(54) **FORMATION OF A REFRACTIVE INDEX GRATING**

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(57)   **ABSTRACT**

An apodised refractive index grating is recorded in a photosensitive optical fibre by forming first and second component interference patterns with different pitches, that are recorded in the grating such as to result in apodisation. The component patterns (**16, 17**) are spatially in phase in a central region and move progressively out of phase towards the ends of the patterns. The patterns may be recorded sequentially or concurrently. The fibre may be stretched one or cyclically.
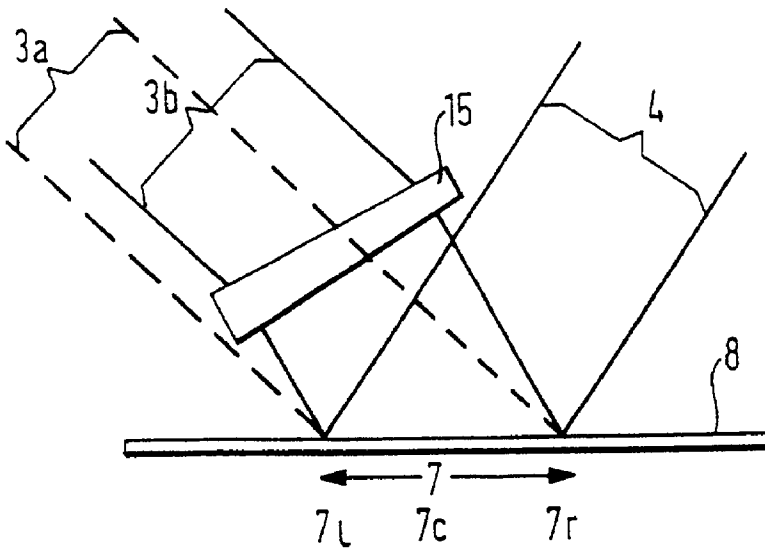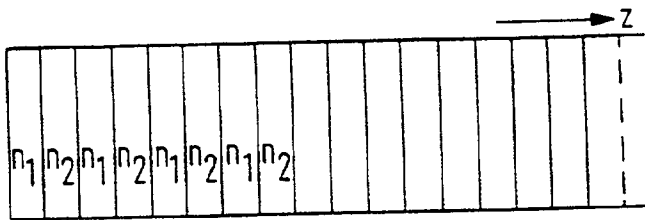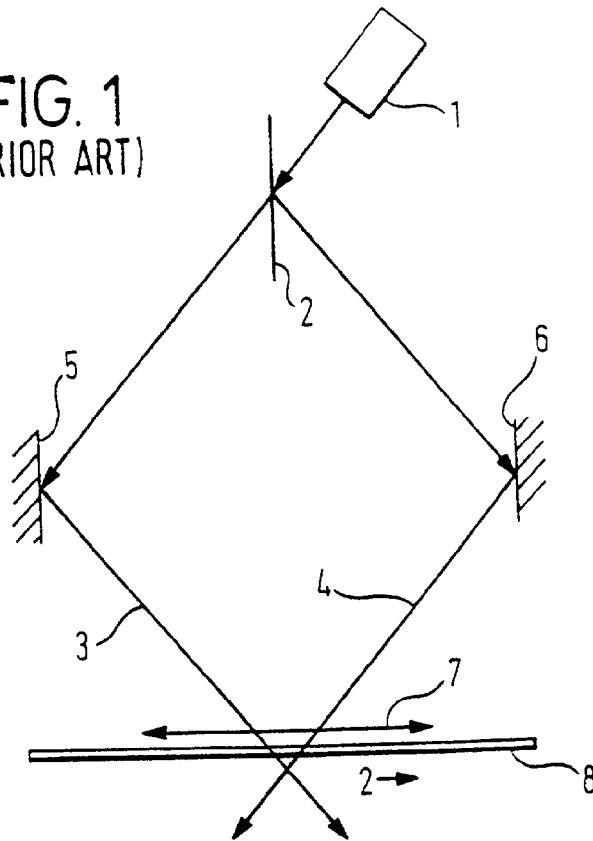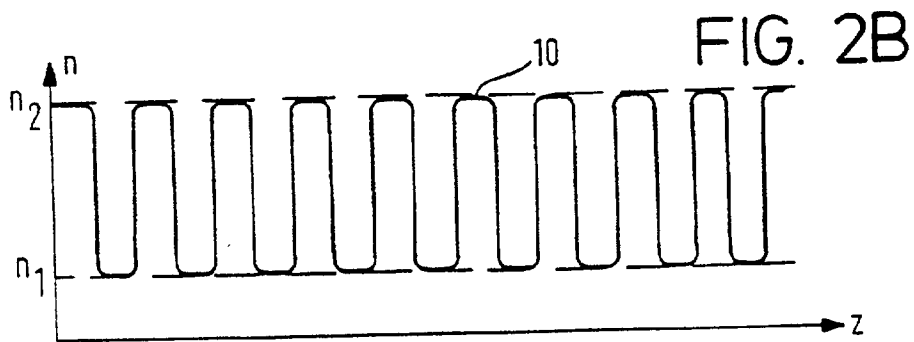
FIG. 1
(PRIOR ART)

