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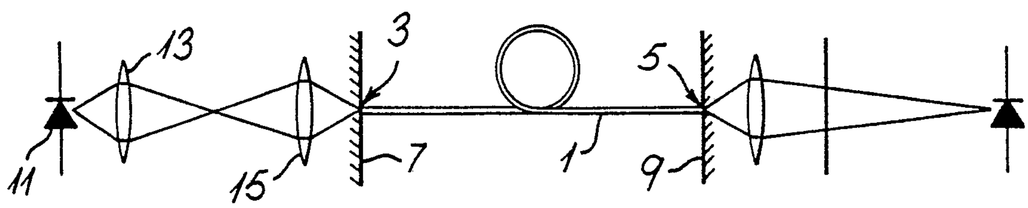

(57) Abstract

An active device comprising a length of doped fibre (1) and an end-coupled pump source (11). The fibre (1) is of single-mode geometry and incorporates rare-earth or transition metal dopant ions. These latter are incorporated at a low-level uniform concentration (< 900 ppm). The fibre host (1) selected exhibits an inherently ultra low attentuation loss (<40 dB/km) at the emission wavelength. The fibres (1) are generally of long length (e.g. 5 m to 300 m) and may be coiled for compact packaging. The fibre (1) may be formed as part of a Fabry-Perot cavity (1, 7, 9); or, as a ring cavity (fig. 8) using a doped fibre coupler (29) spliced to form a ring (27). Q-switch and mode-locking devices (19) and gratings (25) may be included as part of the Fabry-Perot cavity to allow pulse-mode operation and/or wavelength tuning, respectively. The fibre (1) may be utilised as an amplifier and a coupler arrangement (fig. 10) is described. Examples are given for devices using Neodymium, Erbium or Praseodymium doped-fibre.

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FIBRE-OPTIC LASERS AND AMPLIFIERS

Technical Field

This invention concerns improvements in or relating to fibre-optic lasers and amplifiers, these being active devices of the type in which useful gain is afforded by the stimulated emission of radiation. These devices comprise: a length of fibre, in which is incorporated a distribution of active dopant ions; and, an optical-pumping source coupled to the fibre.

Hybrid semiconductor-diode and optical fibre technologies are both well advanced. However, full integration of the components of these technologies has yet to be achieved. There is a need for active devices that would be readily compatible with single-mode fibre systems and that accordingly could bridge these technologies.

Background Art

Details of multimode fibre-geometry lasers were published in the early part of the last decade (1973). By way of background, the interested reader is referred to the following articles by J.Stone and C.A.Burrus:- "Neodymium - doped silica lasers in end-pumped fibre geometry", Appl Phys Lett 23 pp 388-389 (Oct 1973); and "Neodymium - Doped Fibre Lasers: Room Temperature cw Operation with an Injection Laser Pump", Appl Optics

13 pp 1256-1258 (June 1974). The laser described comprised stub lengths of fibre (about 1 cm length) with core diameters ranging from 800 to 15 microns. Continuous (cw) lasing action was demonstrated using an end-coupled gallium arsenide (GaAs) injection laser as optical pumping source.

Notwithstanding considerable advances made in single-mode fibre technology, and the passage of more than a decade since that time, until now no fibre-laser fully compatible with single-mode fibre systems has been developed.

DISCLOSURE OF THE INVENTION

The present invention is intended to meet the need aforesaid, and to provide a fibre-laser or amplifier capable of single-mode operation and compatible with single-mode fibre systems.

In accordance with the invention thus there is provided a fibre-optic laser or amplifier, an active device of the type in which gain is provided by the stimulated emission of radiation, this device comprising:-

a length of cladded glass fibre incorporating active dopant ions; and,

an optical pump source coupled thereto;

wherein the device is <u>characterised in that</u>:-

the fibre is of single-mode geometry and capable thus of sustaining single transverse mode propagation at the emission wavelength; and,

the active dopant ions, ions of rare-earth or transition metal, are incorporated in the fibre at a low-level uniform concentration, the fibre providing an ultra low loss host therefor.

It is convenient to use as the fibre of single-mode geometry, a fibre having a step-index profile. Other types of single mode fibre, however, are not precluded from the scope of this invention and may have the form of polarisation maintaining fibres, polarising fibres dispersion-shifted fibres and helical-core fibres. Dopants may be incorporated in the fibre core, in the fibre cladding or in both. More than one dopant species may be incorporated to extend device versatility.

