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(71) Applicant (for all designated States except US): **QINETIQ LIMITED** [GB/GB]; Registered Office, 85 Buckingham Gate, London SW1E 6PD (GB).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **HODDER, Benjamin** [GB/GB]; Qinetiq Limited, Winfrith Technology Centre, Winfrith Newburgh, Dorset, DT2 8XJ (GB).

(74) Agent: **JOHNSON, Ian**; IP QinetiQ Formalities, Cody Technology Park, A4 Building,, Farnborough, Hampshire GU14 0LX (GB).

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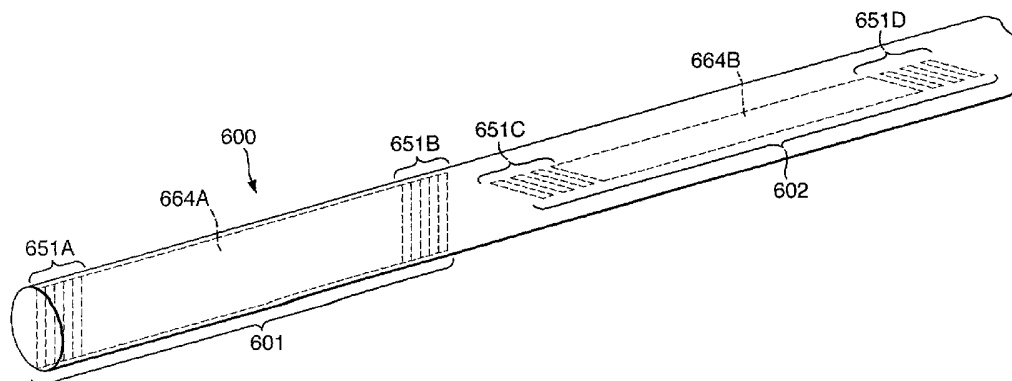
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(54) Title: FIBRE LASER WITH PLATE SHAPED ACTIVE MEDIUM FIBRE GRATINGS



(57) Abstract: A fibre-laser (600) incorporates an optical gain region (664b) which is substantially laminar, and substantially parallel to the fibre-laser's central longitudinal axis. The invention further provides a fibre-laser array, in which several such fibre-lasers are located along the length of a single optical fibre such that, their respective gain (664A, 664B) regions each lie in a different plane. Within a fibre-laser array of the invention, there is a reduced level of cross-talk between fibre-lasers compared to that in prior art fibre-laser arrays. In addition, the amount of pump radiation power absorbed by each laser in the array is substantially constant along the length of the optical fibre.

WO 2004/013941 A1

FIBRE LASER WITH PLATE SHAPED ACTIVE MEDIUM AND FIBRE GRATINGS

The invention relates to fibre-lasers, fibre-laser arrays and sensor systems comprising fibre-laser arrays.

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Fibre-lasers are frequently used in sensing applications, conditions (e.g. temperature and pressure) of an environment surrounding the fibre-laser being inferred from characteristics (e.g. polarisation, phase, wavelength) of radiation output by the fibre-laser. For example, it is known to form a plurality of fibre-lasers serially along the length of an optical fibre to produce a fibre-laser array for use in a sensor system. Each of the fibre-lasers is arranged to have a different signal wavelength. Pump radiation for the fibre-lasers is introduced into one end of the optical fibre (the pump end) and means for receiving and demultiplexing the signal radiation of the various fibre-lasers is provided either at the pump end or at the other end of the optical fibre. Characteristics of the signal radiation at a particular wavelength provide information on environmental conditions at a corresponding section of the optical fibre. This type of sensor system is often employed in marine environments, with the optical fibre being towed along the sea-bed by a ship or boat.

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Such sensor systems have two disadvantages resulting from the structure of standard fibre-lasers. First, the pump power delivered to each laser varies along the length of the fibre. Those fibre-lasers located towards the pump end of the fibre receive higher pump powers than those located towards the other end of the fibre. Signal powers from lasers located towards the pump end are therefore

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greater than those from lasers located towards the other end of the fibre. As a result, more complex processing of signal radiation from the array is required than would be the case if the pump power delivered to (and hence signal power received from) each laser was substantially constant. Furthermore, for a given
5 amount of pump power input to the optical fibre, the number of lasers in the array is limited to a greater extent than would be the case if the pump power absorbed per unit length of the fibre were to be substantially constant along the length of the fibre.