FIG. 2A

n_1 n_2 n_1 n_2 n_1 n_2 n_1 n_2

FIG. 2B

n

n_2

n_1

10

FIG. 3B

A) REFLECTION

FIG. 4B

B) REFLECTION

FIG. 3A

A) TOP HEAD ENVELOPE

FIG. 4A

B) COSINE SQUARE ENVELOPE
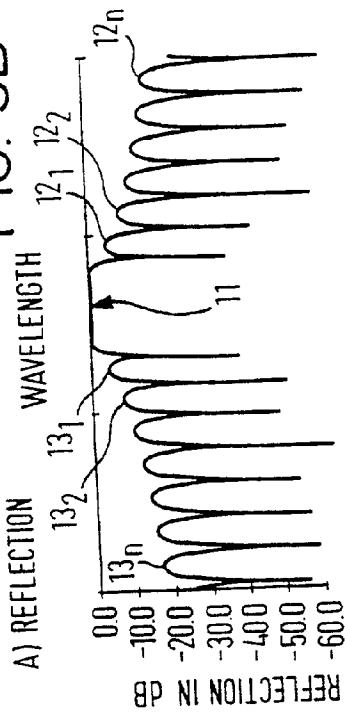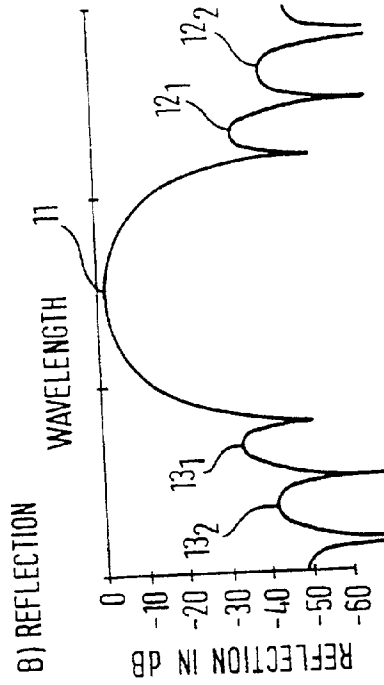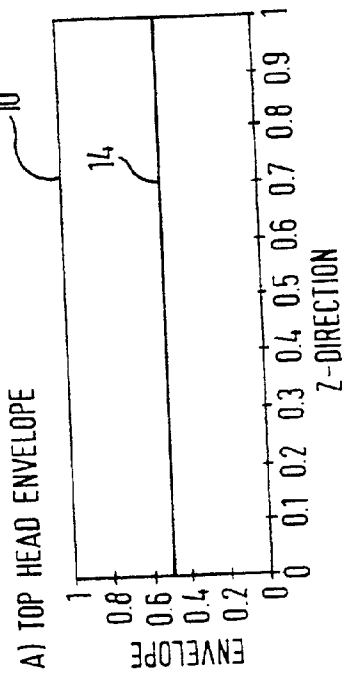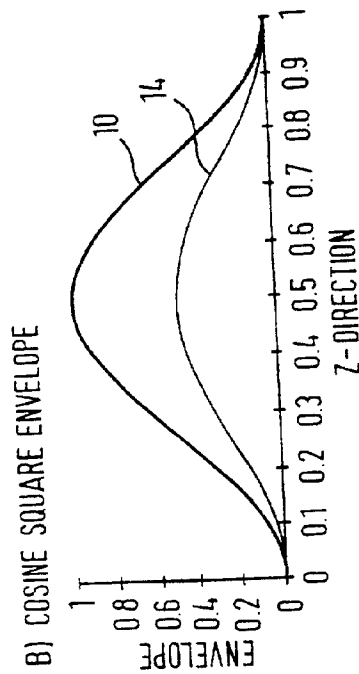
