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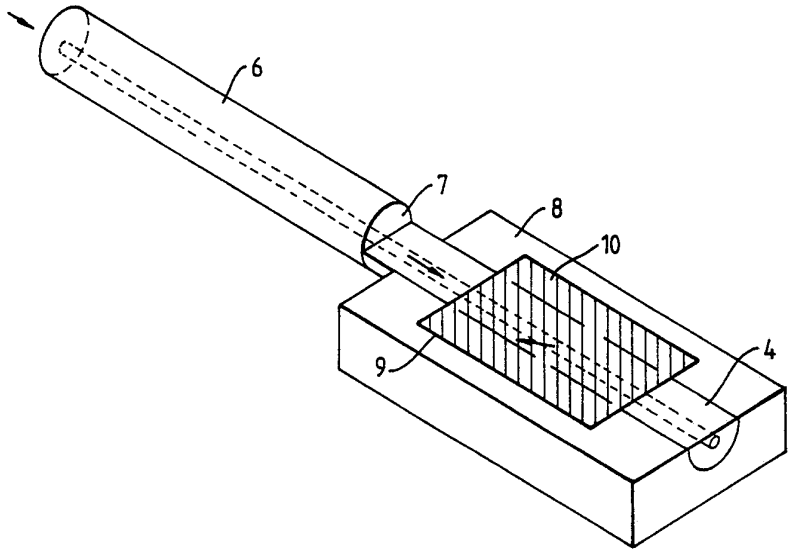
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(57) Abstract

An optical amplifier comprises an erbium-doped, silica-based optical fibre (6) coupled to a second optical waveguide, comprising a fibre (4) having a D-shaped cross-section. The second optical waveguide (4) has an overlaid grating (10) formed on a silica wafer (9) which is constructed and configured so that the waveguide filter provides loss in transmission substantially at the wavelength of the gain peak of the amplifier. The resonant reflection wavelength is chosen to be substantially equal to, or greater than, the wavelength of the gain peak of the amplified gain spectrum. Transmission losses at wavelengths shorter than the resonant reflection wavelength of the grating act to reduce the gain peak thereby flattening the gain spectrum of the amplifier so providing a larger useful gain bandwidth for optical fibre systems having a cascade of such fibre amplifiers.

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AN OPTICAL AMPLIFIER

This invention relates to an optical amplifier, and in particular to an optical amplifier which includes a doped optical waveguide for providing gain to optical signals propagating along the waveguide within an operating band of wavelengths.

Optical amplifiers of this type are well known, and are very attractive devices for optical communications networks, particularly when based on optical fibre waveguides as they are readily spliced to fibres used for optical transmission. It appears likely that they will become widely used in place of opto-electronic repeaters in long distance optical fibre lengths, for example. Some such optical amplifiers have a gain peak within the gain spectrum. For wavelength division multiplexing, a gain spectrum which has a gain peak is not ideal where cascades of amplifiers are to be used as this may result in large differences in gain across the wavelength band. If such large differences are to be avoided, it is necessary to operate in a band of wavelengths which does not include a gain peak. This reduces the useful gain band of an optical amplifier.

An object of the present invention is to provide an optical amplifier with a flatter gain spectrum.

The present invention provides an optical amplifier including a first, doped optical waveguide for providing gain to optical signals propagating along the waveguide within an operating band of wavelengths, the waveguide having a gain peak within the operating band, characterised in that the first optical waveguide is optically coupled to a waveguide filter which comprises a second optical waveguide having an overlaid grating constructed and configured so that the waveguide filter provides loss in transmission substantially at the wavelength of the gain peak.

The waveguide filter can provide flattening of the gain spectrum because the transmission profile of such a grating, overlaid on a waveguide, exhibits attenuation of optical signals to wavelengths shorter than the resonant reflection wavelength of the grating.