10 Second, signal radiation from each of the lasers passes through the lasing volume of one or more other lasers in the fibre-laser array. This results in a so-called 'cross-talk' problem, whereby signal radiation from one laser affects properties of signal radiation from another laser. This can lead to incorrect inferences being drawn about environmental conditions at a particular part of the fibre-laser array.

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An object of the present invention is to provide a fibre-laser which ameliorates these problems in sensor systems which comprise fibre-laser arrays.

According to a first aspect of the invention, this object is achieved by a fibre-laser
20 having a core incorporating a gain region characterised in that the gain region is a substantially laminar volume which extends substantially parallel to the core's central longitudinal axis.

Fabrication of such a laser is made simpler if the gain region has substantially
25 plane parallel sides and passes through the central longitudinal axis of the core,

and if, in addition, gratings of the laser are located within a laminar volume of which the gain region is part, there is additional confinement of signal radiation, further ameliorating the aforementioned cross-talk problem and providing improved optical stability.

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According to a second aspect of the invention, there is provided a fibre-laser array characterised by a plurality of fibre-lasers of the invention disposed along the length of an optical fibre, the gain regions of said lasers having plane parallel sides and passing through the fibre's central longitudinal axis, and arranged with
10 respect to one another such that the plane parallel sides of respective gain regions lie in different planes. Such a fibre-laser array has a low level of cross-talk between lasers and provides for each laser in the array to receive substantially the same pump power.

15 According to a third aspect of the invention there is provided a fibre-laser array characterised by a plurality of fibre-lasers of the invention, the fibre-lasers being co-located in a common length of the optical fibre, and each having a gain region which passes through the central longitudinal axis of the fibre and which has substantially plane parallel sides, the gain regions being arranged with respect to
20 one another such that plane parallel sides of respective gain regions lie in different planes. Such a fibre-laser array allows monitoring of two or more environmental conditions at a given position along the array.

By suitable choices of grating pitch and laser species, a fibre-laser array of the
25 invention may be arranged such that each fibre-laser therein operates at a

different signal wavelength, or alternatively such that two or more fibre-lasers are wavelength-degenerate.

A fourth aspect of the invention provides a sensor system characterised by a fibre-
5 laser array of the invention.

According to a fifth aspect of the invention, there is provided a method of fabricating a fibre-laser of the invention, comprising the steps of

- 10 (i) forming a bundle of glass rods, a portion of the bundle being formed of rods which are doped with a laser species;
- (ii) heating the bundle; and
- (iii) drawing the heated bundle to form an optical fibre.

Embodiments of the invention are described below by way of example only and
15 with reference to the accompanying drawings in which:

- Figure 1 shows an example of a sensor system of a known architecture, the system comprising a fibre-laser array;
- Figure 2 shows the core of a fibre-laser of the prior art;
- 20 Figures 3, 4, 5 and 6 show cores of fibre-lasers of the invention; and
- Figures 7 and 8 show a portion of the core a fibre-laser array of the invention.

In Figure 1 a sensor system 10 of a known architecture comprises a fibre-laser
25 array 20 having a plurality of individual DBR fibre-lasers 21A, 21B, 21C,.....21N

which have signal wavelengths $\lambda_1, \lambda_2, \dots, \lambda_n$ respectively. The system 10 further comprises a source 12 of pump radiation and a wavelength division demultiplexer 18 coupled to the array 20 by optical fibres 14 and 16 respectively. Signal radiation from the lasers 21 of the array 20 is coupled to the demultiplexer 18 and demultiplexed into separate, single-wavelength channels at outputs 22A, 22B, ..., 22N of the demultiplexer 18. If the fibre-laser array 20 comprises prior-art fibre lasers, then the array 20 and the system 10 are of the prior art; if the array 20 comprises fibre-lasers of the invention, the array 20 is a fibre-laser array of the invention and the system 10 is a sensor system of the invention.