Moreover, many passive fibre devices could be used, in conjunction with the active device, to provide spectral control or temporal switching:-

1. Gratings deposited on to the fibre after the field has been exposed by removing the fibre cladding by chemical or mechanical means. Spectral-line narrowing of the laser can thus be obtained;

2. Acousto-optic modulation of the fibre laser either

longitudinally or transversely using piezo-electric materials or acoustic-waves. Switching and modulation can thus be achieved, including cavity Q-switching and mode-locking; and, 3. Fibre polarisers, either exposed field devices or using single-polarisation fibre which can be used to control the output polarisation state.

By using a new manufacturing process (S.B. Poole et al "Fabrication of low-loss optical containing rare-earth ions", Electron Lett 21 pp 737-738 (1985)) it is possible now to fabricate single-mode fibres with uniform low dopant concentrations up to 900 ppm, whilst maintaining the low-losses which are characteristic of modern telecommunications fibres (ie. $\lesssim$ 40 dB/km and typically ~1/dB/km). These fibres are fully compatible with existing fibre devices such as fused couplers, polarisers, filters and phase modulators, (eg to achieve single polarisation operation, wavelength selection, mode locking and Q-switching), and consequently it is possible to envisage a new all-fibre laser/amplifier technology.

Single-mode fibre lasers and amplifiers, as considered herein, possess a number of advantages over their bulk counterparts. By virtue of their small cores (typically 8 μm diameter and less), very-low thresholds (~100μW) and high gains can be achieved. Also since typically fibre diameters overall are about 100 μm, thermal effects prove to be minimal.

As a result of these attributes, useful laser action or amplifier gain can be produced for less commonplace rare-earth transition metal dopants and for less commonplace optical transitions, even where the optical transitions involved are inherently weak. Room temperature continuous laser operation has even been found possible for 3-level laser systems which have previously only operated in a pulsed mode.

Since the dopant concentration is so low, manufacture can be economical. A typical device might use as little as 0.1 μg of dopant oxide.

Although impliedly, at the lowest dopant concentrations lasers and amplifiers, as considered herein, incorporate fibres of a relatively long length, eg 5 cm and greater up to at least 300 m, (the length of the fibre serves as a cladding mode filter and gain is distributed), compact devices can be produced. A coiled 1 m length fibre laser can be readily fitted into a 1 cm^3 enclosure.

Silica, if selected as the fibre host medium, has good power handling characteristics. Moreover in the presence of a high silica glass host, the optical transitions of the rare-earth or transition metal dopant ions are substantially broadened. This, as detailed below allows the realisation of both tunable lasers and broad-band amplifiers.

Most rare-earth dopants and some transition metal dopants have now been investigated experimentally. Remarkably, all exhibit windows in which losses are low notwithstanding the close proximity of high-loss absorption bands. This enables the construction of extremely long amplifiers and lasers. A 300 m length laser has now been proven under test.

In summary, the active devices considered herein provide improved sources/amplifiers for telecommunications applications because they can handle high powers without damage, they provide smaller/lighter/cheaper general purpose active devices and may in conjunction with other fibre devices (eg gratings) provide new and powerful signal processing functions. Note also that non-linear effects can be readily achieved at the optical power levels obtained in fibre lasers, affording exploitation of a number of simultaneous laser and non-linear effects.

BRIEF INTRODUCTION OF THE DRAWINGS

In the drawings accompanying this specification:-

Figure 1, is a plan-schematic illustrating an experimental arrangement for a diode-pumped fibre Fabry-Perot cavity laser;

Figure 2 is a graph depicting output power as a function of pump power, measured for the laser of the preceding figure;

Figure 3 is a plan-schematic illustration of a Q-switched cavity laser, a variant of the laser of figure 1 preceding;

Figure 4 is a plan-schematic illustration of a tunable cavity laser, a variant of the lasers of figures 1 and 3;

Figure 5 is a graph depicting absorption spectra for neodymium-, erbium - and terbium - doped silica fibre;

Figures 6 and 7 are graphs showing emission spectra for erbium and for praseodymium - doped fibres, these showing the tuning response of lasers including these fibres;

Figure 8 is a plan-schematic illustrating an experimental arrangement for a dye-laser pumped fibre ring-cavity laser;

Figure 9 is a graph depicting the output spectrum of the ring-cavity laser shown in the preceding figure; and,

Figure 10 is a plan-schematic illustrating a doped-fibre amplifier.

DESCRIPTION OF EMBODIMENTS

So that this invention may be better understood, embodiments thereof will now be described and reference will be made to the accompanying drawings. The description that follows is given by way of example only.