Preferably the grating is configured to have a resonant reflection wavelength substantially equal to, or greater than, the wavelength of the gain peak, so that the short wavelength attenuation associated with the filter will provide attenuation to the gain peak, thereby producing a flatter gain spectrum. Hence it is possible to use a grating, which when used as a narrow-band reflection filter has a reflection bandwidth of say 1.28 Angstroms, to obtain satisfactory flattening over a relatively broad spectrum gain peak of 20nm for example.

Advantageously the grating is angled relative to the second waveguide so as to substantially suppress counter-propagating radiation at the resonant reflection wavelength of the grating. The operation of the amplifier is thus not disturbed by optical signals at the resonant reflection wavelength being reflected back into the first doped waveguide. Counter-propagating radiation is, in general, undesirable in an optical communications system since it requires optical sources in the system to be optically isolated, and may contribute to crosstalk in duplex systems.

As the grating is rotated away from a position where the grating lines are perpendicular to the waveguide, the effective pitch of the grating experienced by optical signals travelling in the waveguide will increase. This will cause the resonant reflection wavelength of the grating, that is the wavelength at which the Bragg condition is met, to increase, and the wavelength range at which optical radiation is coupled out of the second waveguide to decrease. Hence the transmission loss of the

waveguide filter can be chosen so as to optimize the gain spectrum of the amplifier.

The optical amplifier may be made from a doped optical fibre but may be any other type of optical waveguide, for example a planar waveguide.

A particularly convenient form of optical waveguide for the waveguide filter is an optical fibre having a substantially D-shaped cross-section (commonly and hereafter referred to as a "D-fibre"). Such a fibre has a planar surface close to the waveguiding core of the optical fibre so that an optical grating formed on this pl~anar surface or pressed against the surface will interact with an optical field propagating through the fibre to provide the required diffraction. Conveniently the D-fibre may be mounted in a thermoplastic substrate. A method of so mounting a D-fibre is described in the applicant's published patent application WO 89/11969 published 14th December 1989.

The grating may be formed by etching the grating into a silica wafer using known electron beam lithography techniques, and the waveguide filter may then be formed by pressing the silica wafer against the waveguide.

A specific embodiment of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 a graph of the spontaneous emission measurements on an erbium-doped fibre amplifier which forms part of the embodiment of Figure 2;

Figure 2 is a schematic diagram of an optical amplifier according to the present invention;

Figure 3 is a graph showing the transmission characteristics of the grating filter of the embodiment of Figure 2; and

Figure 4 is a graph showing the gain spectrum of the optical amplifier of Figure 2.

Referring to the drawings, Figure 1 shows the gain spectrum of an erbium-doped optical fibre amplifier. This shows a gain peak centred at about 1.54μm, the gain peak reducing the usable part of the gain spectrum to wavelengths longer than the long wavelength side of this gain peak, that is to about 20nm.

Figure 2 shows a D-fibre 4, which may be made by removing a section of cladding from an optical fibre preform to leave a flat surface close to the core. This preform is then drawn to give a long length of single-mode fibre with a D-shaped cross-section. A short length (of the order of 20mm) of this D-fibre is then fusion spliced to a standard single-mode fibre 6, at a splice 7, and then press moulded, against a heated optical flat (not shown), into a polymer thermoplastic substrate 8, as described in the above-referenced patent application.

A grating 10 (see Figure 2) is then defined using electron beam lithography on a silica wafer 9 coated in photoresist. The grating 10 is subsequently etched into the silica itself to give a surface relief structure with a depth of about 0.25μm and a pitch of about 0.532 μm.

To construct the filter, the D-fibre substrate 8 is mounted in a brass package (not shown), and the grating is placed in contact with the flat surface of the fibre 4 at an angle of about 3°. A layer of silicone rubber is used between the grating 10 and the lid of the package so that the grating is pressed into contact with the fibre 4 when the lid is screwed down.