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Figure 2 shows the core 200 of a prior-art fibre-laser which is typically used in the Figure 1 system, resulting in the aforementioned problems. The core 200 includes a pair of refractive index gratings 251A, 251B written into the core 200 e.g. by interference of two laser beams. The volume of the core between the gratings 251A, 251B is doped with a laser species. High index regions of the gratings 251A, 251B are indicated by 252, although it will be appreciated by the skilled person that the spatial modulation of refractive index within each of the gratings 251A, 251B is typically not in the form of a square wave. Both the gratings 251A, 251B and the laser species extend over the whole cross-section of the core 200.

20

Figure 3 shows the core 300 of a fibre-laser of the invention. The core 300 has a structure similar to that of the core 200 of Figure 1; parts of the core 300 are labelled by reference numerals which differ by a value of 100 from those labelling equivalent parts in Figure 2. Only a fraction of the volume between the gratings 361A, 361B contains a laser species. Figure 4 shows a cross-section through the

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core 300 along the plane IV – IV in Figure 3. In Figures 3 and 4, a volume containing a laser species (i.e. the gain region of the fibre-laser of which the core 300 is part) is indicated by 364, i.e. the gain region 364 is substantially planar and laminar, and extends between the gratings 361A, 361B and passes through the core's central longitudinal axis. When the fibre-laser of which the core 300 is part is operated by optical pumping, optical gain and hence signal radiation is substantially confined to the plane of the gain region 364, forming a substantially laminar lasing volume.

For the purposes of this specification, a laminar volume means a volume having a first dimension which is much greater than its other two orthogonal dimensions; and regarding the other two dimensions, one is substantially greater than the other. For example the laminar volume 364 of Figures 3 and 4 has a (length) dimension along the central axis of the core which may be of the order of several millimetres or centimetres; regarding its two other dimensions (shown in Figure 4) one is substantially equal to the core's diameter (a typical value for the core's diameter is 10 μm) whilst the other is substantially less than this, e.g. less than or equal to the radius (5 μm) of the core 300.

The core 500 of a further fibre-laser of the invention is shown in Figure 5; Figure 6 shows a cross-section of the core 500 along a plane VI – VI in Figure 5. The core 500 has a structure similar to that of the core 300 of Figure 3; parts of the core 500 are labelled by reference numerals which differ by a value of 200 from those labelling equivalent parts in Figure 3. As in the core 300 of Figure 3, a laser species is present only in a substantially planar, laminar region (the gain region)

574 passing through the central longitudinal axis of the core 500. In addition, the core 500 comprises gratings 572A, 572B which are confined to the plane of the gain region 574. Thus in a fibre-laser of the invention having a core 500, optical feedback is limited to the plane of the gain region 574 in addition to optical gain being so limited. As a result, additional confinement of a lasing mode is provided in a fibre-laser of the invention having the core 500 compared to a fibre-laser having the core 300.

A fibre-laser array comprising a plurality of fibre-lasers of the invention having cores such as 300 or 500 and arranged along the length of a optical fibre such that, when the fibre is straight and not subject to torsion, gain regions of the respective fibre-lasers each lie in a different plane, is a fibre-laser array of the invention. A sensor system having the architecture of Figure 1 and comprising such a fibre-laser array is a sensor system of the invention and ameliorates the problems mentioned above. For example, Figure 7 shows a portion 600 of the core of a fibre-laser array comprising four individual fibre-lasers each of which has a core structure as shown in Figures 5 and 6, i.e. both the gain regions and the gratings of the fibre-lasers are confined to substantially planar, laminar volume. The cores 601, 602 of two fibre-lasers of the array are shown in Figure 8. The core 601 has reflective gratings 651A, 651B and a gain region 664A which are substantially confined to a laminar volume in a vertical plane. Similarly, the core 602 has reflective gratings 651C, 651D and a gain volume 664B which are substantially confined to a laminar volume in a horizontal plane. Figure 8 shows an end view of the core of the array; the plane 664B makes an angle $\alpha = 90^\circ$ with the plane 664A. The fibre-laser array comprises two further fibre-lasers having

the same core structure as that of the fibre-lasers 601, 602 and disposed at further positions along the array; gratings and gain regions of these fibre-lasers are confined to planar, laminar volumes 664C, 664D which each make an angle of 45° with the plane 664A. From Figure 8, it may be appreciated that signal
5 radiation from a particular fibre-laser of the array overlaps very little with the lasing volume of any other fibre-laser of the array, and that each fibre-laser receives a fraction $\approx 2t/\pi r$ of the pump power introduced into one end of the array, t being the thickness of gain volume of the array and r being the diameter of its core.