Referring now to the drawings, a single-mode geometry step-index profile fibre with a germania/silica core doped with 300 ppm of Nd^{3+}, cut off wavelength of 1 μm and an index difference of 1%, was fabricated using the method described in our earlier filed patent application No 8520300 dated 13 Aug 1985, published details of which appear in the article "Fabrication of low-loss optical fibres containing rare-earth ions" mentioned hereinbefore. In summary, high-purity hydrated neodymium trichloride is used as dopant source during a modified chemical vapour deposition (MCVD) process. The trichloride is first dehydrated in the presence of a chlorine dying gas and fused to the walls of a carrier chamber. Cladding glass material such as SiO_2 - B_2O_3 is deposited on the inside wall of a heated silica tube in conventional manner. Thereafter the carrier chamber is preheated to above 1000 °C to obtain a desired vapour pressure. During core deposition the reactants (typically $GeCl_4$ and $SiCl_4$) are mixed with oxygen and passed through the heated dopant chamber where controlled amounts of the rare-earth halide are entrained in the gas flow. The temperature of the MCVD hot zone is chosen such that it is not hot enough to fuse the deposited core-glass layers. This essential feature enables further drying of the materials prior to fusion. This latter drying step is performed by prolonged heating at 900°C or so in the presence of eg. a chlorine gas flow. The unsintered layer is then fused to form a glassy layer, the preform collapsed and a fibre drawn to the described geometry.

A fibre 1 having a length of 2 m and an absorption of 5 dB/m at the pump wavelength of 820 nm was chosen. The loss at the lasing wavelength (1.088 μm) for this fibre was less than 4 dB/km. Figure 1 shows the experimental configuration. The fibre ends 3, 5 were cleaved and directly butted to dielectric mirrors 7, 9 having a high reflectivity (~99.5%) at the lasing wavelength and high transmittance (~80%) for the pump. In order to achieve an elevated cavity finesse it is essential to minimise the fibre end angle and thus ensure intimate contact with the mirror. A York Technology cleaving tool type No. 007 was used and the fibre ends 3, 5 inspected before index-matching to the mirrors 7, 9. Alternatively, reflective coatings, eg. multi-layer dielectric coatings can be deposited directly onto the fibre end faces.

End pumping was by a single-mode GaA1As Laser 11 (Hitachi HLP 1400), which was focussed by a lens arrangement 13, 15 and launched into the fibre with an efficiency of 16%. Lasing threshold was observed for a total semiconductor laser power of 600 μW. This corresponds to an estimated absorped pump-power of only 100 μW in the 2 m long fibre 1 and is an indication of the very low intracavity losses.

The output power as a function of pump power for the fibre laser is shown in figure 2. No saturation of the output was observed at pump powers up to the maximum available (20 mW). Operation of the laser at reduced duty cycle gave no decrease in lasing threshold, indicating that thermal effects are negligible. The fibre laser can therefore be easily operated CW without auxiliary cooling, unlike previous neodymium-doped glass lasers. Modulation of the pump produced relaxation oscillations, from which a cavity finesse of 300 was calculated.

The wavelength of operation of the fibre laser was measured to be 1.088 μm i.e. shifted by approximately 30 nm to longer wavelengths than would be expected for conventional neodymium glass lasers.

It is noted that a fibre grating may be used in place of the end mirror 9 and may be spliced to or formed in the doped fibre (1).

The described laser cavity may be modified to afford Q-Switching. A typical arrangement is shown in

Figure 3. Here a microscope objective 17, an acousto-optic deflector 19 and an output mirror 21 are employed in place of the abutted mirror 9 of figure 1. In a tested configuration, the fibre 1 used had the following characteristics: 3.5 μm core diameter, NA of 0.21, length 3.2 m and a total absorption at the pump wavelength of 97% (corresponding to 300 ppm nd^{3+} content). The loss at the lasing wavelength (1.088 m) was negligable (10dB/km). The fibre ends 3, 5 were cleaved and one end 3 butted to the input dielectric mirror 7. This mirror 7 had a high transmission (T=85%) at the pump wavelength and a high reflectivity (R = 99.8%) at the lasing wavelength, although lower reflectivity mirrors could be advantageously used. The pump source 11 used was as above and light was launched into the fibre with an efficiency of approximately 25%. The CW threshold was 3.7 mW absorbed. The acousto-optic deflector 19 was used in transmission mode, the high-Q state being achieved by electronically removing the applied RF with 2 μs duration pulses. The output mirror 21 used in this configuration had a transmission at the lasing wavelength of 12%. Pulse repetition rate was variable between single shot and 4 kH_z with no change in peak output power or pulse duration.

A mechanical chopper with a mark-space ratio of

1:300 was substituted in the cavity to provide an alternative method of Q-switching. Using an output mirror 21 with a transmission of 65% at the lasing wavelength, output pulses of peak power greater than 300 mW and FWHM of 500 nS at a repetition rate of 400 Hz were then obtained. A saturable absorber may also be used for Q-switching and mode-locking. Possibly this could be incorporated within the fibre as an additional dopant.

