

OPTICAL AMPLIFIER AND LASER

This invention relates to an optical amplifier, and in particular to a laser incorporating an optical amplifier.

The impact that an efficient, inexpensive and reliable visible laser source would have on data storage, display technology, undersea communications and optical processing has provided the stimulus for much recent work on solid state visible lasers. One approach that has yielded much success is the use of upconversion processes within rare earth doped materials to produce laser emission at a wavelength significantly shorter than the pump wavelength. Applied to bulk crystals, lasing has been demonstrated at 380nm in Nd:LaF₇, and at 551nm and 671nm in Er:YLiF₄ (see MACFARLANE, R. M., TONG F., SILVERSMITH, A. J., AND LENTH, W.: 'Violet cw neodymium upconversion laser', Appl. Phys. Lett., 1988, 52, (16), pp. 1300-1302, and MACFARLANE, R. M.: 'Dual wavelength visible upconversion laser', Appl Phys. Lett., 1989, 54, (23), pp. 2301-2302, respectively). Unfortunately, all of these schemes require liquid nitrogen cooling. However, the recent demonstration of visible lasing at 480nm in Tm³⁺-doped fluoride fibre (see ALLAIN, J. Y., MONERIE, M AND POIGNANT, H.: 'Blue upconversion fluorozirconate fibre laser', Electron. Lett., 1990, 26 (3), pp. 166-168) coupled with the demonstration of room temperature lasing at red, green and blue wavelengths in praseodymium doped fluorozirconate glass fibre (see SMART, R. G., HANNA, D. C., TROPPER, A. C., DAVEY, S. T., CARTER, S. F., SZEBESTA, D.: 'CW upconversion lasing at blue, green and red wavelengths in an infrared-pumped Pr³⁺-doped fluoride fibre at room temperature', PD paper, CLEO 91, Baltimore, Maryland, USA (also published in Electron. Lett., 1991, 27, (14), pp 1307-1309) has dramatically changed the viability of such upconversion pumped laser schemes.

The applicants have determined that significant gain at 850nm can be achieved when erbium doped fluorozirconate

fibre is pumped at 800nm. This has been reported in Whitley et al "23dB gain up-conversion pumped erbium-doped fibre amplifier operating at 850nm", Electron. Lett., 17 January 1991, pp 184-186 and in Millar et al "Efficient up-conversion pumping at 800nm of an erbium-doped fluoride fibre laser operating at 850nm", Electron. Lett., 25 October 1990, pp 1871-1873. The 850nm emission observed originates from the $^4S_{3/2}$ level, and requires the sequential absorption of 800nm pump photons. The present invention is based on the observation by the applicants that there is also green fluorescence which is ascribed to a transition between the $^4S_{3/2}$ level and the $^4I_{15/2}$ ground state of the system (Fig. 1). In bulk crystals doped with erbium (Er:YLiF₄) this is a well known transition, and has resulted in upconversion lasing at 551nm when cooled to 77K. (See McFarlane *ibid* - Appl. Phys. Lett 54(23))

In such bulk crystal lasers, ions are excited into the upper laser level predominantly through an ion-ion interaction between ions residing in the $^4I_{11/12}$ manifold. However, in lightly-doped fluorozirconate fibre, ion-ion interactions are negligible, and the dominant excitation mechanism is attributed by the applicant to excited state absorption (ESA) of pump photons.

Fig. 1 represents the energy levels of the trivalent erbium ion, with the relevant green lasing transition indicated between the $^4S_{3/2}$ level and the $^4I_{15/2}$ ground state. The upper laser level may be populated by the sequential absorption of 801nm pump photons in a process which involves excitation of ground state ions into the $^4I_{9/2}$ band, some of which then branch into the $^4I_{11/2}$ and the $^4I_{13/2}$ levels. These ions are then further excited by pump photons into the $^4F_{3/2}$, the $^2H_{11/2}$ and other levels. A large proportion of the ions in these higher energy levels then relax into the $^4S_{3/2}$ upper laser level, from which a direct transition to the ground state is responsible for the green emission.