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In an alternative fibre-laser array of the invention two or more fibre-lasers of the invention having cores such as 300 or 500 may be co-located in a single section of an optical fibre such that when the fibre is straight and not subject to torsion, gain regions of respective fibre-lasers each lie in a different plane. In a sensor system
15 of the invention comprising such a fibre-laser array of the invention, signal radiation at two or more wavelengths may be received at an end of the fibre from a single section of the optical fibre and processed simultaneously to give information on two or more characteristics (e.g. temperature and pressure) of an environment surrounding that part of the optical fibre. Alternatively, if two co-
20 located lasers have approximately the same signal frequency, the beat frequency of the two lasers is useful, for example in high-speed temperature sensing.

A sensor system of the invention comprising a fibre-laser array of the invention which incorporates individual fibre-lasers having a core structure as shown in
25 Figure 4 provides further amelioration of the aforementioned cross-talk problem

compared to a sensor system of the invention comprising fibre-lasers having a core structure as shown in Figure 3; this is due to increased optical confinement within fibre-lasers of the invention having core structures as shown in Figure 4 compared to those with core structures as shown in Figure 3. However both
5 sensor systems of the invention achieve the object stated above.

Fibre-lasers of the invention are fabricated using methods similar to those used to fabricate photonic crystal fibres. To fabricate a fibre laser of the invention, a series of glass rods each 2-3 cm in diameter is formed into a bundle, rods making
10 up a central lamina of the bundle being doped with a laser species. The bundle is then heated and drawn into a fibre $\approx 100 \mu\text{m}$ in diameter. Gratings for providing optical feedback are written into the core of the finished fibre using standard techniques. If for example, interference of UV laser radiation is used to write the gratings, rods which go to form parts of the core of the fibre-laser where the
15 gratings are to be located must be of a suitable (photorefractive) material. A fibre-laser array of the invention comprising a series of individual fibre-lasers disposed along the length of an optical fibre is formed by splicing several fibre-lasers of the invention together using known methods. To fabricate an array in which two or more fibre-lasers are co-located in a common length of optical fibre,
20 rods making up two or more central laminas of the bundle must be doped with a laser species before the bundle is heated and drawn into a fibre.

In this specification, the term 'laser' in general includes both laser amplifiers and laser oscillators.

The signal wavelength of a fibre-laser of the invention may be selected by making appropriate choices for the laser species and grating pitch thereof.

CLAIMS

1. A fibre-laser having a core incorporating a gain region (364; 564) characterised in that the gain region is a substantially laminar volume which extends
5 substantially parallel to the core's central longitudinal axis.
2. A laser according to claim 1 wherein the gain region has substantially plane parallel sides and passes through the central longitudinal axis of the core.
- 10 3. A laser according to claim 2 comprising gratings (572A, 572B) for providing optical feedback, the gratings being located within a laminar volume of which the gain region is part.
4. A fibre-laser array characterised by a plurality of fibre-lasers according to claim
15 2 or claim 3 and disposed along the length of an optical fibre, the gain regions (664A, 664B) of said fibre-lasers being arranged with respect to one another such that plane parallel sides of respective gain regions lie in different planes.
5. An array according to claim 4 wherein each fibre-laser is arranged to have a
20 unique signal wavelength.
6. An array according claim 4 wherein the two or more of the fibre-lasers are arranged to have a common signal wavelength.

7. A fibre-laser array characterised by a plurality of fibre-lasers according claim 2 or claim 3 within an optical fibre, the fibre-lasers being co-located in a common length of the optical fibre and having gain regions arranged with respect to one another such that plane parallel sides of respective gain regions lie in different
5 planes.