The Q-switch arrangement of figure 3 may be supplemented with a beam splitter 23 and a reflection grating 25 as shown in Figure 4.

In the experimental arrangement tested, a 5 m length of Nd^{3+} doped fibre 1 with 15 dB/m unsaturated absorption at 514 nm was used as gain medium. An argon-ion laser was used as pump source. Optical feedback was provided with a plane input mirror 7 (R>99% @ 1.09 μm; T = 80% @ 514 nm) and a diffraction grating 25 (600 lines/mm, blazed at 1 μm). An intracavity pellicle was used as the beam splitter/output coupler 23. The lasing wavelength could be selected by changing the angle of the grating 25. The laser was widely tunable, being tunable over an 80 nm region from 1065 nm to 1145 nm. Threshold occurred at 25 mW input corresponding to only 10 mW absorbed in the fibre. Pulsed and cw operation were demonstrated.

Other rare earth or transition metal dopants can be incorporated in fibre using the technique described, using the appropriate halide dopant precursor. These also exhibit high absorption bands at practical pump wavelengths and low-loss windows at useful emission wavelengths. This is illustrated for the rare-earths erbium (Er^{3+}) and terbium (Tb^{3+}) in Figure 5.

A similar arrangement to that of figure 4 has been tested for erbium-doped fibre. The fibre 1 was 90 cm length with an unsaturated absorption of 10dB/m at 514 nm. This was abutted to an input dielectric mirror 7 (R = 82% @ 1.54 μm; T = 77% @ 514 nm). The diffraction grating, also 600 lines/mm, was blazed at 1.6 μm. A full tuning range of 25 nm from 1.528 to 1.542 and from 1.544 to 1.555 μm was obtained at a pump power three times that of threshold (30 mW) (see fig. 6). This thus spans much of the wavelength region of interest for long-haul fibre-optic communications. Praseodymium-doped fibres also afford tuning. Using a CW Rh6G dye laser at 590 nm and a 1 μm blazed grating a 61 nm tuning range 1048 nm - 1109 nm has been obtained. The threshold occurred at 10 mW absorbed power

The long lengths of fibre 1 may be coiled to afford compact packaging. It is also possible to construct ring-cavity laser structures, an example of which is shown in Figure 8. Here a fibre ring 27 (diameter 70 cm) was produced by splicing together two ports of a fused tapered-coupler 29 made from Nd^{3+} doped fibre. The coupler 29 was designed so that more than 80% of the power of a dye-laser pump 31 at 595 nm was coupled into the ring 27, while at the lasing wavelength less than 10% per round trip was extracted. Coupler losses were measured to be 3 dB at 633 nw (fibre multi-mode), and 1 dB at 1 μm. The fibre used was as in the previous embodiment (Figure 1), although the absorption at the dye-laser pump wavelength of 595 nm is considerably higher (30 dB/m). In this ring laser configuration the pump radiation should be largely absorbed within the ring 27 and not in the leads 1. It is therefore an advantage to construct the coupler 29 from one undoped and one doped fibre, such that the leads do not absorb at the pump wavelength.

Lasing threshold was observed at a dye-laser pump power of 80 mW, which, owing to coupler losses and lead absorption, corresponds to a few milliwatts absorbed in the ring. At the maximum dye-laser power of 280 mW, (estimated ring absorption 20 mW), the ring-laser ouput was 2 mW. Allowing for bi-directional ring-laser ouput, the slope efficiency is estimated to be approximately 20%.

The lasing wavelength was centred at 1.078 μm with a full-width half maximum spectral-width of 4 nm (see figure 9). The shift of 10 nm from the linear configuration is due to a slight mismatch between the coupler wavelength response and the laser gain curve. It may thus be possible to tune the laser wavelength over the full gain curve (90 nm width) by varying the coupler characteristics.

An amplifier arrangement is shown in figure 10. this is constructed using an open-ended 4-port coupler 29, 33 comprised of doped fibre 1. As shown this is inserted into a length of conventional transmission fibre 35. Signal at emission wavelength is propagated along the main fibre 1 which serves as gain medium. Pumping radiation from the source 31 is coupled to the coupling fibre 33 and thence into the main fibre 1.

Increased efficiency can be obtained using a coupler designed to couple the pumping radiation into fibre 1, but which does not couple at the emission wavelength. Moreover, it is an advantage that the lead 33 is of undoped fibre in order to ensure that the pump power is absorbed largely in the selection of amplifying fibre 1.

A single pass gain of 25 dB has been measured for a 3 m length of erbium-doped fibre (300 ppm

Er^{2+}) using a similar arrangement. To prevent the onset of laser action, the optical feedback resulting from fresent reflections was reduced by index matching one end of the fibre. In practice, splicing the fibre into a fibre system would be sufficient to largely eliminate etalon effects, since low-reflectivity splices are readily achievable.