FIG. 5
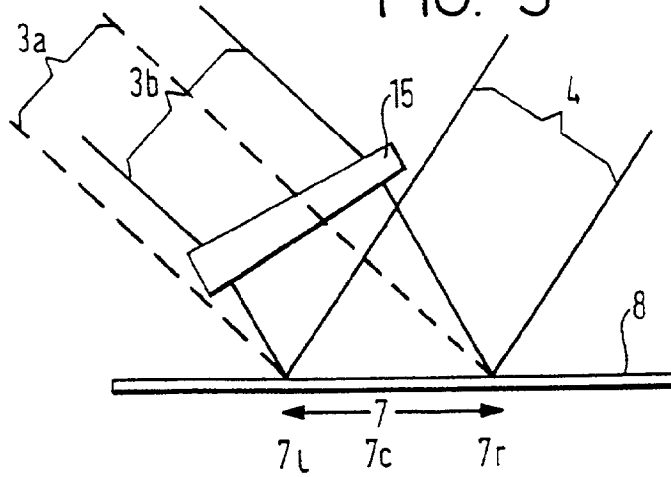
FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10
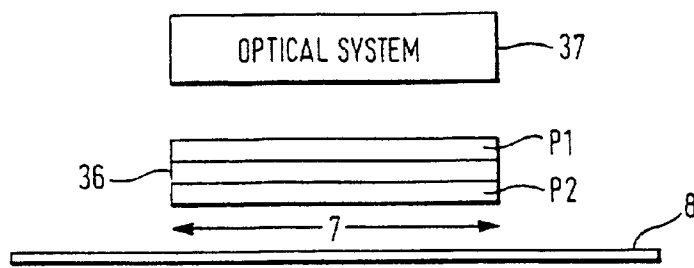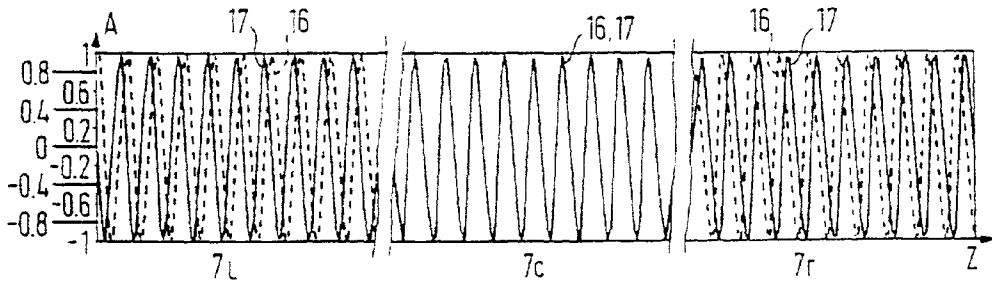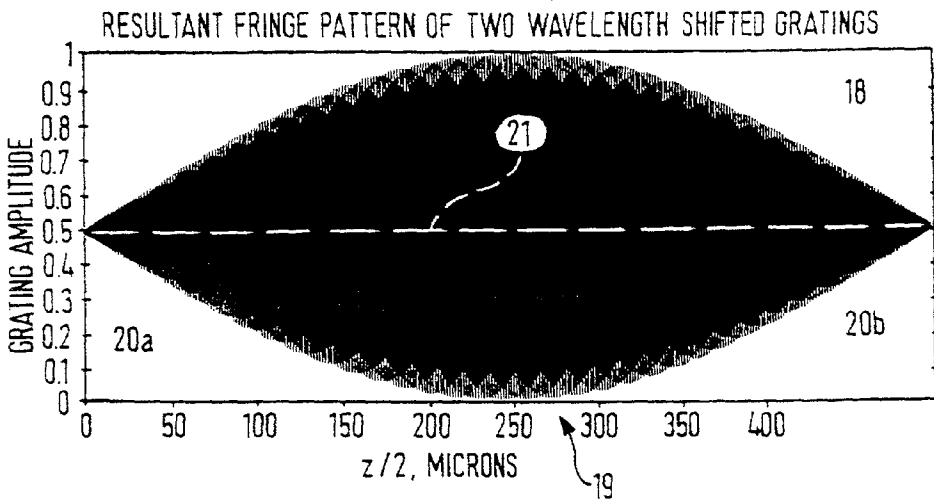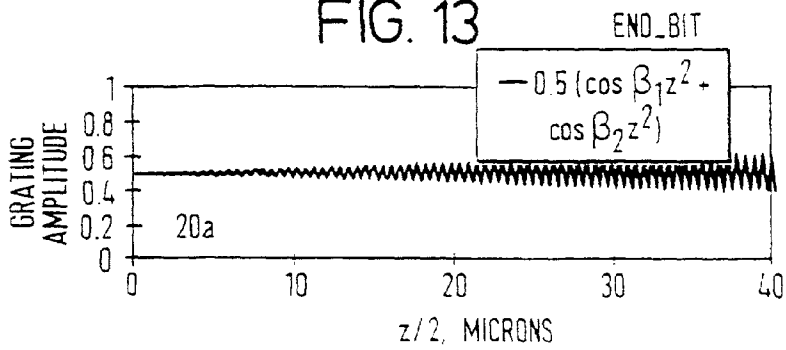
OPTICAL SYSTEM — 37