The present invention provides an optical amplifier comprising a fluorozirconate waveguide doped with erbium

ions, and an optical pump means coupled to the waveguide to provide an optical pump signal for exciting the erbium ions into the $^4S_{3/2}$ energy level by ESA of pump photons, characterised in that said pump signal is capable of providing a population inversion of erbium ions between the $^4S_{3/2}$ energy level and the $^4I_{15/2}$ energy level, whereby the amplifier provides optical gain at about 546nm.

The waveguide may conveniently comprise a fluorozirconate optical fibre waveguide but other types of waveguide may be employed. For example, it is expected that a useful configuration would be a planar waveguide structure formed by doping a fluorozirconate glass substrate. High dopant concentration would lead to compact (short waveguide length) devices.

The invention has been demonstrated in standard ZBLAN fluorozirconate waveguides; the proportions of the glass components is not expected to be critical.

The pump may be coupled to the fibre by any known appropriate technique. The high numerical aperture fluorozirconate fibre may be spliced to a silica fibre so that readily-available fused couplers, for example, can be used to couple pump and signal sources to the doped fibre.

The $^4S_{3/2}$ energy level of the erbium ions can be excited by pump wavelengths in the range 791nm to 812nm, preferably 801nm.

The invention also provides a laser comprising an optical amplifier and a pair of reflectors, the optical amplifier being as defined above, and the reflectors being positioned, one at each end of the waveguide, the reflectors defining a resonant cavity and having reflectivities such as to provide lasing action at about 546nm when the waveguide is pumped by the pumping means.

The reflectors, which may be mirrors or other reflectors such as Sagnac loop reflectors, define a Fabry-Perot cavity, and in known manner are selected to provide reflections sufficient to sustain lasing only at the desired wavelength.

When pumped at 801nm the green emission suffers from competition with the 4-level 850nm transition. The applicants have determined that, for lasing to occur on this $^4S_{3/2}-^4I_{13/2}$ transition, it is necessary to pump ions out of the, long-lived, $^4I_{13/2}$ terminal state. In the 801nm pumped scheme, this condition is met through the strong pump ESA out of $^4I_{13/2}$ state.

It has been found preferable to use a pump wavelength of about 971nm. In this 971nm pumping scheme, a population is allowed to build up in the $^4I_{13/2}$ level, and thus reduce the likelihood of transitions at 850nm.

The dopant concentrations useful with the present invention are governed by certain general criteria applicable to doped waveguide amplifiers. For low dopant levels of about 0.01 wt% (100ppm by weight), the length of the doped waveguide must be long enough to provide the required gain, but this competes with the fibre background loss of about 0.2dB/m which effectively diminishes the amplifier or laser performance. To optimise the length-density product, values of concentration of 0.1wt% (1000ppm by weight) are typically chosen. At a concentration of about 1wt% (10⁴ppm by weight), various ion-ion interactions occur which degrade the amplifier or laser performance. At concentrations in excess of about 4wt% (4x10⁴ppm by weight), the glass becomes unstable and unusable. These considerations are well known, and the level of dopant required in a given application can be readily determined.

These considerations are well known, and the level of dopant required in a given application can be readily determined. Thus, the upper limit to dopant concentration is imposed by the effect of the ion-ion interactions. This process occurs when two or more ions are sufficiently close to each other within the fibre to exchange energy. Such an energy transfer usually results in one ion being excited to a higher energy level and the other ion decaying to the ground state. Though, in some cases, this mechanism can be usefully employed to excite a particular energy level, it is

more often a parasitic process and should, therefore, be avoided. In a fluoride fibre, ion-ion interactions can be avoided if the dopant level is kept below around 1wt%.

The lower limit for dopant concentration is set by fibre background loss. In a fibre, the total propagation loss consists of two components, one due to the ionic loss and the other due to the fibre background loss. The first of these loss terms is useful, whilst the second is not. If the dopant concentration is reduced, then the ionic loss reduces also (i.e. the ionic loss coefficient is linearly proportional to the dopant concentration). In a doped fibre device, one clearly wants the useful ionic loss to dominate the parasitic background loss. For erbium-doped fluoride fibre of typical loss and with typical fibre parameters, this condition is satisfied for dopant concentrations above 0.001wt% (10ppm by weight). As such this sets the practical lower limit to dopant concentration.