CLAIMS

1. A fibre-optic laser or amplifier, an active device of the type in which gain is provided by the stimulated emission of radiation, this device comprising:-

a length of cladded glass fibre (1) incorporating active dopant ions; and,

an optical pump source (11) coupled thereto wherein the device is characterised in that:-

the fibre (1) is of single-mode geometry and capable thus of sustaining single transverse mode propagation at emission wavelength; and,

the active dopant ions, ions of rare-earth or transition metal, are incorporated in the fibre (1) at a low-level uniform concentration, the fibre providing an ultra-low loss host therefore.

2. A device, as claimed in claim 1, including first and second mirrors (7,9), the fibre (1) being inserted between these mirrors (7,9) and forming a Fabry-Perot cavity.

3. A device, as claimed in claim 1, including a first mirror (7), a reflecting member (9; 25), and wavelength selective tuning means (25), the fibre (1) being inserted between the mirror (7) and the reflecting member (9), and, the tuning means (25) being co-operative with the cavity thus formed.

4. A device as claimed in claim 3, including a reflection grating (25), this serving as reflecting member and as tuning means.

5. A device, as claimed in any one of the preceding claims 2 to 4, wherein a switching member (19) is interposed in the cavity.

6. A device, as claimed in any one of the preceding claims 1 to 5, wherein the fibre (1) is coiled.

7. A device, as claimed in claim 1, wherein the fibre (1) is included as part of an optic-coupler (29), the doped fibre (1) having the form of a ring (27), and providing thus a ring-cavity.

8. A device, as claimed in claim 1, an amplifier, wherein the fibre (1) is included as part of an optic coupler (29), the coupled remainder part of this coupler (29), also a fibre, being open ended.

9. A device, as claimed in claim 1, wherein the dopant ions comprise neodymium, the concentration of these ions being no greater than 900 ppm.

10. A device, as claimed in claim 1 wherein the stimulated emission produced thereby results from a three-level optical transition.

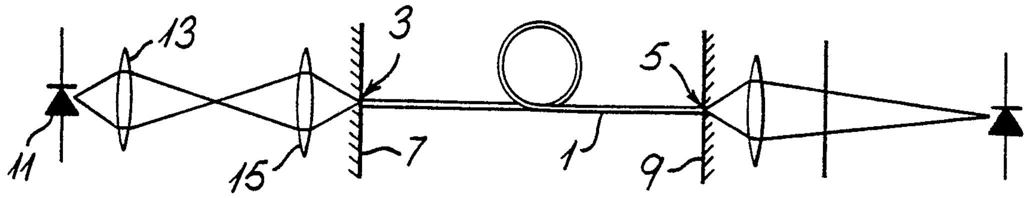
11. A device, as claimed in claim 10, wherein the dopant ions comprise erbium or praseodymium.

12. A device as claimed in claim 11, a Fabry-Perot cavity or ring cavity laser, when operated in CW mode.

13. A device, as claimed in claim 1, when integrated as part of a single-mode fibre transmission system.

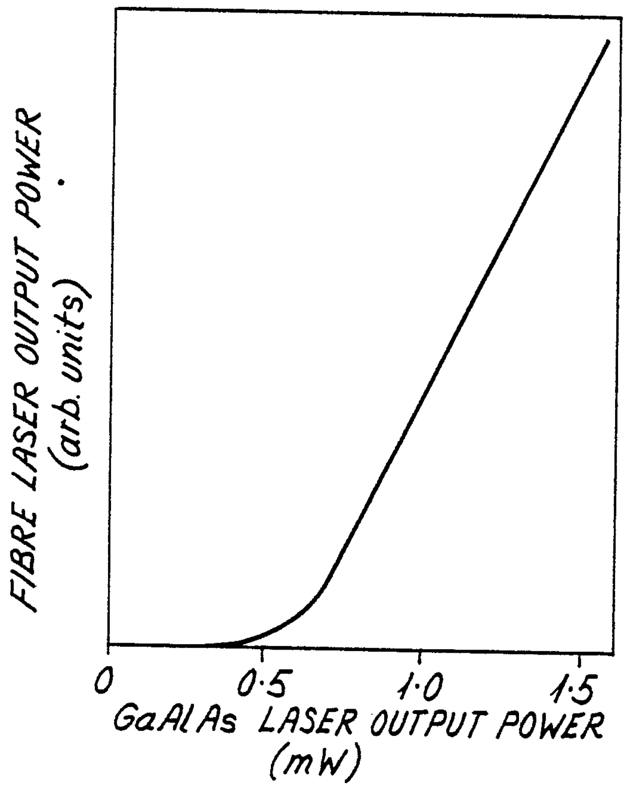
14. A device, as claimed in claim 1, wherein a plurality of different dopant ion species, ions of rare earth or transition metal dopants, are incorporated in the fibre (1).