FIG. 11

FIG. 12

RESULTANT FRINGE PATTERN OF TWO WAVELENGTH SHIFTED GRATINGS

FIG. 13

FIG. 14

19   MID_BIT

GRATING AMPLITUDE

$-0.5 (\cos \beta_1 z^2 + \cos \beta_2 z^2)$

z/2, MICRONS

FIG. 15

CONSTANT INTENSITY OF UV LIGHT FOR BOTH PLOTS

REFLECTION, dB

WAVELENGTH, nm

FIG. 16.

FIG. 19.

FIG. 17.

REFLECTIVITY
THEARY

MEASURED
UNAPODISED
REFLECTIVITY

MEASURED
APODISED
REFLECTIVITY

Reflectivity
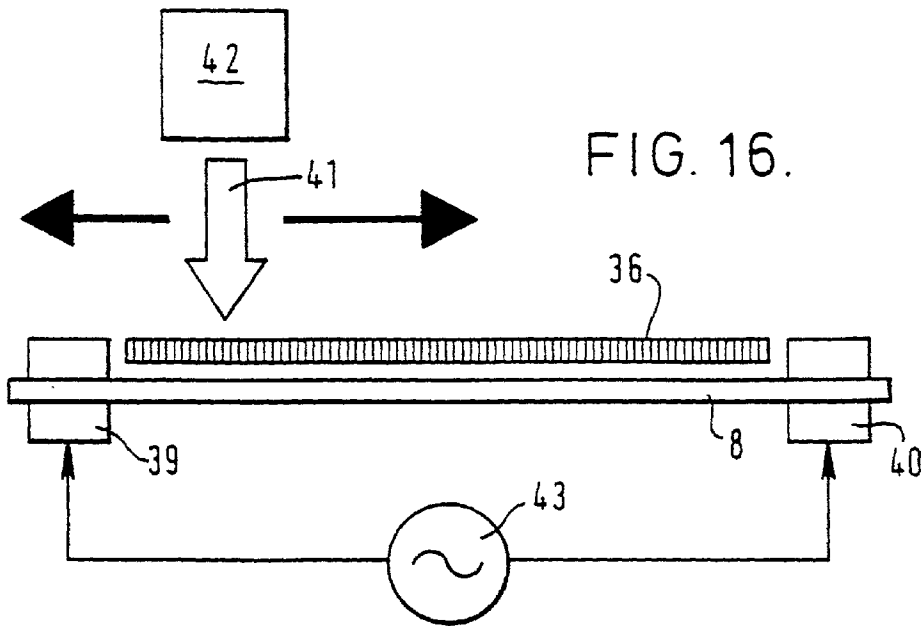
Wavelength, nm

FIG. 18.

FORMATION OF A REFRACTIVE INDEX GRATING

FIELD OF THE INVENTION

[0001] This invention relates to a method of recording an apodised refractive index grating in a photosensitive optical medium and has particular but not exclusive application to forming gratings in optical fibres.

BACKGROUND

[0002] It is known that the refractive index of an optical fibre can be altered by exposing it to high intensity light. Germanium doped fibre exhibits a photosensitivity in this manner and the effect can be used to form a so-called refractive index grating in the fibre. Reference is directed K. O. Hill et al, "Photosensitivity in Optical Waveguides: Application to reflection filter fabrication", Appl. Phys. Lett., Vol 32, no. 10, 647 (1978). The grating can be produced by forming an optical interference pattern with two interfering beams, and exposing the optical fibre to the interference pattern, so as to record a grating in the fibre.

[0003] The interference pattern may be formed by directing an optical beam longitudinally through the fibre and reflecting it back along its path through the fibre, so as to produce a standing wave pattern, which becomes recorded in the fibre due to its photosensitivity. In an alternative method, beams derived from a coherent source are directed transversely of the length of the fibre, so as to interfere with one another and produce an interference pattern externally of the fibre, which becomes recorded in the fibre as a result of its photosensitivity. A block for producing an external interference pattern for this purpose is described in EP-A-0523084.

[0004] Another way of forming the grating is to use a phase mask in which the desired amplitude pattern has been recorded holographically as a mask pattern. The phase mask is placed adjacent to the fibre and th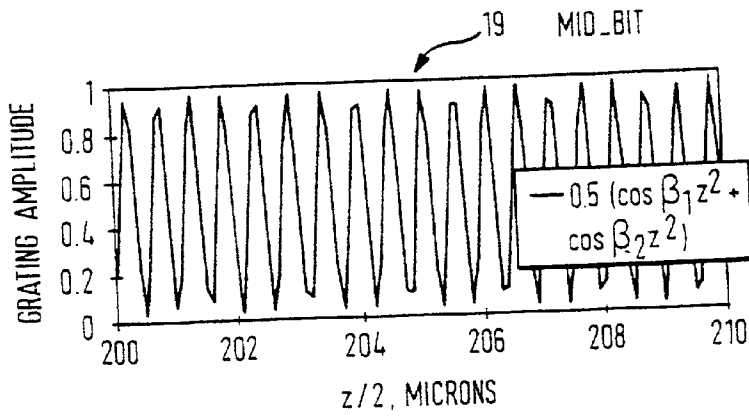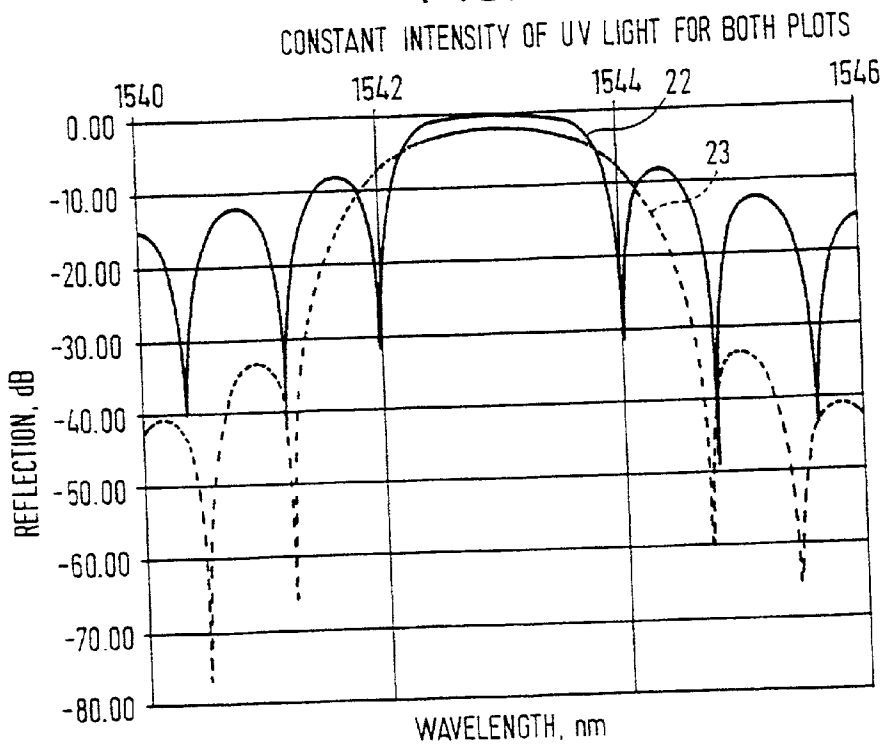e illuminated laser light, so as to expose the fibre to the holographic pattern. Reference is directed to K. O. Hill et al "Bragg grating fabricated in monomode photosensitive fiber by u.v. exposure through a phase mask" Appl. Phys. Lett. Vol. 62, No. 10, 1035 (1993).

