λ_s in die Verstärkungsfasereinrichtung hinein, und einer Filterfaser zum Filtern von Signallicht, dadurch gekennzeichnet, daß die Verstärkungsfasereinrichtung erste und zweite optische Verstärkungsfaserabschnitte (46a, 46b) einschließt, von denen jeder erste und zweite Enden hat,
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- der Verstärker erste und zweite Pumplichtabschwächungsfilterabschnitte (52a, 52b) einschließt, von denen jeder einen Kern hat, der einen Dotierstoff enthält, der optische Leistung in zumindest einem Wellenlängenband abschwächt, das die Wellenlänge λ_p enthält, während optische Leistung bei der Wellenlänge λ_s dadurch im wesentlichen unabgeschwächt bleibt, wobei jeder Pumplichtabschwächungsfaserabschnitt erste und zweite Enden hat, wobei das erste Ende jedes der Pumplichtabschwächungsfaserabschnitte an ein jeweiliges der zweiten Enden der Verstärkungsfaserabschnitte geklebt ist,
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- die Enden der Filterfaser (53) jeweils an die zweiten Enden der Pumplichtabschwächungsfaserabschnitte angeschlossen sind, wobei die Filterfaser mit den Dotierstoffverstärkungsionen zum Filtern von Signallicht dotiert sind,
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- die Pumplichteinleitungseinrichtung (43, 44, 47, 48) Pumplicht in das erste Ende jedes der Verstärkungsfaserabschnitte einleitet, und
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- die Signaleinleitungseinrichtung (43) ein Signal in das erste Ende von einem der Verstärkungsfaserabschnitte einleitet, wobei die Verstärkungsionen der Filterfaser während des Betriebs aufgrund der Pumplichtfilterwirkung der Pumplichtabschwächungsfaser unerregt bleiben.
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Revendications

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1. Amplificateur à fibre optique, comprenant:
- une fibre optique à gain (10, 10', 46a, 46b, 57, 62, 78, 81) ayant un coeur monomode contenant des



- ions de dopant à gain aptes à produire une émission stimulée de lumière dans une bande prédéterminée de longueurs d'onde incluant une longueur d'onde λ_s lorsqu'ils sont pompés par une lumière de longueur d'onde λ_p , ladite fibre optique à gain ayant des extrémités d'entrée et de sortie;
- des moyens (11, 11', 14, 14', 43, 45) pour introduire un signal de longueur d'onde λ_s dans ladite extrémité d'entrée de la fibre optique à gain;
 - des moyens (11, 11', 15, 15', 41, 43, 47, 48) pour introduire une lumière de pompage de longueur d'onde λ_p dans ladite fibre optique à gain; et
 - des moyens de filtrage à ions absorbants (17, 27, 32, 32', 53, 64, 74, 79, 82) pour atténuer la lumière à au moins certaines des longueurs d'onde comprises dans ladite bande prédéterminée de longueurs d'onde, caractérisé en ce que lesdits moyens de filtrage à ions absorbants comprennent des ions à gain non pompés qui sont les mêmes que lesdits ions de dopant à gain, et en ce que ledit amplificateur comprend en outre des moyens (31, 38, 38', 52a, 52b, 57, 61, 74, 79, 83) pour empêcher l'excitation desdits ions à gain non pompés par la lumière de longueur d'onde λ_p .
2. Amplificateur à fibre optique selon la revendication 1, dans lequel lesdits ions à gain non pompés sont situés dans une fibre optique filtrant le signal (32, 32', 53, 64, 74) qui est montée en série avec ladite fibre optique à gain (10', 46a, 46b, 57, 62).
 3. Amplificateur à fibre optique selon la revendication 2, dans lequel lesdits moyens (31, 38, 38', 52a, 52b, 61) pour empêcher l'excitation sont montés en série entre ladite fibre optique à gain (10', 46a, 46b, 62) et ladite fibre optique filtrant le signal (32, 32', 53, 64), et/ou comprennent un réflecteur à réseau de diffraction du type à fibre optique (31) pour réfléchir la lumière de pompage, et/ou comprennent des moyens formant filtre interférentiel (31) pour réfléchir la lumière de pompage, et/ou comprennent une fibre optique (38, 38', 52a, 52b, 74) contenant un dopant qui atténue sensiblement la lumière à la longueur d'onde λ_p .
 4. Amplificateur à fibre optique selon la revendication 3, dans lequel ladite fibre optique atténuant la lumière de pompage (38') connecte ladite fibre optique filtrant le signal (32') à l'extrémité d'entrée de ladite fibre optique à gain (10'), ou dans lequel ladite fibre optique à gain comprend des premier et deuxième tronçons (46a, 46b) et ladite fibre optique atténuant la lumière de pompage comprend des premier et deuxième tronçons (52a, 52b), et ledit amplificateur à fibre optique comprend l'agencement monté en série du premier tronçon (46a) de ladite fibre optique à gain, dudit premier tronçon (52a) de ladite fibre optique atténuant la lumière de pompage, de ladite fibre optique filtrant le signal dopée par des ions à gain non pompés (53), du deuxième tronçon (52b) de ladite fibre optique atténuant la lumière de pompage, du deuxième tronçon (46b) de ladite fibre optique à gain, et desdits moyens (43, 44, 47, 48) pour introduire la lumière de pompage dans lesdits premier et deuxième tronçons de fibre optique à gain.
 5. Amplificateur à fibre optique selon la revendication 2, 3 ou 4, dans lequel lesdits moyens pour empêcher l'excitation desdits ions à gain non pompés par la lumière de pompage comprennent une longueur suffisante de ladite fibre optique à gain (57) pour dissiper toute la lumière de pompage introduite dans celle-ci, et/ou un coupleur de fibres optiques (61) qui ne couple essentiellement pas de lumière de pompage de ladite fibre optique à gain à ladite fibre optique filtrant le signal.
 6. Amplificateur à fibre optique selon l'une quelconque des revendications 1 à 5, dans lequel lesdits moyens de filtrage à ions absorbants comprennent une fibre optique (74) contenant des ions à gain non pompés et un dopant pour absorber la lumière de pompage, la concentration dudit dopant étant beaucoup plus grande que celle des ions à gain non pompés.
 7. Amplificateur à fibre optique selon l'une quelconque des revendications 1 à 5, dans lequel la répartition radiale desdits ions à gain dans ladite fibre optique à gain (79) s'étend au-delà du rayon de champ de modes de la lumière de longueur d'onde λ_p , ce par quoi les ions à gain situés à des rayons plus grands que ledit rayon de champ de modes ne sont pas excités par la lumière de pompage et sont libres d'absorber la lumière du signal.
 8. Amplificateur à fibre optique selon l'une quelconque des revendications précédentes, dans lequel un tronçon de ladite fibre optique à gain (81) est joint par fusion dans une disposition côte-à-côte à un autre tronçon de fibre optique (82) dopé avec lesdits ions à gain pour former une région à jonction par fusion dans laquelle la lumière du signal, mais non la lumière de pompage, peut se propager de ladite fibre optique à gain dans ledit autre tronçon, ce par quoi les ions à gain dudit autre tronçon ne sont pas excités par la lumière de pompage et sont libres d'absorber la lumière du signal.