15. A fibre-optic laser or amplifier constructed, adapted and arranged to perform substantially as described hereinbefore with reference to and as shown in the accompanying drawings.



13
3
5
11
15
7
1
9

Fig. 1



FIBRE LASER OUTPUT POWER
(arb. units)
0
0·5
1·0
1·5
GaAlAs LASER OUTPUT POWER
(mW)

Fig. 2

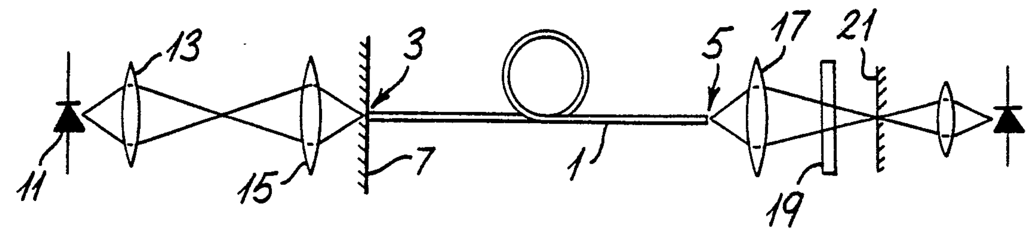


Fig. 3

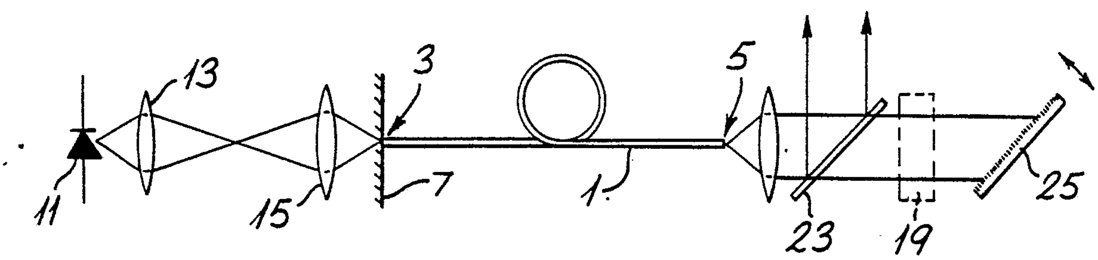


Fig. 4

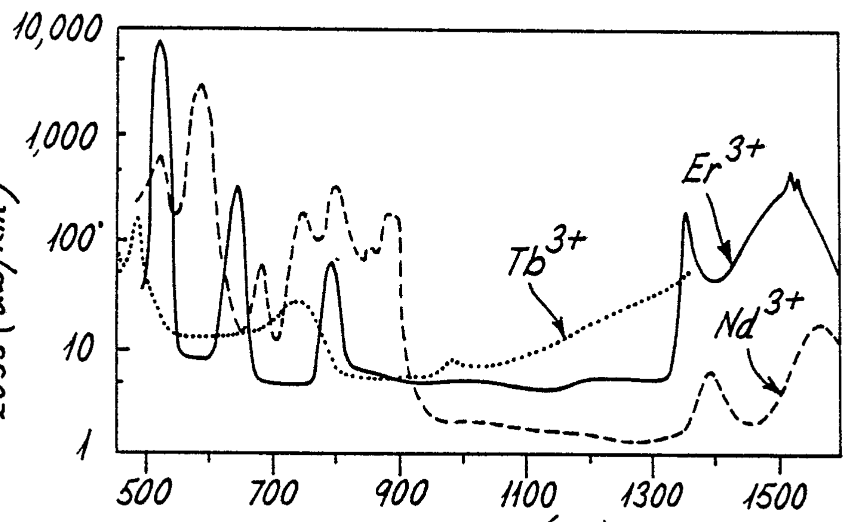


Fig. 5

LASER TUNING RANGE AND FLUORESCENCE SPECTRUM OF Er^{3+} DOPED FIBRE LASER

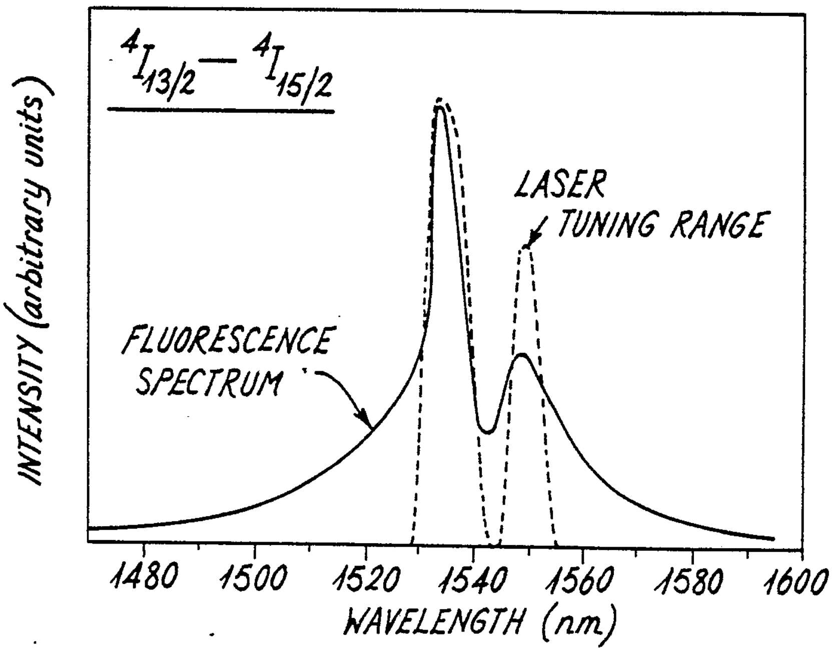


Fig. 6

TUNING RANGE AND FLUORESCENCE SPECTRUM OF Pr-DOPED FIBRE LASER

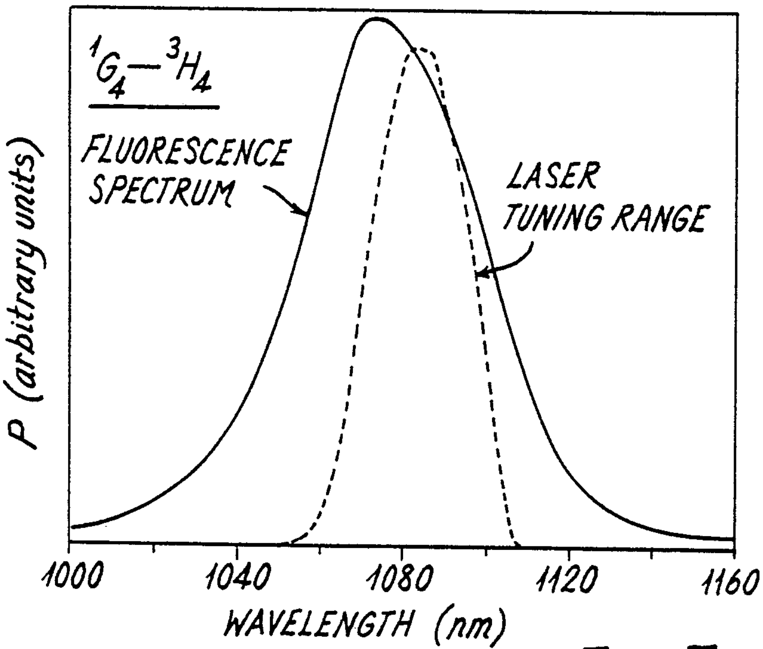


Fig. 7

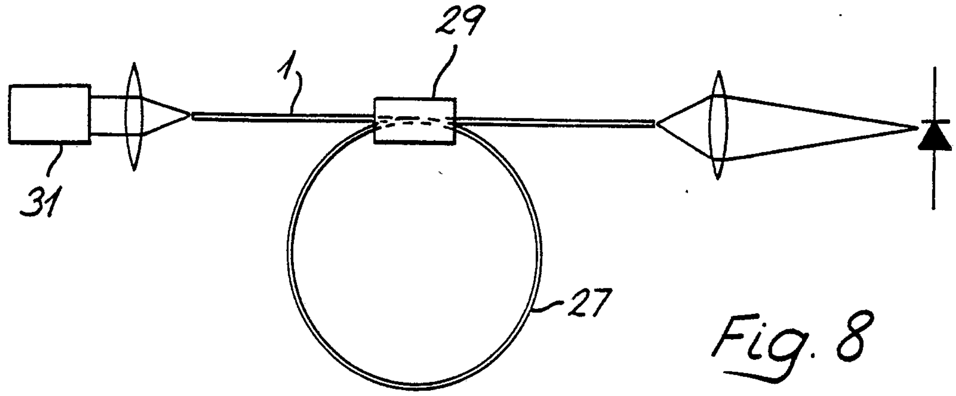


Fig. 8

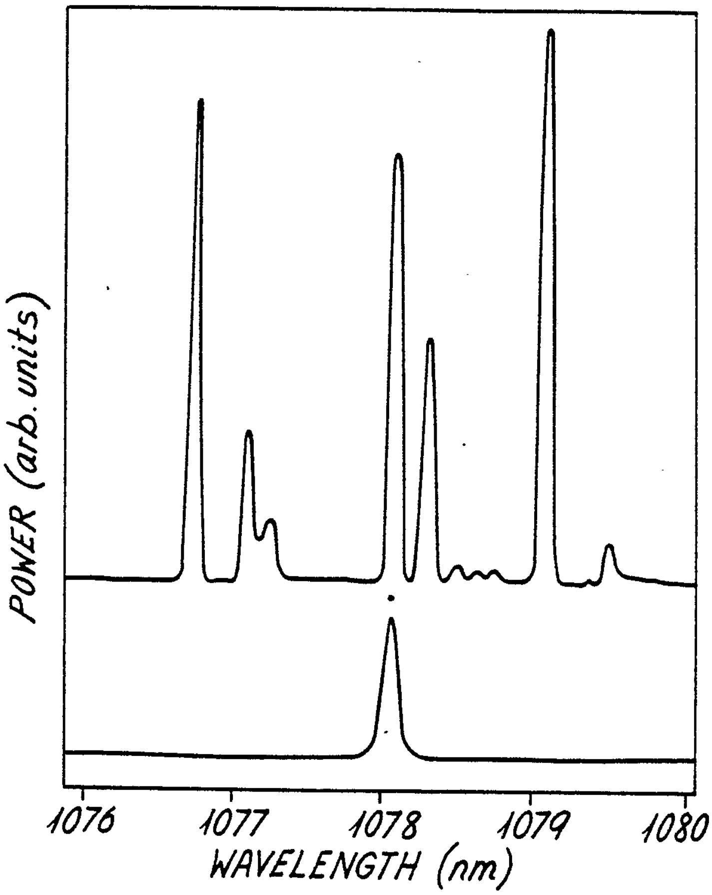


Fig. 9

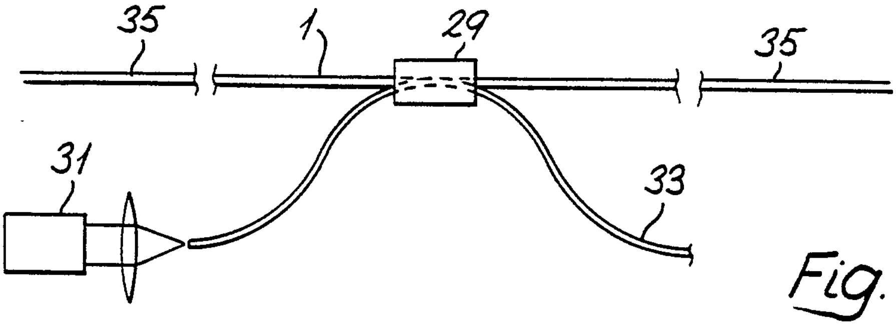


Fig. 10

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 86/00485

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: H 01 S 3/06; H 01 S 3/17