[0005] For a general review of refractive index gratings, reference is directed to "Photosensitive Optical Fibres: Devices and Applications" R. Kashyap, Optical Fiber Technology 1, 17-34 (1994).

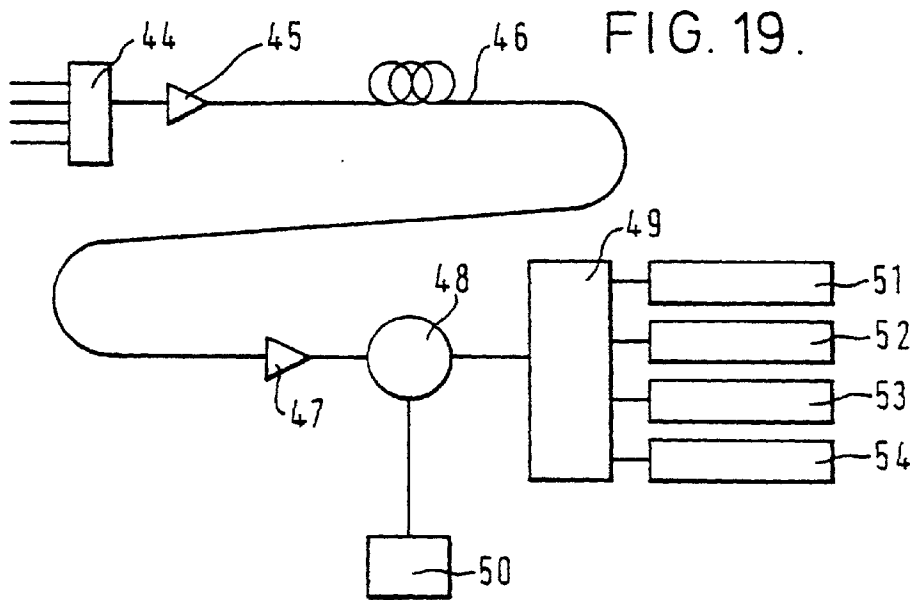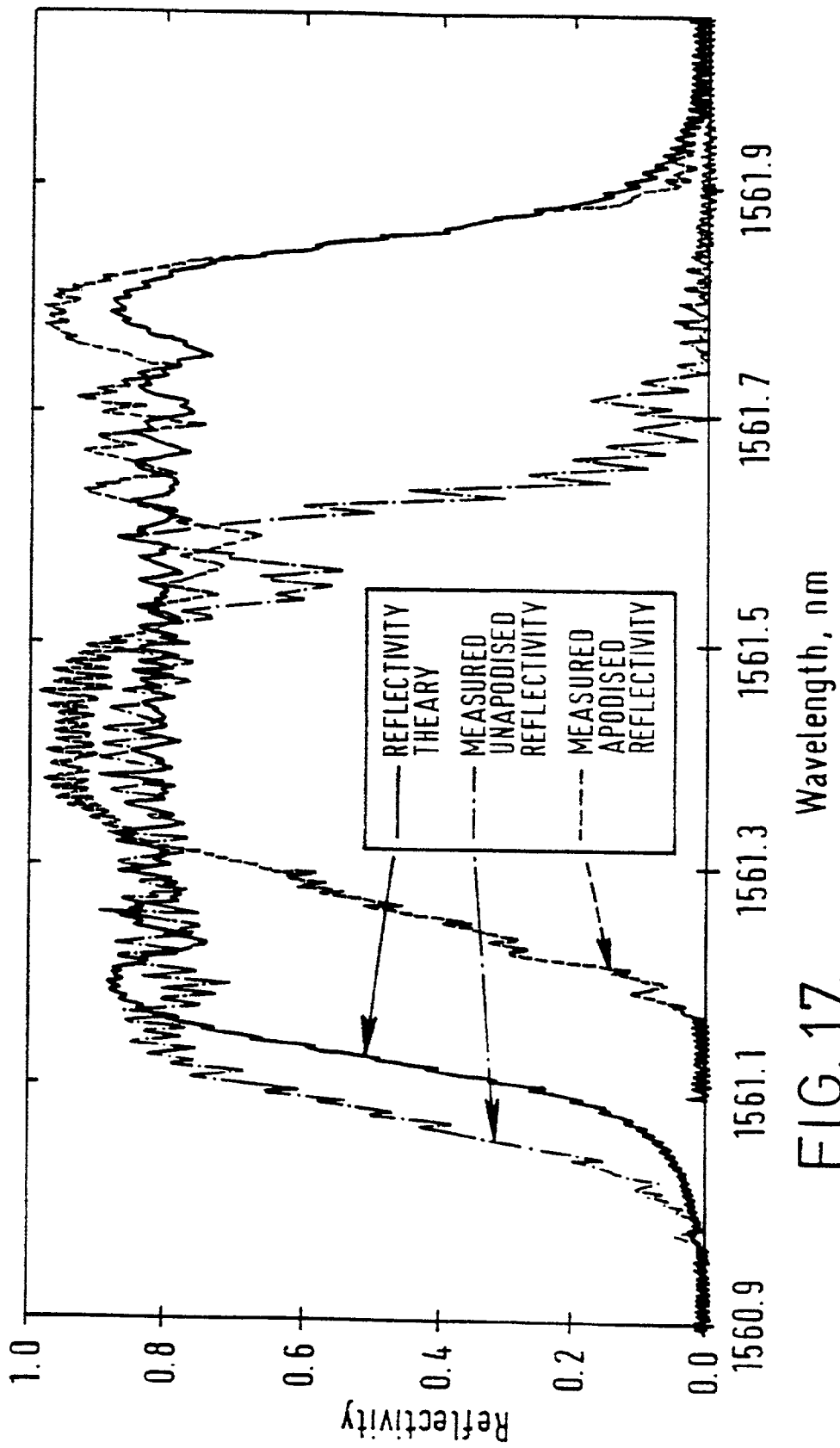