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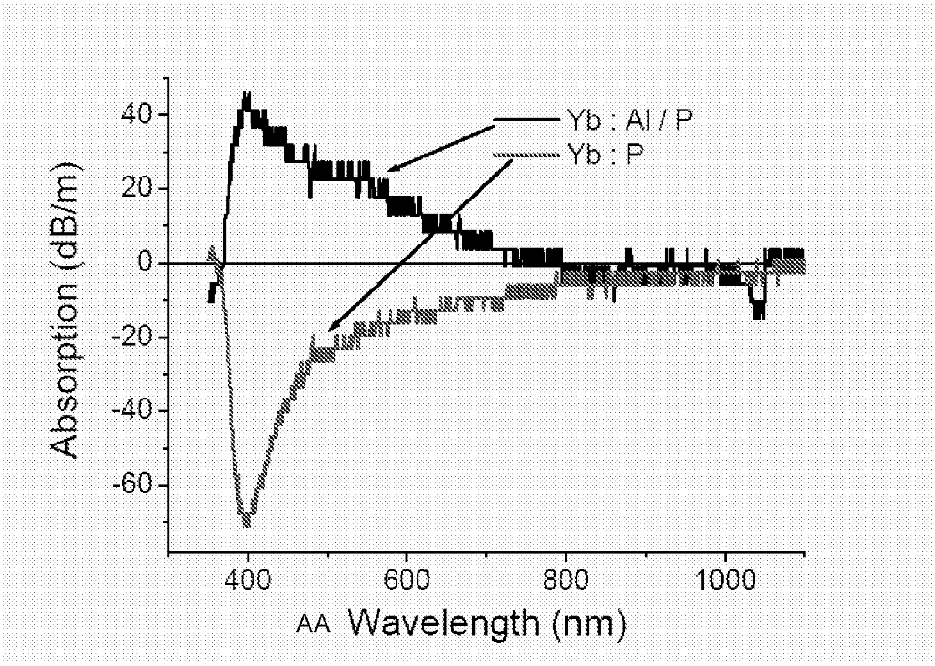
(54) Title: HIGH POWER AMPLIFIER SILICA GLASS MATERIAL



(57) Abstract: A high power amplifier silica glass material is provided wherein photo darkening due to high optical flux is reduced considerably. The conventional counter part amplifier and laser based on conventional silica glass material have a problem in that their characteristics are deteriorated with the elapse of time due to photo darkening. The new fibre amplifier and laser silica glass material shows through reduction of the non-binding oxygen electron concentration less photo darkening. This is achieved through hydrogen or deuterium load of the amplifier glass material or by co-doping with phosphorous $P_4O_{8-x}(OH)_{4+2x}$, (0 x 2).

High power amplifier silica glass material

TECHNICAL FIELD OF THE INVENTION:

The invention relates to the field of high power light amplification in rare earth doped silica glass materials. In particular, this invention relates to reduced photo darkening in rare earth doped high power amplifier silica glass materials.

BACKGROUND OF THE INVENTION:

High power optical fibre lasers are becoming of increasing interest as a consequence of their efficiency, low cost, and the availability of arrays of high power diode pump lasers. Such arrays of diode pump lasers can have an output power of several hundred watts or greater, and serve as ideal pump sources for optical fibre lasers.

The function of the optical fibre is to convert the highly multi-mode output from a diode array to a high power single mode output of a power amplifier or laser. The fibre converts the multimode high power low brightness diode array to a high brightness single mode source. There are many situations in which the beam quality of a single mode fibre with less power is more desirable than a higher powered multi-mode array. These applications include materials processing (cutting, welding, and marking) and surgery.

Diode bar arrays are commercially available, and can be arranged to produce power levels of many hundreds of watts. The power is delivered through multi-mode fibres, or arrays of fibres bundled together. However, a fibre having a low numerical aperture will not efficiently accept the radiation of these devices in such a manner that single mode laser radiation will result, as would occur by having the pump radiation from the diode array serve as the energy source to create an inversion in a rare earth doped optical fibre laser. Since single mode operation is desired for high brightness, with a core typically 5 - 30 µm in diameter, it is not possible to focus the light from the fibre output of the diode array into the single mode core. The brightness theorem specifies that the numerical aperture of the fibres coming from the diode sources, times the fibre area, must be a constant. Thus, the high intensity light from the fibre output of the diode array cannot be focused into the core of a single mode fibre. To circumvent this problem the double clad fibre construction is applied. Here a high numerical aperture outer cladding is constructed to accept the pump power whereas the ytterbium doped core with a low numerical aperture is placed in the inner core of the double clad fibre. Hereby the multimode diode low brightness light is effectively brought in overlap with the ytterbium doped core material in which high power single mode light is generated through stimulated emission inside a laser cavity consisting of two fibre gratings constructed either directly in the ytterbium doped fibre or in a separately fibre spliced to the ytterbium doped fibre.

Due to the relative small diameter of the fibre core, the optical flux, i.e. the optical lasing power transmitted per unit area of the fibre core, is extremely high. Consequently, absorption effects at gratings or inside the core can result in unwanted degradation of the device within a time frame which is substantially shorter than the lifetime required for the respective application of such lasers. It has been observed experimentally that with constant pump power, the lasing output decreased by several percent during a 1000 hour time period. It has further been observed experimentally that a considerable increase in propagation loss is experienced in un-seeded amplifiers after only a few hours of operation.

Due to the high pump power intensity (optical flux), a material that is suitable for relatively low optical fluxes will darken at a relatively high rate as the flux increases. The photo darkening of ytterbium and other rare earth doped silica materials has been attributed to the formation of colour centres in the glass material. The exact factor responsible for the increased absorption has not been identified but the effect is observed when irradiating the glass material with high energy photons (such as UV-, x- or γ-rays) or with radiation that is resonant with the absorption bands of the rare earth material comprised in the glass.