8. An array according to claim 7 wherein each fibre-laser is arranged to have a unique signal wavelength.

10 9. An array according claim 7 wherein the two or more of the fibre-lasers are arranged to have a common signal wavelength.

10. A sensor system (10) characterised by a fibre-laser array according to any one of claims 4 to 9.

15

11. A fibre-laser characterised by a core substantially as hereinbefore described and illustrated in Figure 3 and Figure 4.

12. A fibre-laser characterised by a core substantially as hereinbefore described
20 and illustrated in Figure 5 and Figure 6.

13. A method of fabricating a fibre-laser according to claim 1 comprising the steps of

(i) forming a bundle of glass rods, a portion of the bundle being formed
25 of rods which are doped with a laser species;

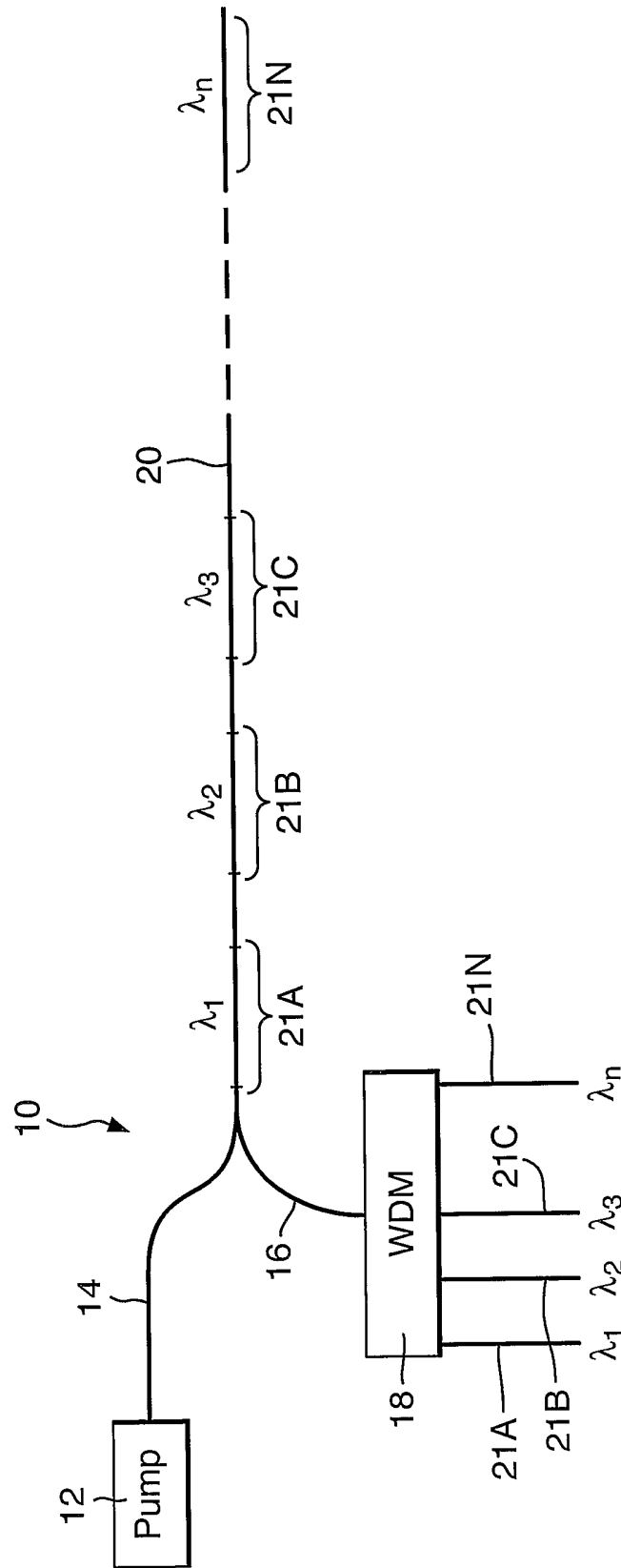
13

(ii) heating the bundle; and

(iii) drawing the heated bundle to form an optical fibre.