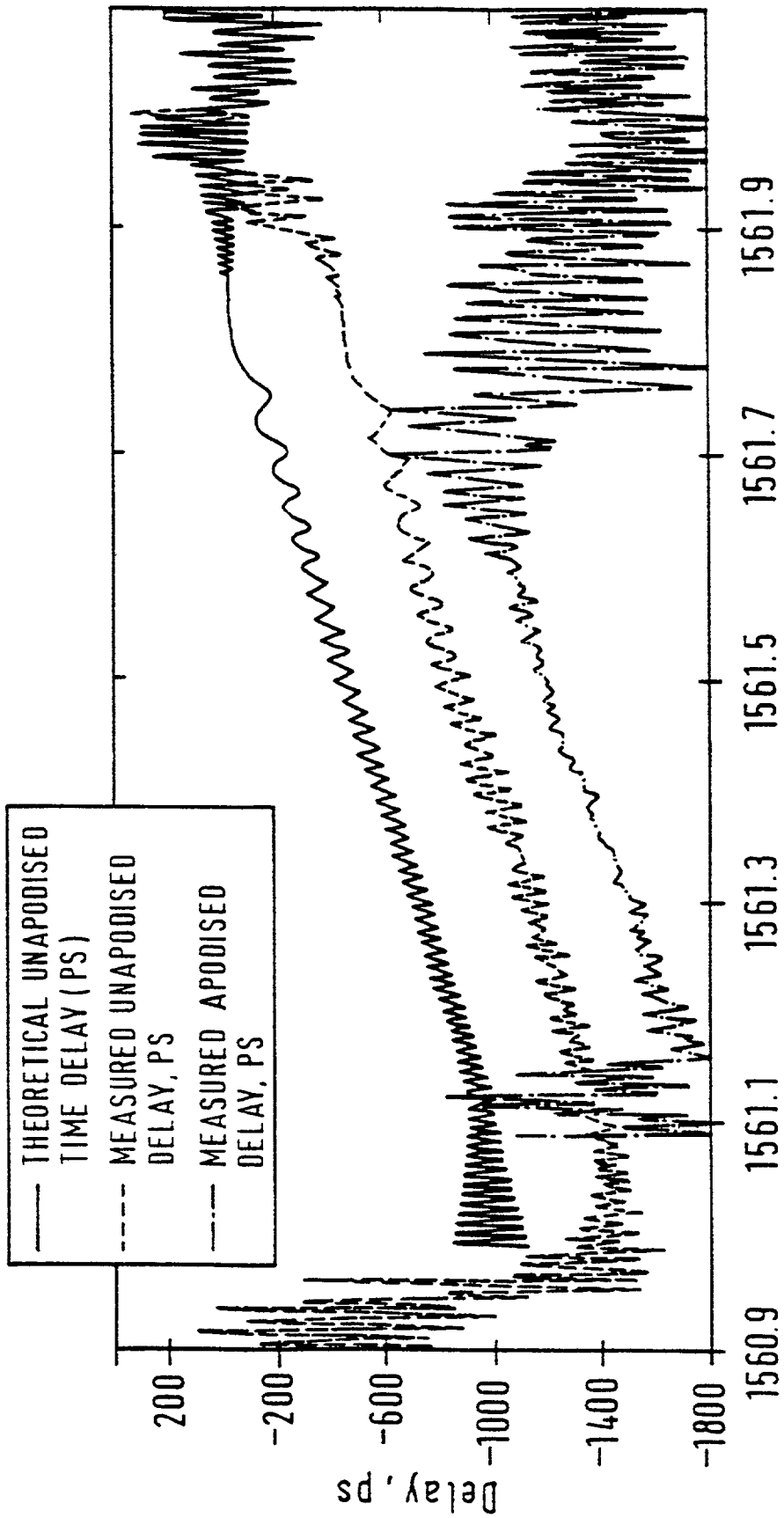[0006] Also, reference is directed to U.S. Pat. No. 4,474, 427 to Hill and PCT/GB91/01968 (WO92/08999) which disclose the formation of more than one refractive index grating pattern in a common optical fibre.