In connection with Thulium co-doped silicate fibres it has been observed by Brocklesby et al. (Optics Letters, Vol.18, No.24, (1993)) that the fibre material photo darkens when irradiated with (476 nm) radiation resonant with the Thulium absorption band. This photo darkened material can partly be recovered by irradiating with non-resonant radiation at 514 nm or when heating the fibre at temperatures >350°C. For Terbium co-doped silicate fibres, 488 nm resonant radiation is by Atkins et al. (Optics Letters, Vol. 19, No. 13, (1994)) observed to photo darken the fibre material, whereas bleaching can be performed with non resonant radiation at the 514 nm laser line of an argon ion laser.

For ytterbium co-doped silicate fibres Gavrilovic et al. (US patent 6,154,598) claims that photo darkening is due to unintentionally incorporated impurities disposed in the lasing medium which up-convert a portion of the lasing radiation to radiation of a shorter wavelength, thereby introducing defects in the medium, which result in increased absorption due to photo darkening.

Whatever the factor responsible for the increased absorption is, it is observable after irradiating the glass material with high intensity radiation. Photo darkening of Yb-doped silica fibres has been attributed to the formation of colour centres in the rare-earth doped glass, but the mechanism behind this phenomenon is not understood. As a result, it is difficult to predict how a particular fibre glass material will perform under a given set of operating conditions and further difficult to choose a proper glass material composition for such fibres.

SUMMARY OF THE INVENTION

It is an object of the invention to provide an optical material, such as in the form of an optical waveguide or optical fibre structures, wherein the period in which a lasing or an amplifier output power level at constant pump power may be maintained substantially constant is improved.

In preferred embodiments the lasing or amplifier output power level at constant pump power is maintained substantially constant over an extended operating period.

It is a further object of the invention to reduce photo darkening precursors in the waveguide laser and amplifier material.

A waveguide laser or amplifier material according to the present invention comprises a glass host material doped with one or more rare earth elements in concentrations adapted to the intended level of amplification, pump wavelength, amplifying wavelength, intended length of fibre, etc. Additionally the glass host material comprises network modifier elements. Preferably the ratio of atomic concentrations of the modifier elements to that of the rare earth elements is larger than 5, such as larger than 6, such as larger than 7.

The invention relates to glasses with a ‘tetrahedron-like structure’. The glass host material is preferably silica. This has the advantage of providing a material that is compatible with a huge variety of existing systems comprising optical fibres for communications, sensing and other applications. Alternatively the material may be based on other appropriate material systems having a ‘tetrahedron-like structure’, cf. e.g. Michel. J.F. Digonnet, “Rare-Earth-Doped Fiber Lasers and Amplifiers”, 2nd edition, 2001, Marcel Dekker, Inc., Chapter 2, p.17-p.112, the book being referred to elsewhere in this application as [Digonnet].

The network modifier atoms for use in silica host glasses are preferably selected from the group of tri- or pentavalent atoms, such as e.g. aluminium, phosphor, boron, etc. for reducing the number of photo darkening pre-cursors (‘chain-igniters’). Alternatively or additionally the addition of fluorine has the effect of reducing the number of non-binding oxygen lone or paired electrons.

An object of the invention is attained in an embodiment by choosing the concentration of network modifiers in the silica glass material relative to the rare earth doping concentration. The composition / ratio between rare earth atoms and other network modifiers (such as e.g. aluminium, phosphor, boron) determines the amount of ytterbium-ytterbium pairs inside the glass material and hereby the inherent generation of co-operative frequency up-converted light produced.

An object of the invention is in an embodiment for example as an alternative to the above or in combination therewith, achieved by a waveguide laser or amplifier material comprising a silica glass host material, one or more rare earth elements in concentrations c_{RE} at.% (mol.), one or more network modifier elements selected from the group of tri- or pentavalent atoms of the periodic table of the elements in concentrations c_{NME} at.% (mol.), and fluorine in concentrations c_F at.% (mol.), wherein $c_{NME} \geq c_{RE}$ and $c_F \geq c_{RE}$.

The network modifier atoms are added to the glass to counteract devitrification when the concentration of rare earth atoms is increased above approximately 0.01 at %. An additional effect of the network modifiers are that when a sufficient amount of these is present, the concentration of rare earth pairs decreases with a reduction in the co-operative frequency up-conversion as result. The co-operative frequency up-conversion is unwanted as it reduces the amplification efficiency of the glass material. An additional effect of the adding of network modifiers is, for example for an ytterbium-doped glass, that the concentration of Yb-Al-Yb atom strings is reduced with increasing Al concentration or alternatively increasing phosphor or boron concentration. The presence of Yb-Al-Yb atom strings are the main suppliers of electrons to lone-electron pair colour centres established near non-binding oxygen sites due to the large absorption cross section of ytterbium when pumped resonantly. The Yb-Al-Yb atom strings initiate the formation of paired- / empty non-binding oxygen sites (colour centre). A similar function is observed for Yb-Al-Al atom strings with much less dominance for low population inversion of the ytterbium atoms, which are found when stimulated feed-back is given to the glass material (such as when operating the material in a laser setup). The role of Al-Al-Al chains is negligible due to a much smaller absorption cross section when pumped resonant with the ytterbium absorption band.

According to the invention, an object is in an embodiment attained by loading the pre-form glass material with hydrogen and/or deuterium at elevated temperature in a sufficiently long period for the hydrogen and/or deuterium to diffuse through the core material. Alternatively, the hydrogen/deuterium can be supplied in the form of H_2O/D_2O. Advantageously the loading can be performed in a post glass formation / fibre drawing process. The function of the added hydrogen or deuterium is to occupy non-binding oxygen sites near tri- or penta-valence atoms in substitute tetra-valence atom sites. I.e. to occupy non-bridging oxygen near rare earth atoms or other network modifier atoms (such as e.g. aluminium, phosphor, boron) in substitute silicon sites. Hereby the non-binding oxygen site will be occupied with a hydrogen or deuterium atom and no longer participate in the formation of colour centres when exposed to radiation resonant with the rare earth absorption bands. A similar effect can be obtained by the addition of fluorine to the glass matrix, e.g. during preform fabrication. Alternatively, the hydrogen/deuterium can be supplied by co-doping with phosphorous P_4O_{10} that under water and/or hydrogen load is converted into $P_4O_{8-x}(OH)_{4+2x}$, $(0 \leq x \leq 2)$ complexes in the silica glass during or after fibre manufacture. The hydrogen incorporated in these complexes is permanently incorporated into the glass material even under high optical load.