9. Amplificateur à fibre optique, comprenant des moyens formant fibre optique à gain ayant un coeur monomode contenant des ions de dopant à gain aptes à produire une émission stimulée de lumière formant signal dans une bande prédéterminée de longueurs d'onde incluant une longueur d'onde λ_s lorsqu'ils sont pompés par une lumière de longueur d'onde λ_p dans ladite fibre optique à gain, des moyens pour introduire une lumière de pompage de longueur d'onde λ_p et un signal de longueur d'onde λ_s dans lesdits moyens formant fibre optique à gain, et une fibre optique filtrante pour filtrer la lumière formant signal, caractérisé en ce que:

- lesdits moyens formant fibre optique à gain comprennent des premier et deuxième tronçons de fibre optique à gain (46a, 46b), chaque tronçon de fibre optique à gain ayant des première et deuxième extrémités;
- ledit amplificateur comporte des premier et deuxième tronçons de fibre optique atténuant la lumière de pompage (52a, 52b), chacun ayant un coeur contenant un dopant qui atténue la puissance optique dans au moins une bande de longueurs d'onde incluant ladite longueur d'onde λ_p , tandis que la puissance optique à ladite longueur d'onde du signal λ_s reste sensiblement non atténuée par celui-ci, chaque tronçon de fibre optique atténuant la lumière de pompage ayant des première et deuxième extrémités, la première extrémité de chacun desdits tronçons de fibre optique atténuant la lumière de pompage étant raccordée à une extrémité respective parmi les deuxième extrémités desdits tronçons de fibre optique à gain;
- les extrémités de chacune desdites fibres optiques filtrant le signal (53) sont respectivement connectées aux deuxième extrémités desdits tronçons de fibre optique atténuant la lumière de pompage, ladite fibre optique filtrant le signal étant dopée avec lesdits ions de dopant à gain pour filtrer ladite lumière formant signal;
- lesdits moyens d'introduction de la lumière de pompage (43, 44, 47, 48) introduisent la lumière de pompage dans la première extrémité de chacun desdits tronçons de fibre optique à gain; et
- lesdits moyens d'introduction de signaux (43) introduisent un signal dans la première extrémité de l'un desdits tronçons de fibre optique à gain, les ions à gain de ladite fibre filtrant le signal restant non excités pendant le fonctionnement en raison de l'action de filtrage de la lumière de pompage de ladite fibre optique atténuant la lumière de pompage.