[0007] Refractive index gratings, which operate as Bragg gratings, have many applications in optical data communication systems as discussed by Kashyap, supra and in particular can be used as wavelength filters. It is well known that the large bandwidth offered by an optical fibre can be used to transmit data at a number of different wavelengths, for example by wavelength division multiplexing (WDM). It has been proposed to use refractive index gratings to separate information from adjacent WDM channels. Conventionally, optical telecommunication networks transmit data in channels centred on 1.3 μm and 1.5 μm. In either of these wavelength regions, a Bragg grating can be used to reflect

out a narrow wavelength channel of the order of μm or less, in order to permit WDM demultiplexing. A series of gratings can be provided to select individual closely spaced channels. The gratings exhibit a main wavelength peak centred on the wavelength of the channel to be filtered, but each grating also exhibits a series of side lobes at harmonics of the wavelength peak, which produce reflection in adjacent channels, resulting in cross-talk. As a result, it has proved necessary to apodise the Bragg gratings so as to suppress the effect of the side lobes and reduce the cross-talk.

[0008] Prior apodisation techniques will now be discussed. Referring to **FIG. 1**, this shows a conventional method of forming a refractive index grating in an optical fibre, in which light from a laser source **1** is fed through a beam spitter **2** in order to form coherent beams **3, 4**, which are directed by a mirror arrangement **5, 6** so as to interfere with one another in region **7** adjacent to an optical fibre **8** which exhibits photosensitivity at the wavelength of operation of the laser **1**. The result is an optical interference pattern, which is recorded in the fibre as a result of its photosensitivity. The result of the recording is shown in **FIG. 2**. The spatially periodic intensity of the interference pattern produces a corresponding pattern of refractive index variations along the length of the fibre, which in **FIG. 2** are schematically shown as refractive index regions n_1 and n_2. These regions act as a reflection grating in a manner well known per se. The grating has a wavelength dependent reflection characteristic with a main lobe centred at a particular wavelength depending upon the periodic spacing of the refractive index regions n_1, n_2, together with is a series of side lobes at harmonics of the centre wavelength. The reflection wavelength λ_{Bragg} is given by

$$\lambda_{Bragg} = 2\Lambda n_{eff}/N$$

[0009] where Λ is the period of diffraction pattern and n_{eff} is the effective refractive index of the waveguide. N is an integer.

[0010] Referring to **FIG. 2b** which shows the variation in refractive index recorded in the fibre, the spatially periodic function has an envelope **10** which in the simple example shown in **FIG. 2b** is theoretically flat for an infinitely long grating. This is shown again in **FIG. 3a**, with the periodic function omitted. The corresponding spectral characteristic for the grating, i.e. the response in the wavelength domain, is shown in **FIG. 3b** and it can be seen that the grating exhibits a main lobe **11** and a series of side lobes 12_n, 13_n on either side of the main lobe. When the grating is used as an optical filter e.g. in a WDM demultiplexer, the spacing of the grating pattern is chosen so that the main lobe **11** corresponds to the centre wavelength of the WDM channel, but a problem arises in that the side lobes **12, 13** extend into adjacent wavelength channels for the WDM system, particularly when the channels are closely spaced in wavelength. The side lobes thus will produce reflection in the adjacent channels and result in cross-talk.

[0011] Apodisation suppresses the effect of the side lobes. This has been achieved hitherto in a number of different ways. Referring to **FIG. 1**, the grating pattern formed in the region **7** will not in fact have a constant amplitude along its length and as a result, the refractive index pattern recorded in the fibre does not in practice have a flat envelope **10** as shown in **FIG. 2b**. Actually, the beams **3, 4** have an approximately Gaussian amplitude spread across their

physical width, with the result that the envelope **10** in practice has a shape more like that shown in **FIG. 4a**. It can be shown that suppression of the side lobes will be achieved if the envelope **10** has a shape which tapers from a central region towards its opposite ends, for example in accordance with the function $\cos^2 z$ along the length z of the recorded grating. In the past, this has been attempted by modifying the amplitude distribution across the width of the beams **3**, **4**. The corresponding spectral response of the filter is shown in **FIG. 4b**, from which it can be seen that the effect of side lobes is suppressed.

[0012] For gratings recorded in a phase mask, apodisation has been achieved by varying the intensity of the pattern across the mask, or by selective destruction of the phase pattern recorded in the mask. Reference is directed to "Apodised in-fibre Bragg grating reflectors photoimprinted using a phase mask", B. Malo et al Electronics Letters Feb. 2, 1995, Vol 31, No. 3, pp 223-225; and also to "Apodisation of the spectral response of fibre Bragg gratings using a phase mask with variable diffraction efficiency", J. Albert et al, Electronics Letters, Feb. 2, 1995, Vol 31, No. 3 pp 222-223.