In an embodiment of the invention, a combination of hydrogen and/or deuterium loading and/or fluorine addition and a selection of silica glass material with a low number of photo darkening pre-cursors is advantageously applied to achieve a relatively low photo darkening rate and a relatively low steady state photo darkening. Because of these features, the present invention can be used in practical equipments for applications such as materials processing (cutting, welding, and marking) and surgery.

DISCLOSURE OF INVENTION:

The objects of the invention are achieved by the invention described in the accompanying claims and as described in the following.

In an embodiment of the invention an object of the invention is achieved by a high power amplifier comprising a diode bar array pump laser which operates at a wavelength λ_{pump} and with a pump power exceeding 5 W, a coupling device, a silica host glass fibre with a rare earth doped core co-doped with one or more network modifiers (such as aluminium, boron, and/or phosphor) in a concentration such that the total atomic network modifier concentration is at least 5 times, such as at least 6 times, such as at least 7 times the rare earth atomic concentration, an output delivery fibre, wherein the wavelength λ_{pump} is resonant with said rare earth doping absorption band. Alternatively or additionally, fluorine in a concentration larger than or equal to the concentration of the rare earth element can be added. At least part of the core or cladding is doped with phosphorous. The co-doping with phosphorous leads by reaction with residual hydrogen or water during or after processing of the fibre to formation of $P_4O_{8-x}(OH)_{4+2x}$, $(0 \leq x \leq 2)$ complexes in the silica glass. These complexes act as sources for hydrogen that effectively blocks non-binding oxygen sites (photo darkening precursors) during pump radiation to convert into absorption centres.

An advantage of this present aspect of the invention is that the concentration of rare earth atoms in chains with network modifiers, wherein more than one rare earth atom is present, is reduced when the network modifier concentration is increased. This will reduce the photo darkening steady state concentration of non-binding oxygen colour centres. The term ‘the wavelength λ_{pump} is resonant with the rare earth doping absorption band’ is in the present context taken to mean that λ_{pump} is within the absorption band of the rare earth dopant element(s).

The term ‘atomic concentration’ (abbreviated at.% (mol.)) of a given network modifier or rare earth element, etc. in a given region of the waveguide laser and amplifier material is in the present context taken to mean the ratio of the number of atoms or the network modifier or rare earth element in question to the total number of atoms in a given volume of the material (e.g. one mole).

In an embodiment of the invention, it is further possible to optimize the amplification of the glass material (in the 976 nm – 1150 nm band) by pumping ytterbium doped glass with radiation resonant with the ytterbium absorption band (880 nm – 976nm). An increased amplification will be reached by increasing the ytterbium atomic concentration above 0.1 atomic percent, such as to more than 0.2 atomic percent, such as to more than 0.3 atomic percent, such as to more than 0.5 atomic percent, such as to more than 1.0 atomic percent.

To reduce photo darkening of this material, an addition of network modifiers, such as aluminium in a concentration of at least 7 times the ytterbium atomic concentration, such as at least 8 times the ytterbium concentration, such as at least 10 times the ytterbium concentration, such as at least 12 times the ytterbium concentration, such as at least 14 times the ytterbium concentration, is advantageous.

To achieve high pump efficiency, it is an advantage to configure the silica host glass fibre to have a core diameter $d_{core} > 4$ µm with a numerical aperture less than 0.1, surrounded by a first cladding diameter > 30 µm with a numerical aperture larger than or equal to 0.4, surrounded by a second cladding comprising either polymeric material or an air/glass microstructure, and to provide that the coupling device is a fused fibre bundle tapered to fit in numerical aperture to the numerical aperture of the first cladding and that the fibre bundle fibres are attached to diode bar array lasers.

To achieve laser operation of the silica host glass material, the high power amplifier can advantageously be configured such that between the coupling device and the silica host glass fibre a first fibre Bragg grating is formed, and wherein between the silica host glass fibre and the output delivery fibre a second fibre Bragg grating is formed. These gratings can be either formed by fusion splicing a section of fibre wherein the fibre Bragg grating is formed to the respective fibre ends of the silica host glass fibre or be written directly into the rare earth doped core of the silica host glass fibre. The latter option requires the additional co-doping with germanium.

In an embodiment of the invention an object of the invention is achieved by a high power amplifier comprising a diode bar array pump laser which operates at a wavelength λ_{pump} and with a pump power exceeding 5 W, a coupling device, a silica host glass fibre with a rare earth doped core co-doped with one or more network modifiers (such as aluminium, boron, phosphor), and an output delivery fibre, where said rare earth doped core is loaded with hydrogen or deuterium. The loading with hydrogen or deuterium can be performed either during or after formation of a rod preform from which the silica host glass fibre is drawn. Alternatively (or additionally), the loading with hydrogen or deuterium can be done during, and/or after drawing and possibly coating of said silica host glass fibre.

The loading with hydrogen or deuterium reduces the concentration of non-binding lone electrons and paired electrons in non-binding oxygen sites in the core material. The non-binding lone electrons are partly produced during fibre preform production due to oxygen deficiency in the silica matrix and are partly due to the three- or pentavalent nature of the network modifiers. The silica matrix non-binding oxygen sites can not be activated by the rare-earth resonant pumping radiation whereas the non-binding oxygen sites near network modifiers and rare earth atoms are activated by the resonant pumping radiation. Now, loading the silica glass material with hydrogen or deuterium will reduce the non-binding lone electrons by connecting hydrogen or deuterium to the non-binding sites. This removes the colour centres in the silica matrix and reduces the number of non-binding sites of the network modifiers considerably.

To achieve high pump efficiency it is an advantage to configure the silica host glass fibre to comprise a core having a core diameter $d_{core} > 4$ µm and a numerical aperture less than 0.1, and a first cladding surrounding the core and having a diameter > 30 µm and a numerical aperture larger than or equal to 0.4, surrounded by a second cladding comprising either polymeric material or an air/glass microstructure, and wherein the coupling device is a fused fibre bundle tapered to fit in numerical aperture to the numerical aperture of the first cladding and the fibre bundle fibres are attached to diode bar array lasers.