14. The method of claim 13 further comprising the step of writing reflective
5 gratings into the fibre by interference of UV laser beams.

Fig.1.



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Fig.2.

Prior Art

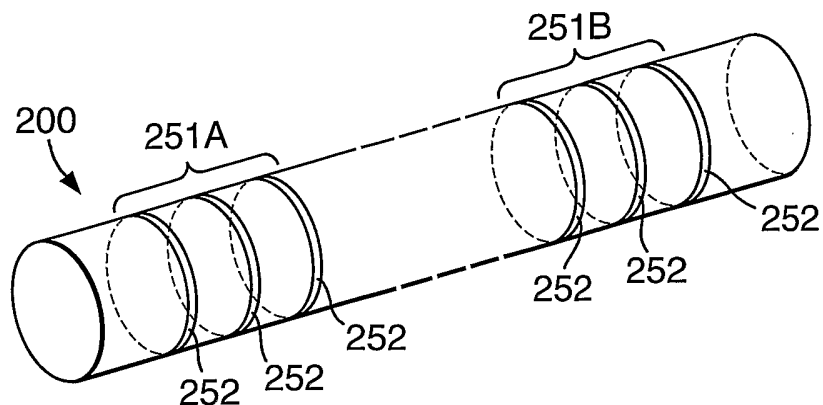


Fig.3.

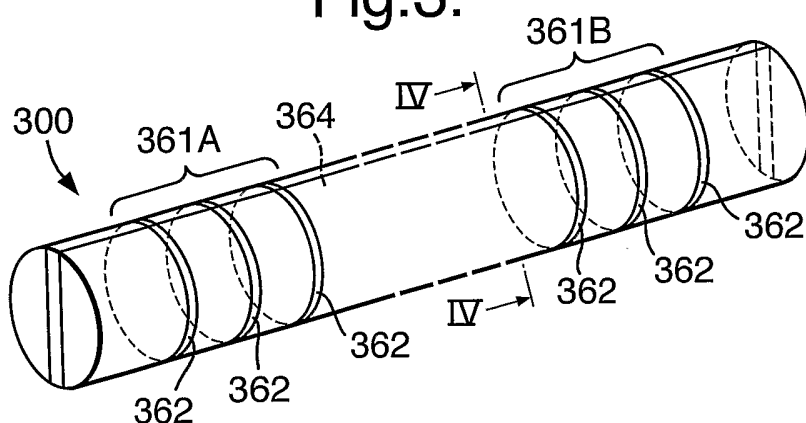


Fig.4.

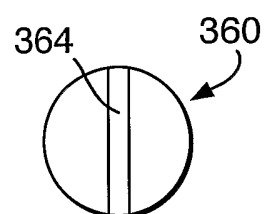


Fig.5.

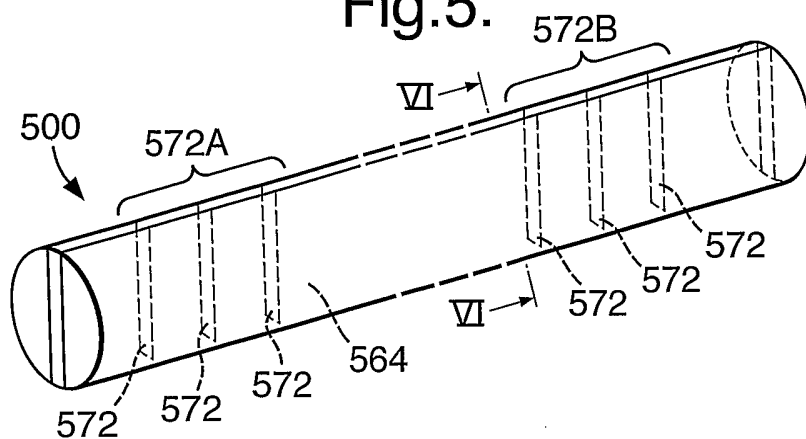
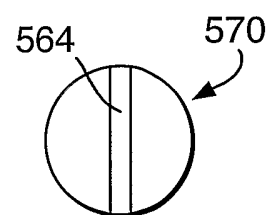


Fig.6.