Fibre grating devices such as couplers and reflection filters have been reported previously (see for example Yennadhiou, P and Cassidy, S A: "D-Fibre Grating Reflection Filters" OFC 1990). For such a reflection filter, the grating lines are perpendicular to the fibre, and give a Bragg reflection which is coupled into the counter-propagating fibre mode. The grating of the present invention is used in transmission mode, and is configured

to suppress the resonant reflection wavelength of the grating. Light at wavelengths shorter than the resonant reflection wavelength is coupled out of the fibre, either up through the grating itself into radiation modes, or down into cladding modes. This results in a transmission filter with loss at the wavelengths which are coupled into radiation or cladding modes, and hence which provides loss at shorter wavelengths than the resonant reflection wavelength. The wavelength at which this loss occurs is dependent on the grating pitch and on the angle of the fibre 4 to the grating 10, and can thus be chosen to coincide with the gain peak 2 of the amplifier.

In this embodiment the pitch of the grating is chosen to be about 0.532 μm to give a resonant reflection wavelength of about 1.54 μm when the grating lines are perpendicular to the waveguide. The resonant reflection wavelength is increased by about 2nm by rotating the grating by about 3^0 relative to the waveguide. At an angle of about 3^0 the counter-propagating radiation at the resonant reflection wavelength was found to be substantially supressed.

Figure 3 shows the transmission characteristics of the waveguide filter of Figure 2, these characteristics being determined by monitoring the transmission of the filter using an ELED and optical spectrum analyser. Tuning of the resonant reflection wavelength results in a slight reduction of filter depth, because the interaction length of the grating (that is to say the length of the fibre in contact with the grating) is limited by its width, which in this case is approximately 1mm.

Once a suitable filter transmission characteristic is obtained, it can be tested by measuring the spontaneous emission from a short length of the optical amplifier, in this case an erbium-doped silica fibre, pumped with a 980nm diode laser (not shown).

Figure 4 shows the spectrum after the filter is spliced onto the end of the doped fibre. Clearly, the filter has improved the flatness to within about 0.5 dB over a 30nm span. The excess loss of 4 to 6 dB is mostly due to D-fibre to circular fibre splice losses. This could be reduced, as a more typical loss for a D-fibre substrate is 2 dB.

It will be apparent that modifications to the specific embodiment can be made. In particular the preferred angle, of 3^0, of the grating to the second waveguide, although theoretically predictable, is ultimately chosen for a particular type of amplifier and system by trial and error. As will be evident to the skilled person in this field the choice will depend, among other criteria, on the refractive index profile of the D-fibre, the structure of the grating, the distance of the core of the D-fibre from its planar surface, the type of doped waveguide, the wavelength of operation of the system, and the susceptibility of the system to counter-propagating radiation. It is estimated that the useful range of angles is from 1^0 to 10^0.

CLAIMS

1. An optical amplifier including a first, doped optical waveguide for providing gain to optical signals propagating along the waveguide within an operating band of wavelengths, the waveguide having a gain peak within the operating band, characterised in that the first optical waveguide is optically coupled to a waveguide filter which comprises a second optical waveguide having an overlaid grating constructed and configured so that the waveguide filter provides loss in transmission substantially at the wavelength of the gain peak.

2. An optical amplifier as claimed in claim 1, in which the grating is configured to have a resonant reflection wavelength substantially equal to, or greater than, the wavelength of the gain peak.

3. An optical amplifier as claimed in claim 1 or 2, in which the grating is configured to couple optical radiation substantially at the wavelength of the gain peak out of the second waveguide.

4. An optical amplifier as claimed in claim 3, in which the grating is angled relative to the second waveguide so as to substantially suppress counter-propagating radiation at the resonant reflection wavelength of the grating.

5. An optical amplifier as claimed in claim 4, in which the angle between the perpendicular to the grating lines and the axis of the second waveguide is greater than 1^0.

6. An optical amplifier as claimed in claim 4, in which the angle between the perpendicular to the grating lines and the axis of the second waveguide is substantially 3^0.