To achieve laser operation of the silica host glass material, the high power amplifier can advantageously be configured such that between the coupling device and the silica host glass fibre a first fibre Bragg grating is formed, and wherein between the silica host glass fibre and the output delivery fibre a second fibre Bragg grating is formed. These gratings can be either formed by fusion splicing a section of fibre wherein the fibre Bragg grating is formed to the respective fibre ends of the silica host glass fibre or be written directly into the rare earth doped core of the silica host glass fibre. The latter option requires an additional co-doping of the core with germanium.

In an embodiment an object of the invention is achieved by a high power amplifier by choosing a combination of silica host material with a low concentration of photo darkening pre-cursors (Yb-Al-Yb chains) and loading of the silica host material with hydrogen. This is in one aspect done by choosing the rare earth doping to be ytterbium in a concentration exceeding 0.1 atomic percent, such as more than 0.2 atomic percent, such as more than 0.3 atomic percent, such as more than 0.5 atomic percent, such as more than 1.0 atomic percent. This can preferably be done in combination with the addition to the doped silica host material of a network modifier such as aluminium in a network modifier atomic concentration of at least 7 times the ytterbium atomic concentration, such as at least 8 times the ytterbium concentration, such as at least 10 times the ytterbium concentration, such as at least 12 times the ytterbium concentration, such as at least 14 times the ytterbium concentration.

Further objects of the invention are achieved by the embodiments defined in the dependent claims and in the detailed description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS:

In the following, the invention will be explained in more detail with reference to the high power amplifier according to the invention shown in the drawing, in that

Fig. 1	shows a diagram of the high power amplifier according to the present invention;
Fig. 2	shows a diagram of the high power amplifier according to the present invention in a laser configuration;
Fig. 3	shows optical absorption spectra of high power amplifiers, where the upper curve represents an amplifier configuration with an ordinary network modifier to ytterbium concentration and the lower curve represents an amplifier with increased network modifier to ytterbium concentration, and wherein the core is co-doped with phosphorous according to the present invention;
Fig. 4	shows optical absorption spectra of high power amplifiers, where the upper curve represents an amplifier configuration with ordinary network

modifier to ytterbium concentration and the lower curve represents the same fibre loaded with deuterium according to the present invention;

Fig. 5	shows optical absorption spectra of high power amplifiers, where the upper curve represents an amplifier configuration with increased network modifier to ytterbium concentration, wherein part of the core is co-doped with phosphorous, according to the present invention and the lower curve represents an amplifier with high phosphorous to ytterbium concentration according to the present invention;

The figures are schematic and simplified for clarity, and they just show details which are essential to the understanding of the invention, while other details are left out. Throughout, the same reference numerals are used for identical or corresponding parts.

Fig. 1 shows a schematic diagram of a high power amplifier according to the present invention. The input signal 1 is amplified through the high power amplifier 4 and delivered as output 6 from the output delivery fibre 5. The pump radiation from diode bar arrays 2 is coupled into a double cladding fibre 4 through a section of fused and tapered fibre bundle 3, tapered to fit the bundle output numerical aperture to the numerical aperture of the inner cladding of the double cladding fibre 4. The signal radiation 1 is here shown to be coupled into the centre core of the double cladding fibre by the same tapered fibre bundle 3. The output signal is delivered by output fibre 5 to the output 6 in a substantially single mode core. The coupling device or fused and tapered fibre bundle is spliced (preferably fusion spliced) - as indicated with 7 - to the double cladding fibre 4 as is the output delivery fibre 5.

Fig. 2 shows a schematic diagram of a high power amplifier according to the present invention in a laser configuration. Fig. 2 is identical to Fig. 1, except that the input signal port (1, in Fig. 1) is replaced with a pump diode fibre receiving pump light from diode bar arrays 2. In Fig. 2, the single mode input fibre 1 of Fig. 1 of the coupling device 3 (here a fused and tapered fibre bundle) has been substituted by a multimode input fibre carrying pump light. The laser action is achieved through adding gratings 8 in or next to (i.e. optically coupled to) the amplifier fibre 4.

The silica glass host fibre is preferably a double clad fibre and more preferably a micro-structured fibre, such as an air-clad fibre. This has the advantage of providing a fibre that is suitable for high-power applications. In the present context, the term an 'air-clad' fibre is taken to mean a micro-structured fibre wherein light to be propagated is confined to a part of the fibre within a circumferential distribution of longitudinally extending voids in the cladding of the fibre, cf. e.g. US-5,907,652 or WO-03/019257. An example of such a fibre (without the material modifications of the present invention) is a DC-225-22-Yb fibre from Crystal Fibre A/S (Birkeroed, Denmark).

Aspects of rare-earth doped silica fibre lasers are described in a variety of sources, e.g. in [Digonnet], chapter 3, pp. 113-170.

Aspects of hydrogen/deuterium loading in silica optical fibres are discussed in various text books in connection with photosensitivity enhancements prior or during the writing of Bragg gratings in optical fibres, cf. e.g. A. Othonos & K. Kalli in 'Fibre Bragg Gratings', Artech House, 1999, chapter 2.6.1, pp. 43-48. The same processing conditions may be used for the loading of H_2 or D_2 in connection with the present invention.

Examples

In the following, the design and application of a high power amplifier according to the invention will be discussed in connection with a number of examples.

Example 1

This example discloses how the photo darkening of a high power amplifier silica glass host material doped with a rare earth atom such as ytterbium is reduced by adding an excess amount of network modifiers to the glass matrix and wherein a part of the core is doped with phosphorous.

The photo darkening of fibre samples are performed in a un-seeded amplifier setup where the input signal 1 indicated in fig. 1 is zero and the absorption as a function of wavelength and time is characterised by measuring the absorption in the fibre 4 by coupling in white light radiation through the output port 6 and measuring the transmitted signal to the input port in a given interval of time.