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	H 01 S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category [*]	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US, A, 3729690 (E. SNITZER) 24 April 1973 see column 2, lines 26-60; column 4, lines 6-17; column 5, lines 28-34; column 11, lines 35-50; column 12, lines 41-43; column 13, lines 19-20, 46-54	1,2,9,11,14,15
A	Applied Physics Letters, volume 23, no. 7, October 1973, (New York, US), J. Stone et al.: "Neodymium-doped silica lasers in end-pumped fiber geometry", pages 388-389 see abstract (cited in the application)	1,2
A	Applied Optics, volume 13, no. 6, June 1974, (New York, US), J. Stone et al.: "Neodymium-doped fiber lasers: Room temperature CW operation with an injection laser pump", pages 1256-1258 see page 1256, column 2, lines 4-6 (cited in the application)	1,2,12
A	IEEE Journal of Quantum Electronics, volume QE-16, no. 2, February 1980, (New York, US), ./.	

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
11th November 1986	18 DEC 1986
International Searching Authority	Signature of Authorized Officer
EUROPEAN PATENT OFFICE	M. VAN MOL

Form PCT/ISA/210 (second sheet) (January 1985)

International Application No. PCT/GB 86/00485

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
	P. Labudok et al.: "Bandwith reduction in CW fiber ramon lasers", pages 115-117 see figure 1	1-4,6
A	EP, A2, 0136871 (THE BOARD OF TRUSTEES OF THE LELAND STAMFORD JUNIOR UNIVERSITY) 10 April 1985 see page 4, lines 9-18; figure 1	1,7,8,13
A	US, A, 4136929 (Y. SUZAKI) 30 January 1979 see figure 4A	1,7,8

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/GB 86/00485 (SA 14209)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 21/11/86

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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
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For more details about this annex :
see Official Journal of the European Patent Office, No. 12/82