On the basis of the above criteria, waveguide lengths will generally be in the range 0.1 to 10m, with lengths in the range 1 to 5m being preferred.

The present invention also provides a method of amplifying and providing lasing at a wavelength of around 546nm, as described in the claims.

The invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a diagram showing the energy levels of a trivalent erbium ion in a fluorozirconate host;

Figures 2 and 3 are schematic diagrams of first and second forms of laser constructed in accordance with the present invention;

Figure 4 is a graph of the absorbed pump power at threshold as a function pump wavelength for the laser of Figure 2;

Figures 5 and 6 are graphs of the power emitted at a wavelength of 546nm by the lasers of Figures 2 and 3 when pumped at at 801nm and 971nm respectively, as a function of

launched pump power; and

Figure 7 is a schematic diagram of a third form of laser constructed in accordance with the present invention.

5 Referring to Figure 1, lasing at a wavelength of 546nm is achieved by establishing a population inversion between the $^4S_{3/2}$ upper level and the $^4I_{15/2}$ ground state. Two alternative pump excitation schemes can be employed to achieve this inversion. In the first, pump light at a
10 wavelength of about 801nm is used to excite ions into the $^4I_{9/2}$ level, a proportion of which excited ions then branch into the long-lived $^4I_{11/2}$ and $^4I_{13/2}$ states. These ions then undergo further excitation through the sequential absorption of pump photons. This process of pump excited state absorption (ESA)
15 excites ions into the $^2H_{11/2}$ and $^4F_{3/2}$ states, from where they decay non-radiatively into the $^4S_{3/2}$ upper laser level.

In the second excitation scheme, pump light at a wavelength of about 971nm is used to excite ions into the $^4I_{11/2}$ state from which ESA of pump photons promotes ions into
20 the $^4F_{7/2}$ state. Non-radiative decay from this level then establishes a population in the $^4S_{3/2}$ upper laser level, from which green lasing can once again occur to the ground state.

Referring now to Figure 2, a laser according to the present invention is based on a 2.4m length of standard
25 formulation ZBLAN fluorozirconate fibre 2 doped to about 0.05wt% (500ppm by weight) with erbium ions. The fibre Δn is 0.007 and the LP11 mode cut-off is 790nm. The fibre background loss at both pump and signal wavelengths is estimated to be around 1.2dB/m. A simple Fabry-Perot laser
30 cavity is formed by butting an input end 4 of the fibre 2 against a dielectric mirror 6, the mirror being highly reflecting at 546nm and highly transmitting at 800nm/850nm; and by butting an output end 8 of the fibre against a mirror
10 which is 65% reflecting to green light and highly
35 transmitting at 800nm/850nm. 801nm pump light is derived from an Ar^+ pumped Ti:Sapphire laser 12 which is end-fire

launched through the input mirror 6. A pump blocking filter 12 is used to separate the remnant pump and green emission after transmission through the output mirror 10.

5 Fig. 5 depicts the evolution of output power at a wavelength of around 546nm with the absorbed pump power at a wavelength of 801nm. The threshold for lasing is around 100mW absorbed pump power, which corresponds to a launched pump power of 160mW. The maximum output power achieved is
10 23mW for an absorbed pump power of 780mW. Two definite slopes are apparent from this lasing characteristic. Taking the gradient of the initial part of this graph, a slope efficiency against absorbed pump power of 11% is obtained. The saturation behaviour beyond pump powers of 250mW is

thought to be associated with the competing laser transition at 850nm. In general, it is found that the linear region below 250mW corresponds to green lasing alone, whereas the reduced slope beyond 250mW corresponds to simultaneous lasing at both 850nm and 546nm.