7. An optical amplifier as claimed in any one of claims 4, 5 or 6 in which the angle between the perpendicular to the grating lines and the axis of the second waveguide is less than 10^0.

8. An optical amplifier as claim in any preceding claim, in which the second optical waveguide comprises an optical fibre having a substantially D-shaped cross-section.

9. An optical amplifier as claimed in claim 8, in which the D-fibre is mounted in a thermoplastic substrate.

10. An optical amplifier as claimed in any one of the preceding claims, in which the grating is etched into a substrate.

11. An optical amplifier as claimed in claim 10, in which the grating is etched into a silica substrate.

12. An optical amplifier as claimed in claim 11, as dependent on claim 10, in which the substrate with the grating is held against the second waveguide between two holding means at least one of which includes a resilient layer.

13. An optical amplifier as claimed in any one of the preceding claims, in which the first, doped optical waveguide comprises an erbium-doped silica optical fibre.

14. An optical amplifier as claimed in claim 13, in which the shortest resonant wavelength the grating can be configured to have is approximately 1.54μm.

Fig.1.

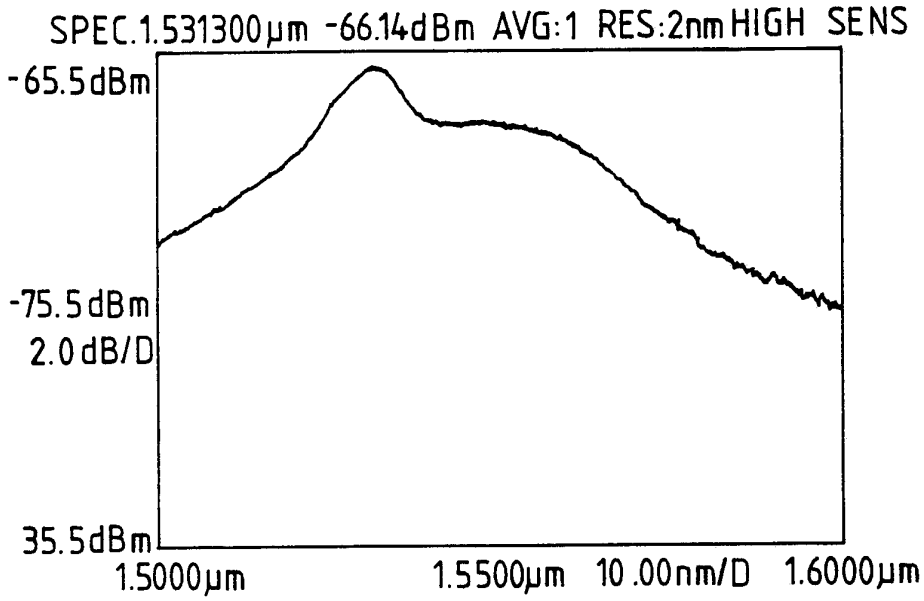
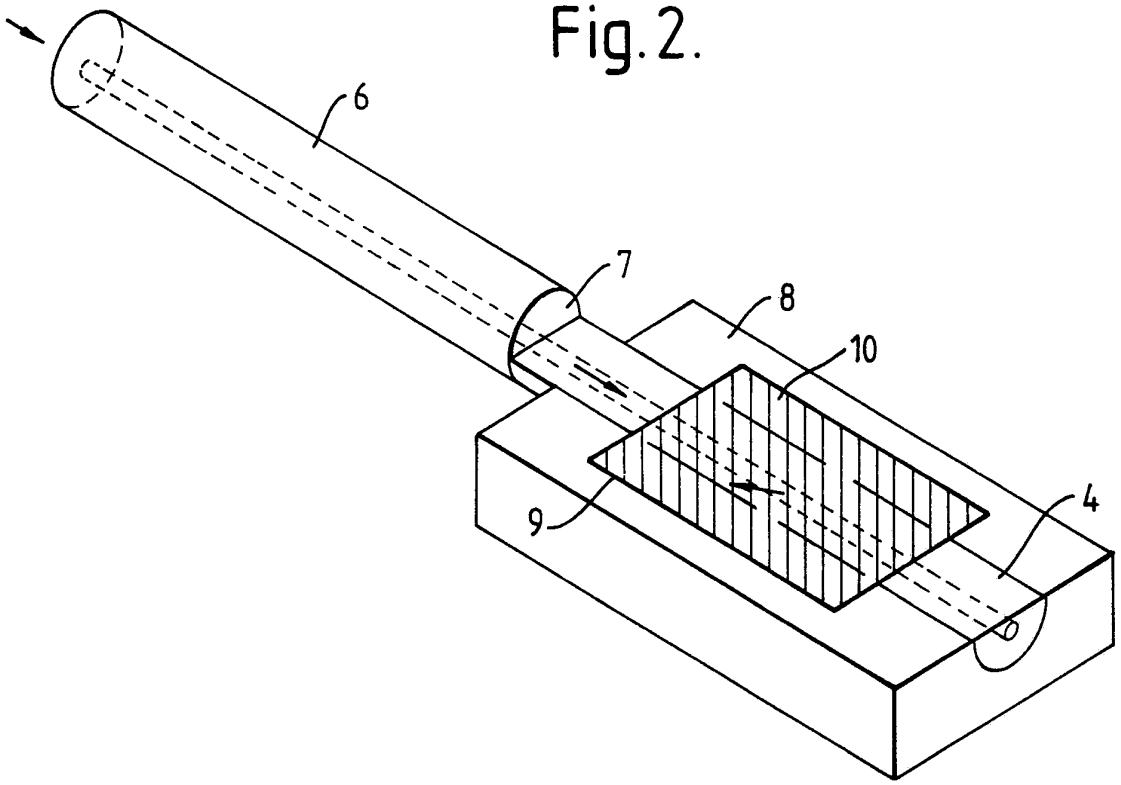