In fig. 3 the result of two such measurements are shown for a sample with a glass composition corresponding to a conventional ytterbium silica glass composition (upper curve) and an amplifier ytterbium silica glass according to the present invention (lower curve). The conventional ytterbium silica glass composition is 0.3 at. % ytterbium and 1.2 at. % network modifiers (aluminium) whereas the ytterbium silica glass composition according to the present invention is 0.25 at. % ytterbium and 2.25 at. % network modifiers (aluminium and phosphor).

It is observed from Fig. 3 that the absorption due to photo darkening as a function of wavelength is a factor of five less for the ytterbium glass composition according to the present invention compared with that of the conventional ytterbium glass composition after 2 hours of operation.

The two fibre cores are experiencing identical optical fluxes (160 kW/cm^2, 915 nm radiation).

Example 2

In this example the conventional composition fibre of example 1 is subjected to deuterium loading prior to the photo darkening experiment. As in example 1 the fibres are operated in un-seeded amplifier setup to achieve the highest possible photo darkening. This time the samples are run until no further increase in absorption is observed, which is after approximately 12 hours of operation at 160 kW/cm^2 optical flux at 915 nm pump.

It is observed from Fig. 4 that the un-loaded fibre sample exhibits considerably higher losses in the core compared with that of the hydrogen loaded fibre sample after 2 hours of operation. The peak absorption is reduced with a factor of 2.75, and much more importantly, the tail of the absorption is reduced considerably, especially for wavelengths above 900 nm.

The explanation for this observation could be that apart from the non-binding oxygen associated with Yb-Al-Yb and Yb-Al-Al chains, other non-binding oxygen sites have been removed by the hydrogen /deuterium loading.

A colour centre is a defect where at least one of the four bonds to neighbouring oxygen atoms has been replaced by non-binding oxygen (paired or empty) electrons. The colour centres with more than one bond to neighbouring oxygen atoms replaced by non-binding oxygen electrons are to be located in the glass as lone atoms surrounded by silica material (three missing bonds) and in chains surrounded by silica material (two missing bonds). These types of non-binding bonds can not be excited by pump radiation resonant with the ytterbium rare earth atom, as the photon energy of this radiation typically is below 1.4 eV and will require radiation from for example frequency up-converted light generated by ytterbium-ytterbium ion pairs (2.54 eV). On the contrary, the colour centre with only one missing bond can be excited with the present applied radiation.

The loading with hydrogen or deuterium will remove a considerable amount of the non-binding oxygen un-paired and paired electrons and hereby reduce the colour centre concentration in the as drawn glass material. Further the adding of hydrogen or deuterium to these non-binding oxygen sites will remove the possibility of forming colour centres here due to the presence of hydrogen, which blocks the transition of the electron to other non-binding sites.

The loading with hydrogen will therefore be observable in the optical spectrum of the fibre material through the absence of excess absorption for radiation with a wavelength longer than 600 nm. This is due to the reduced formation of colour centres based on two and three missing bond centres. It can be noted that it is advantageous for the H_2 and D_2 to connect to such sites as the two missing electrons of the hydrogen or deuterium electron is supplied by such sites. It can further be noted that the three missing bonds will be converted to a single missing bond site. These sites could possibly still give absorption to the radiation but the absorption centre has now shifted towards shorter wavelengths. This shift is believed to be from around 640 nm to around 400 nm. The hydrogen load appears to diffuse out of the samples after 60 – 100 hours of operation when operated at high optical load. Excess amount of hydrogen in the surrounding air counteracts this behaviour.

The loading with hydrogen and/or deuterium is preferably performed at elevated pressures and temperatures over a certain time period, e.g. 72 hours at 150 bar at 87 °C, cf. also U.S. Pat. No. 5,235,659.

Example 3

This example discloses how the photo darkening of a high power amplifier silica glass host material doped with a rare earth atom such as ytterbium is reduced by adding an excess amount of network modifier (phosphorous) to the glass matrix.

The photo darkening of fibre samples are performed in a un-seeded amplifier setup where the input signal 1 indicated in fig. 1 is zero and the absorption as a function of wavelength and time is characterised by measuring the absorption in the fibre 4 by coupling in white light radiation through the output port 6 and measuring the transmitted signal to the input port in a given interval of time.

In fig. 5 the result of two such measurements are shown for two ytterbium silica glass compositions both according to the present invention. The ytterbium silica glass composition according to the present invention is for the first fibre 0.25 at % ytterbium and 2.25 at % network modifiers (aluminium and phosphor) (upper curve) and the ytterbium silica glass composition according to the present invention is for the second fibre 0.25 at % ytterbium and 4.26 at % network modifier (phosphor).

It is observed from Fig. 5 that the change in absorption due to photo darkening as a function of wavelength is negative for the second fiber. I.e. the transmission increases when the fibre has been pumped for two hours – this in contrary to the first fibre where the absorption increases after two hours of pump operation. The two fibre cores are experiencing identical optical fluxes (160 kW/cm^2, 915 nm radiation).

The release of hydrogen from the $P_4O_{8-x}(OH)_{4+2x}$, $(0 \leq x \leq 2)$ hydrogen traps under pump radiation effectively blocks the photo darkening precursors for the second fiber whereas it only partly blocks the photo darkening precursors for the first fiber, where the aluminium co-doping increases the amount of photo darkening precursors.

The phosphorous doped sample exhibit reduced pump absorption at 915 nm (not shown) compared with the phosphorous and aluminium co-doped sample. This suggest that a trade off between pump absorption and photo darkening is to be made and that a suitable composition is to be found in a trial an error process.

Both fibres exhibit slope efficiencies exceeding 82 % under active operation of the fibre with external high reflector and end facet reflection, which indicates that the ytterbium in both fibres is efficiently incorporated into the glass as Er^{3+}.