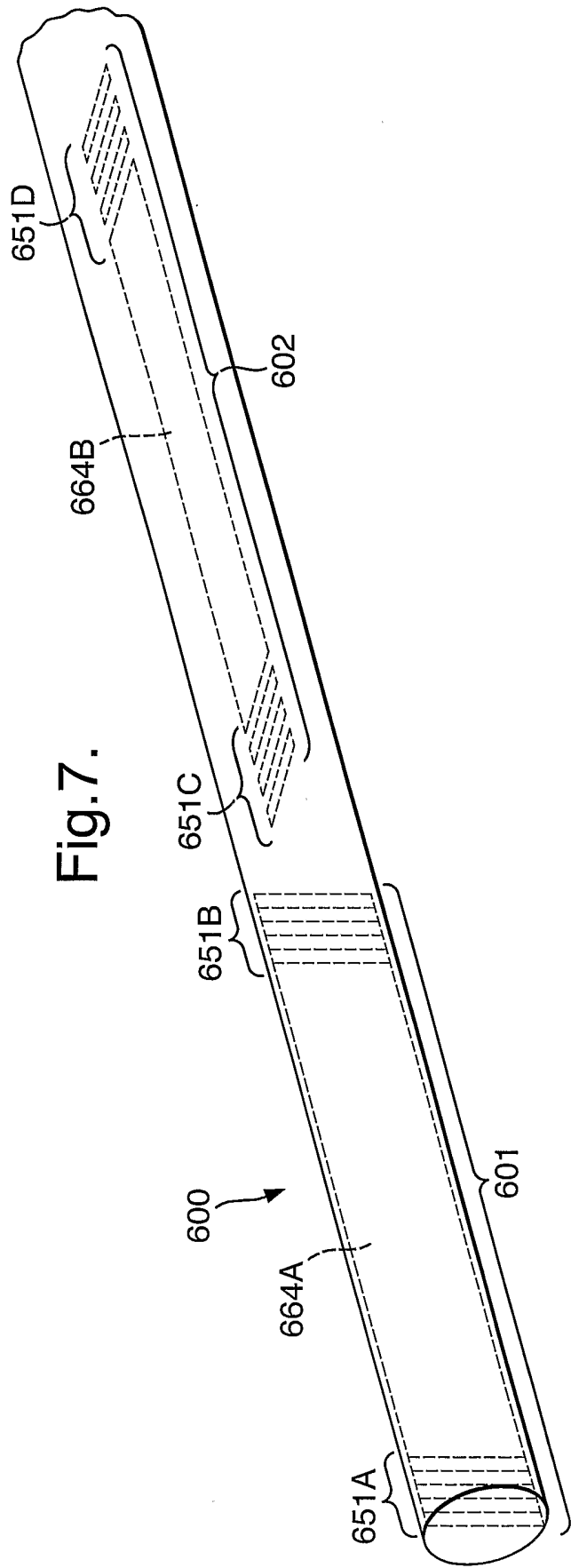


Fig. 7.

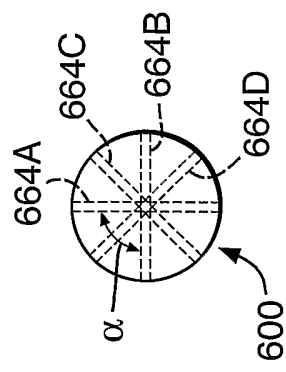


Fig. 8.

INTERNATIONAL SEARCH REPORT

International Application No.
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S3/067 G02B6/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	EP 0 800 098 A (FUJIKURA LTD) 8 October 1997 (1997-10-08) page 12, line 48 -page 13, line 8; figure 9 ---	3
A	PATENT ABSTRACTS OF JAPAN vol. 1996, no. 02, 29 February 1996 (1996-02-29) -& JP 07 263797 A (TOSHIBA CORP), 13 October 1995 (1995-10-13) abstract; figure 1 --- -/--	4,6,7,9

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

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European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
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Laenen, R

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 03/03124

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

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