To assess the sensitivity to pump wavelength, the pump power absorbed at threshold is measured for different pump wavelengths. These results are shown in Figure 4. Lasing action in the green could be sustained using pump wavelengths ranging from 791 to 812nm, though most efficient operation was achieved using a pump wavelength of 801nm. The relative insensitivity to pump wavelength (less than 20% change in lasing threshold for $\pm 5\text{nm}$ change in pump wavelength) means that standard Fabry-Perot laser diodes could be used as a pump source. It should also be noted that the lasing threshold rises more rapidly when the pump wavelength is moved to longer wavelengths. This asymmetry could possibly be explained by the presence of an ESA at 550nm between the $^4\text{I}_{13/2}$ and $^2\text{H}_{9/2}$ levels. In tuning the pump wavelength, the relative rate at which ions are pumped out of the $^4\text{I}_{13/2}$ and $^4\text{I}_{11/2}$ levels is changed, ESA from the $^4\text{I}_{13/2}$ level being centred at 790nm, and ESA from the $^4\text{I}_{11/2}$ level being at 810nm. The sharp rise in lasing threshold observed when the pump wavelength is tuned beyond 805nm could, therefore, be explained by a reduced pump depopulation of the $^4\text{I}_{13/2}$ level, coupled with the strong signal ESA in the green from this level.

As mentioned above, simultaneous lasing at 850nm and 546nm is observed under certain conditions, though at present it is not clear exactly what dictates which lasing transition dominates. It is also noted that, if the laser is not operated for a period of time greater than a few hours, then the 850nm transition preferentially lases instead of the green transition, the green lasing threshold having risen significantly ($>1\text{W}$). However, once lasing has been achieved in the green, the green threshold drops consistently to a value around 100mW, whereas the 850nm lasing is suppressed.

This 'memory' of the recent past of the laser is consistently observed, though difficult to investigate because of its several hour period.

Spectral analysis of the green laser emission indicates simultaneous lasing on several lines ranging from 543nm to 548nm, variations in pump wavelength and power causing changes, as yet to be quantified, in the output spectrum.

The slope efficiency with which 801nm pump photons are converted into green light is around 11%. This figure is quite remarkable when one considers the pump excitation mechanism and the background loss in the fibre at both pump and signal wavelengths. In a system with such complicated population dynamics, it is difficult to predict the exact effect which these losses will have on the device efficiency and threshold, but a reduction of the 2.9dB single pass pump loss and the 5.8dB round-trip loss at the lasing wavelength will result in a substantial increase in overall efficiency.

As described above, when pumped at 801nm the green emission suffers from competition with the 4-level 850nm lasing transition. The applicants have determined that, for lasing to occur on this $^4S_{3/2} - ^4I_{13/2}$ transition, it is necessary to pump ions out of the long-lived, $^4I_{13/2}$ terminal state. In the 801nm pumped scheme described above, this condition is met through the strong pump ESA out of the $^4I_{13/2}$ level.

Figure 3 shows an embodiment similar to that of Figure 2 with common elements assigned the same reference numerals. In this case the laser is pumped by a 971nm optical pump signal derived from the Ar^+ pumped Ti:Sapphire laser 12. In this pumping scheme, a population is allowed to build up in the $^4I_{13/2}$ level to reduce the likelihood of lasing at 850nm.

As in the embodiment of Figure 2, a laser cavity is formed between a highly-reflecting mirror 6 and a mirror 10 65% reflecting to green wavelengths. The 3m fluoro-zirconate fibre 14 used in Figure 3 has a An of 0.014, and a cut-off wavelength of around 790nm. The fibre background loss at the

pump wavelength has been measured as 0.25dB/m, which for this cavity corresponds to a 0.75dB loss at the pump wavelength of 971nm. Initial measurements using this fibre 14 have shown that green lasing can indeed be achieved when pumping at 5 971nm; and, although 850nm fluorescence is observed, no competing lasing is noted.

Figure 6 shows the evolution of lasing output power with launched pump power for the laser of Figure 3. The pump threshold improves to 40mW absorbed (50mW launched), and the 10 slope efficiency increases to 15% with respect to launched pump power. The maximum output power observed is 27mW for a launched pump power of 500mW.

The present invention provides room temperature lasing at 546nm on the $^4S_{3/2} - ^4I_{15/2}$ transition of erbium, in a 15 fluorozirconate glass host when pumped at wavelengths of either 801nm or 971nm.

In both pumping schemes, lasing output powers in excess of 20mW have been observed combined with slope efficiencies in excess of 10%. Though further measurements 20 are required fully to assess the relative merits of 801nm and 971nm pumping it appears that suppression of the parasitic 850nm lasing transition can be achieved by pumping at a wavelength of 971nm.