High power amplifier silica glass material

C L A I M S :

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1) A high power amplifier comprising:
   a) a diode bar array pump laser which operates at a wavelength λ_{pump} and with a pump power exceeding 5 W,
   b) a coupling device,
   c) a silica host glass fibre with a rare earth doped core co-doped with at least one network modifier (such as aluminium, boron, phosphor) either
      i) in a concentration such that the total atomic network modifier concentration is at least 5 times the rare earth atomic concentration, or
      ii) in a concentration such that the total atomic network modifier concentration is at least equal to the rare earth atomic concentration and in combination with fluorine co-doping in an atomic concentration at least equal to the rare earth atomic concentration
   d) wherein at least part of the core or cladding is doped with at least one phosphorous complex, such as a phosphorous complex having the formula$P_4O_{8-x}(OH)_{4+2x}$, $0 \leq x \leq 2$,
   e) an output delivery fibre, and
   f) wherein the wavelength λ_{pump} is resonant with said rare earth doping absorption band.

2) A high power amplifier according to claim 1 wherein the rare earth doping is ytterbium in a concentration exceeding 0.1 atomic percent, such as more than 0.2 atomic percent, such as more than 0.3 atomic percent, such as more than 0.5 atomic percent, such as more than 1.0 atomic percent.

3) A high power amplifier according to claim 2 wherein the network modifier is aluminium and said network modifier atomic concentration is at least 7 times the ytterbium atomic concentration, such as at least 8 times the ytterbium concentration, such as at least 10 times the ytterbium concentration, such as at least 12 times the ytterbium concentration, such as at least 14 times the ytterbium concentration.

4) A high power amplifier according to any one of the preceding claims wherein said silica host glass fibre has a core diameter $d_{core} > 4$ µm with a numeric aperture less than 0.1, and a first cladding diameter > 30 µm with a numeric aperture larger than or equal to 0.4, surrounded by a second cladding comprising either polymeric material or an air/glass microstructure, and wherein said coupling device is a fused fibre bundle tapered to fit in numeric aperture to the numeric aperture of the first cladding and the fibre bundle fibres are attached to one or more diode bar array lasers.

5) A high power amplifier according to any one ofthe preceding claims wherein between said coupling device and said silica host glass fibre is formed a first fibre Bragg grating, and wherein between said silica host glass fibre and said output delivery fibre is formed a second fibre Bragg grating.

6) A high power amplifier according to claim 5 where said first and second fibre Bragg gratings are formed by fusion splicing a section of fibre wherein the fibre Bragg grating is formed to the respective fibre ends.

7) A high power amplifier according to claim 5 where said rare earth doped core is additionally co-doped with germanium and said first and second Bragg gratings are written directly into said rare earth doped core.

8) A high power amplifier comprising
   a) a diode bar array pump laser which operates at a wavelength λ_{pump} and with a pump power exceeding 5 W,
   b) a coupling device,
   c) a silica host glass fibre with a rare earth doped core co-doped with network modifiers (aluminium, boron, phosphor)
   d) an output delivery fibre
   e) where said rare earth doped core either
      i) during or after formation of said silica host glass into a rod pre-form it is loaded with hydrogen and/or deuterium
      ii) after drawing and coating of said silica host glass into a fibre form it is loaded with hydrogen and/or deuterium.

9) A high power amplifier according to claim 8 wherein said silica host glass fibre holds a core diameter $d_{core} > 4$ µm with a numeric aperture less than 0.1, and a first cladding diameter > 30 µm with a numeric aperture larger than or equal to 0.4, surrounded by a second cladding comprising either polymeric material or an air/glass microstructure, and wherein said coupling device is a fused fibre bundle tapered to fit in numeric aperture to the numeric aperture of the first cladding and the fibre bundle fibres are attached to diode bar array lasers.

10) A high power amplifier according to any one of claims 8 and 9 wherein between said coupling device and said silica host glass fibre is formed a first fibre Bragg grating, and wherein between said silica host glass fibre and said output delivery fibre is formed a second fibre Bragg grating.

11) A high power amplifier according to claim 10 where said first and second fibre Bragg grating are formed by fusion splicing a section of fibre wherein the fibre Bragg grating is formed to the respective fibre ends.

12) A high power amplifier according to any one of claims 10 1nd 11 wherein said rare earth doped core is additionally co-doped with germanium and said first and second Bragg gratings are written directly into said rare earth doped core

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13) A high power amplifier according to any one of claims 8-12 wherein the rare earth doping is ytterbium in a concentration exceeding 0.1 atomic percent, such as more than 0.2 atomic percent, such as more than 0.3 atomic percent, such as more than 0.5 atomic percent, such as more than 1.0 atomic percent.

14) A high power amplifier according to claim 13 wherein the network modifier is aluminium and said network modifier atomic concentration is at least 7 times the ytterbium atomic concentration, such as at least 8 times the ytterbium concentration, such as at least 10 times the ytterbium concentration, such as at least 12 times the ytterbium concentration, such as at least 14 times the ytterbium concentration.

15) A waveguide laser or amplifier material comprising
a silica glass host material,
one or more rare earth elements in total concentration c_{RE} at.% (mol.),

one or more network modifier elements selected from the group of tri- or pentavalent atoms of the periodic table of the elements in total concentration c_{NME} at.% (mol.), wherein the ratio of atomic concentrations of the modifier elements to that of the rare earth elements c_{NME}/c_{RE} is larger than 5, and wherein at least part of the core or cladding is doped with at least one phosphorous complex, such as at least one phosphorous complex having the formula $P_4O_{8-x}(OH)_{4+2x}$, $(0 \leq x \leq 2)$.

16) A material according to claim 15 wherein c_{NME}/c_{RE} is larger than 6, such as larger than 7, such as larger than 8, such as larger than 9, such as larger than 10, such as larger than 12, such as larger than 14, such as larger than 20.

17) A material according to claim 15 or 16 wherein the network modifier elements are selected from the group of elements comprising aluminium, phosphor, boron, and combinations thereof.

18) A material according to any one of claims 15-17 silica glass host material further comprising fluorine.

19) A waveguide laser or amplifier material comprising
a silica glass host material,
one or more rare earth elements in total concentration c_{RE} at.% (mol.),
one or more network modifier elements selected from the group of tri- or pentavalent atoms of the periodic table of the elements in total concentration c_{NME} at.% (mol.) , and
fluorine in concentration c_F at.% (mol.),
wherein $c_{NME} \geq c_{RE}$ and $c_F \geq c_{RE}$.

20) A material according to any one of claims 15-19 having been loaded with hydrogen and/or deuterium.