SPEC.1.531300µm -66.14dBm AVG:1 RES:2nm HIGH SENS
-65.5dBm
-75.5dBm
2.0dB/D
35.5dBm
1.5000µm
1.5500µm 10.00nm/D 1.6000µm

Fig.2.


6
7
8
10
9
4

2/2

Fig. 3.

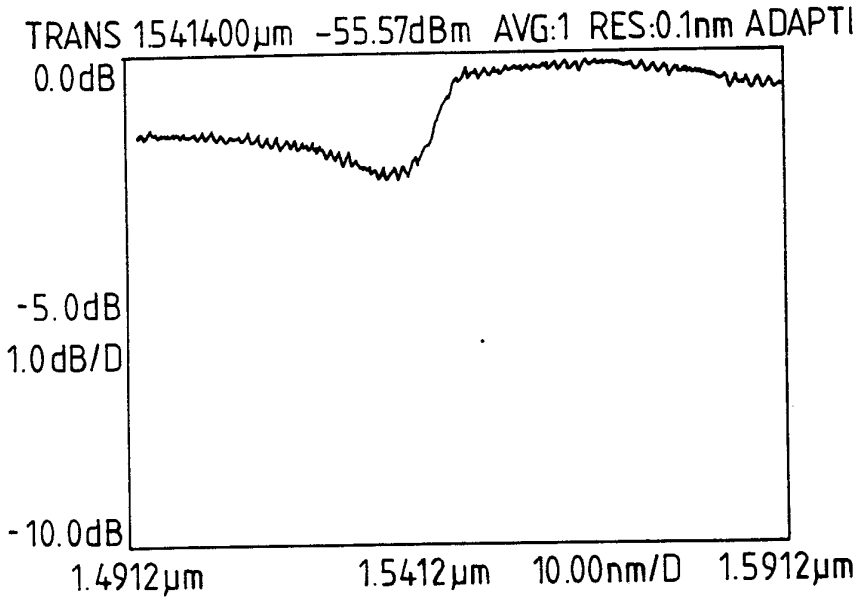
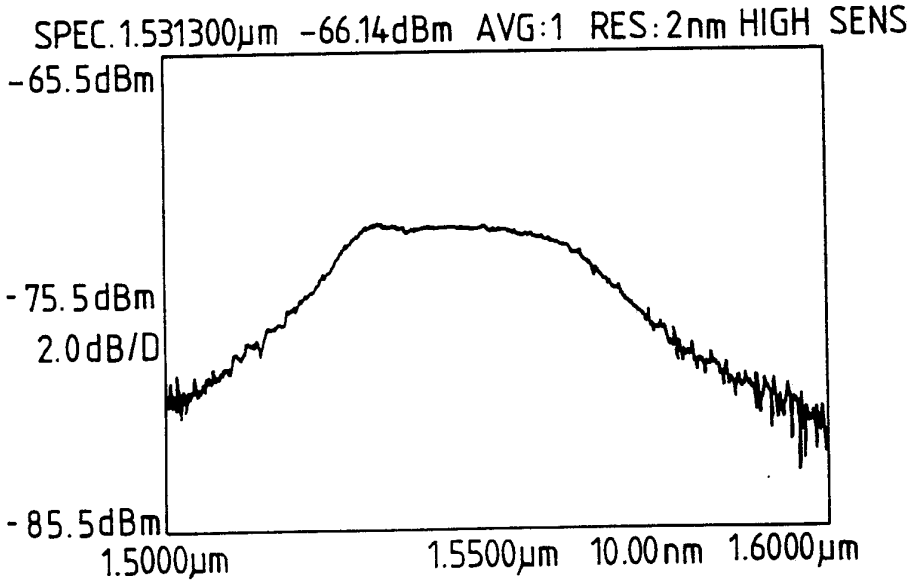

TRANS 1541400µm -55.57dBm AVG:1 RES:0.1nm ADAPTIVE
0.0dB
-5.0dB
1.0dB/D
-10.0dB
1.4912µm
1.5412µm
10.00nm/D
1.5912µm

Fig. 4


SPEC. 1.531300µm -66.14dBm AVG:1 RES: 2nm HIGH SENS
-65.5dBm
-75.5dBm
2.0dB/D
-85.5dBm
1.5000µm
1.5500µm
10.00nm
1.6000µm

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 92/01808

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

Int.Cl. 5 H01S3/06; G02B6/34

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01S ; G02B

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	IEEE PHOTONICS TECHNOLOGY LETTERS vol. 3, no. 2, February 1991, NEW YORK US pages 118 - 120 M. TACHIBANA ET AL. 'Erbium-doped fiber amplifier with flattened gain spectrum' see page 118, left column, paragraph 3 see page 118, right column, paragraph 2 see figures 1,2	1,10,13, 14
Y		2-9
A		12
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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
17 DECEMBER 1992	11. 01. 93
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	BATTIPEDE F.

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.
Y	OPTICAL FIBER COMMUNICATION CONFERENCE. TECHNICAL DIGEST SERIES vol. 1, 22 January 1990, WASHINGTON US page 27 P. YENNADHIOU ET AL. 'D-fiber grating reflection filters (Pap. TUG 4)' cited in the application see page 27, left column, paragraph 1 -paragraph 3 ---	2,3,8,9
Y	JOURNAL OF LIGHTWAVE TECHNOLOGY. vol. 3, no. 5, October 1985, NEW YORK US pages 1041 - 1043 W.V. SORIN ET AL. 'A single-mode fiber evanescent grating reflector' see abstract; figure 1 see page 1042, right column, paragraph 2 ---	4-7
A	EP,A,0 438 759 (UNITED TECHNOLOGIES) 31 July 1991 see abstract; figure 1 -----	3,4

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. GB 9201808 SA 65145

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 The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information. 17/12/92

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-0438759	31-07-91	US-A- 5042897	27-08-91
		JP-A- 4288510	13-10-92