The potential impact of an efficient and reliable 25 visible laser source is vast. The particular attraction of either of the above schemes is that they employ a single pump laser operating at a wavelength compatible with the present range of commercially-available, high power FP laser diodes. Erbium doped fluorozirconate fibre lasers may offer efficient 30 means of converting practical semiconductor laser diodes into the much coveted blue/green region of the spectrum.

Figure 7 shows an embodiment similar to that of Figure 3 with common elements assigned the same reference numerals. In this instance, the 971nm pump signal is obtained from a 35 semiconductor laser (18) which is expected to operate successfully on the basis of the fibre characteristics

determined above. Pumping at about 800nm with a semiconductor source is also expected to be readily achieved.

CLAIMS

1. An optical amplifier comprising a fluorozirconate waveguide doped with erbium ions, and an optical pump means coupled to the waveguide to provide an optical pump signal
5 for exciting the erbium ions into the $^4S_{3/2}$ energy level by excited state absorption of pump photons, characterised in that said pump signal is capable of providing a population inversion of erbium ions between the $^4S_{3/2}$ energy level and the $^4I_{15/2}$ energy level, whereby the amplifier provides optical
10 gain at about 546nm.
2. An amplifier as claimed in claim 1, wherein the waveguide is in the form of an optical fibre.
3. An amplifier as claimed in claim 1 or claim 2, wherein the optical pump signal has a wavelength in the range of
15 791nm to 812nm.
4. An amplifier as claimed in claim 3, wherein the optical pump signal has a wavelength of about 801nm.
5. An amplifier as claimed in any one of claims 1 to 4, wherein the fluorozirconate waveguide is doped to between
20 0.001wt% (10ppm by weight) and 1wt% (10^4 ppm by weight).
6. An amplifier as claimed in claim 5, wherein the fluorozirconate waveguide is doped to a maximum of about 0.1wt% (10^3 ppm by weight) with erbium ions.
7. An amplifier as claimed in claim 5, wherein the
25 fluorozirconate waveguide is doped to about 0.05wt% (5×10^2 ppm by weight) with erbium ions.
8. An amplifier as claimed in any one of claims 1 to 7, wherein the optical pump source is a semiconductor laser diode.



9. A laser comprising an optical amplifier and a pair of reflectors, the optical amplifier being as claimed in any one of claims 1 to 8, and the reflectors being positioned one at each end of the waveguide, the reflectors defining a resonant cavity and having reflectivities such as to provide lasing action at about 546nm when the waveguide is pumped by the pumping means.

10. A laser as claimed in claim 9, wherein the reflectors are mirrors.

10 11. A method of amplifying an optical signal in the green region of the visible spectrum, the method comprising:

optically pumping a fluorozirconate glass optical waveguide doped with erbium ions to promote said erbium ions into the $^4S_{3/2}$ level by excited state absorption; and

15 coupling the optical signal to be amplified into said waveguide wherein the waveguide provides optical gain at around 546nm through stimulated emission from the $^4S_{3/2}$ level.

12. A method of amplifying an optical signal having a wavelength in the green region of the visible spectrum, the method comprising:

20 optically pumping a fluorozirconate glass waveguide doped with erbium ions to create a population inversion of erbium ions between the $^4S_{3/2}$ energy level and the $^4I_{15/2}$ energy level wherein erbium ions are promoted to the $^4S_{3/2}$ energy level by excited state absorption; and

25 coupling the optical signal to be amplified into said waveguide, wherein the waveguide provides optical gain at around 546nm through stimulated emission of photons from erbium ions relaxing from the $^4S_{3/2}$ level back to the $^4I_{15/2}$ level.

13. A method of providing laser emission in the green region of the visible spectrum, the method comprising:

optically pumping a laser cavity, the cavity comprising a fluorozirconate glass lasing medium doped with



erbium ions and reflectors arranged about the medium to define the cavity, wherein said pumping produces a population inversion of erbium ions between the $^4S_{3/2}$ and $^4I_{15/2}$ energy levels by excited state absorption, and wherein stimulated emission at a lasing wavelength of about 546nm is provided.