21) A material according to claim 20 wherein the hydrogen and/or deuterium has been added in the form of H_2 and/or D_2 and/or H_2O and/or D_2O.

22) A preform for fabricating an optical fibre comprising a waveguide laser or amplifier material according to any one of claims 15-21.

23) An optical fibre comprising a waveguide laser or amplifier material according to any one of claims 15-21.

24) An optical fibre according to claim 23 comprising a core region surrounded by two or more cladding regions wherein at least one of said core and cladding regions comprises said waveguide laser or amplifier material and is adapted to guide light at a signal wavelength.

25) An optical fibre according to claim 24 wherein at least one other of said core and cladding regions is adapted to guide light at a pump wavelength.

26) An optical fibre according to claim 24 or 25 comprising micro-structural elements in one or more of the core and/or cladding regions.

27) An optical fibre according to claim 26 comprising an air-clad region.

28) A fibre laser or amplifier comprising an optical fibre according to any one of claims 23-27.

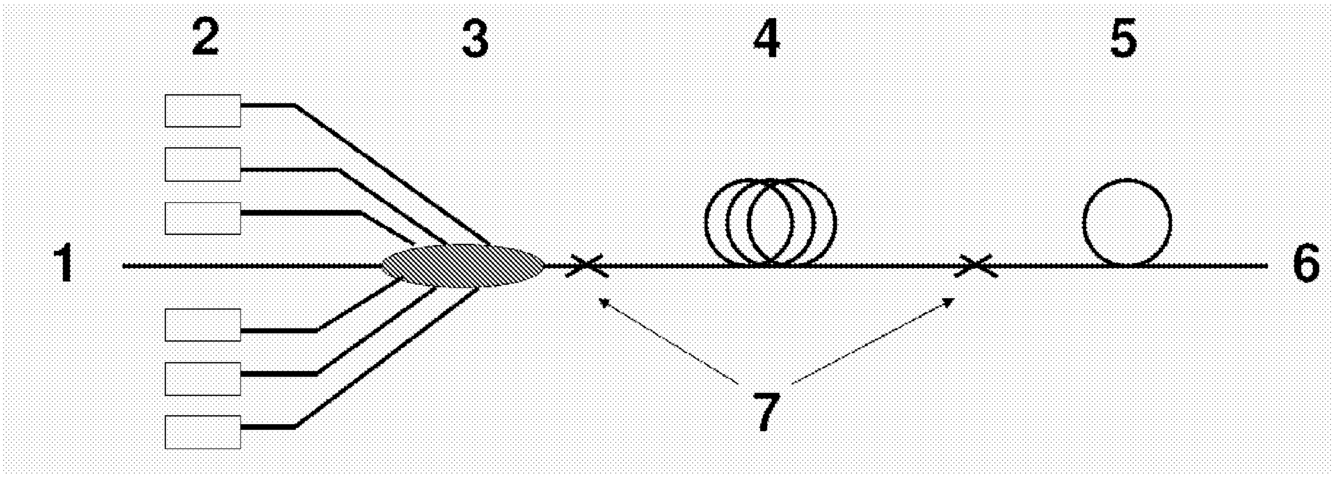

Fig. 1.

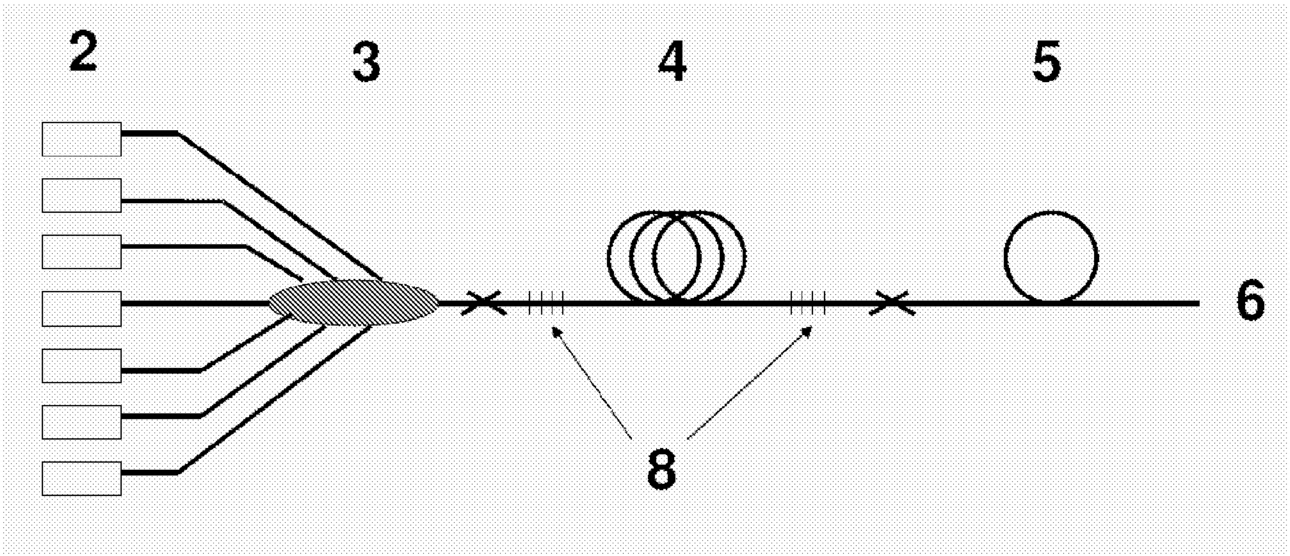

Fig. 2.

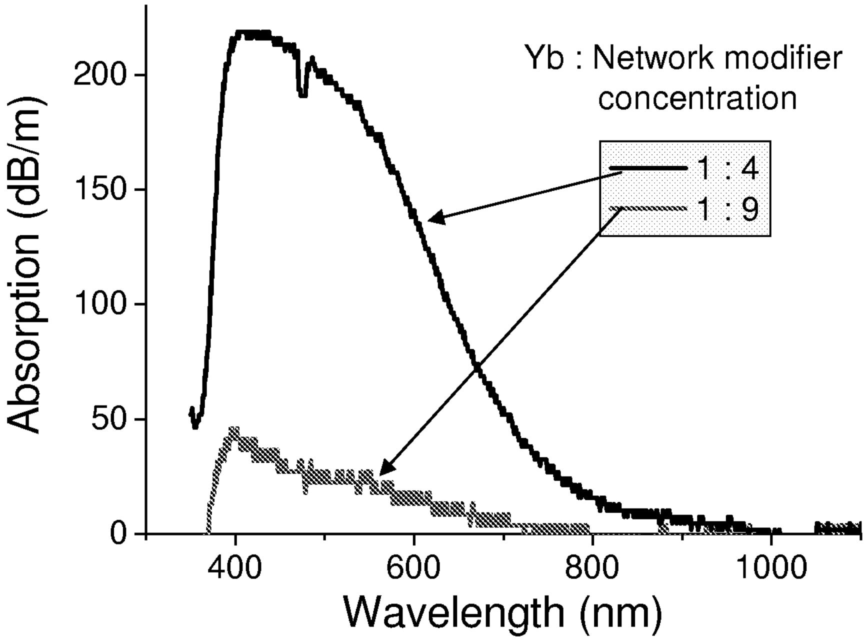
Absorption (dB/m)
0
50
100
150
200
Wavelength (nm)
400
600
800
1000
Yb : Network modifier concentration
1 : 4
1 : 9

Fig. 3.

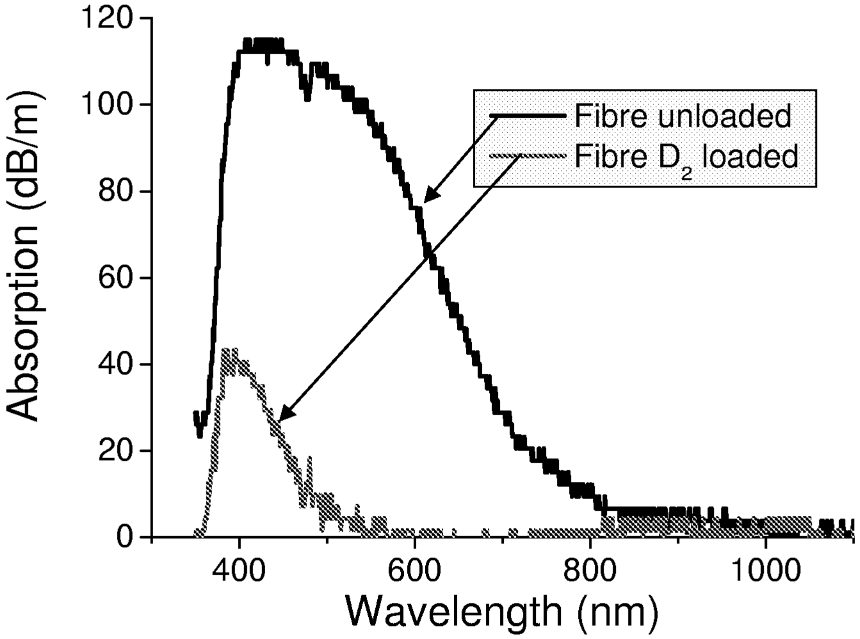
Absorption (dB/m)
0
20
40
60
80
100
120
Wavelength (nm)
400
600
800
1000
Fibre unloaded
Fibre D_2 loaded

Fig. 4.

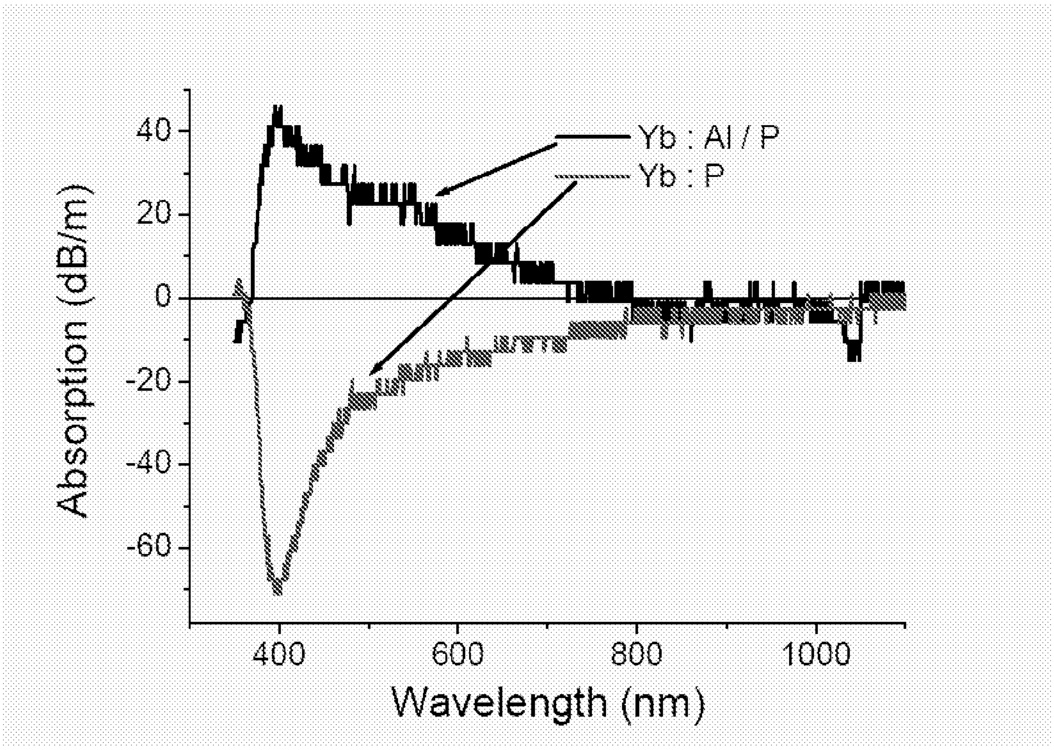
Absorption (dB/m)
Wavelength (nm)
Yb : Al / P
Yb : P
40
20
0
-20
-40
-60
400
600
800
1000

Fig. 5.