[0013] However, a problem with all of these prior techniques is that the side lobes are not suppressed completely, due to the fact that the overall refractive index exhibited by the fibre n_{eff} varies along the length z of the grating. It will be recalled that the value of refractive index n recorded in the fibre is a function of the intensity of the illuminating light, so that with the configuration shown in **FIG. 4a**, the effective refractive index n_{eff} varies along the length of the grating in a non-uniform manner **14**. This non-uniform variation itself produces chirp in the Bragg wavelength of the grating, and as a result side lobes in the spectral response of the structure.

[0014] Hitherto, post-processing techniques have been used in order to linearize n_{eff}. However, these techniques have been difficult to implement in practice. Reference is directed to Hill et al, supra.

[0015] An alternative apodisation technique has recently been proposed in "Moving fibre/phase mask scanning beam technique for enhanced flexibility in producing fibre gratings with uniform phase mask" M. J. Cole et al, Electronics Letters, Aug. 17, 1995, Vol 31, No. 17, pp 1488-1490. In this technique, the grating is recorded in a manner generally shown in **FIG. 1** and, additionally, a piezoelectric device is moved along the fibre from a central position in the grating, during its formation, so as to apply vibration to the fibre, the amplitude of which increases towards the exterior edges. In this way, the recorded pattern is "blurred" towards the ends of the recorded grating which has the effect of apodising the grating, but without reducing the intensity of the recording light towards the ends of the grating as in the previously described methods, with the result that n_{eff} need not vary significantly along the length of the grating.

[0016] A method of providing a surface relief diffraction grating for use in a distributed feedback (DFB) optical fibre laser is described in GB-A-2209408. The grating is formed by exposing a layer of photoresist on an optical fibre to two different optical interference patterns of different periodicities, produced by interfering beams of optical radiation. The resulting, exposed composite pattern formed in the photoresist is then developed, and the fibre is etched using the developed pattern as a mask, to provide a surface relief

pattern in the fibre. The two component patterns are chosen so as to support a common longitudinal mode in the output of the laser. However, the configuration does not produce apodisation because the surface grating pattern has an effective refractive index which varies along the length of the optical fibre, which results in unwanted sidelobes in the wavelength characteristic.

[0017] The present invention provides a technique for controlling the spectral characteristic of a refractive index grating recorded in a photosensitive optical medium, which can be used to produce apodisation.

[0018] The present invention provides a method of recording an apodised refractive index grating in a photosensitive optical medium with a pattern of optical radiation, comprising producing a plurality of spatially periodic component optical patterns for forming the grating, with a relative spatial phase which varies along the length thereof in such a manner as to result in apodisation of the grating recorded in the optical medium.

[0019] In accordance with the invention, the effective refractive index of the optical medium may be substantially constant along the length of the recorded grating, so as to provide effective apodisation.

[0020] The relative phase of the component patterns may progressively increase in directions along the patterns away from an intermediate region towards ends thereof. The patterns may have zero relative phase in the intermediate region, and a relative phase of $\pm\pi/2$ with respect to the spatial periodity of the pattern, at the ends thereof.

[0021] The overlying component patterns may be formed sequentially. They may comprise optical interference patterns. The interference patterns may be formed by causing beams of optical radiation to interfere to produce a first of the patterns, and thereafter introducing a phase shift across the width of at least one of the beams, so as to form a second of the interference patterns. An optically transparent wedge may be used to introduce the phase shift.

[0022] Alternatively, the optical medium may be moved relative to the pattern, so as to provide the first and second component patterns. The waveguide in one example is rotated through a small angle, and in another, is stretched between recording the patterns in the optical medium.

[0023] The component optical patterns may be formed concurrently. For example beams of optical radiation with a predetermined spectral content may be caused to interfere so that light at different wavelengths interferes to produce the component patterns concurrently.

[0024] In another method, the component patterns are derived from corresponding patterns recorded in a phase mask.

[0025] The invention has particular application to recording an apodised grating in an optical waveguide such as photosensitive optical fibre e.g. a germanium doped fibre that is photosensitive to u.v. radiation. The recording method according to the invention has the advantage that the recorded pattern is both apodised and has an average intensity which need not vary significantly along the length of the pattern, so that the average refractive index n_{eff} need not vary, thereby avoiding chirp and resultant cross talk.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] In order that the invention may be more fully understood, embodiments thereof will now be described, reference being had to the accompanying drawings in which:

[0027] **FIG. 1** illustrates a prior art method of forming a refractive index grating in an optical fibre;

[0028] **FIG. 2a** illustrates the refractive index pattern of the grating formed in the fibre;

[0029] **FIG. 2b** is a graph of the refractive index variation along the length of the fibre;

[0030] **FIG. 3a** illustrates the envelope of the refractive index variation along the length of the fibre, and;

[0031] **FIG. 3b** illustrates the corresponding spectral characteristic of the grating;

[0032] **FIGS. 4a** and **4b** correspond to **FIGS. 3a** and **3b**, but for an amplitude mask apodised grating;

[0033] **FIG. 5** is a schematic illustration of apparatus for recording a grating by a first method according to the invention;

[0034] **FIG. 6** illustrates apparatus for recording a grating by a second method in accordance with the invention;

[0035] **FIG. 7** is a schematic illustration of the recording of a grating by a third method in accordance with the invention;

[0036] **FIG. 8** illustrates a method of recording a grating by a fourth method according to the invention;

[0037] **FIG. 9** is a graph of the wavelength distribution of the laser used in the method described with reference to **FIG. 8**;

[0038] **FIG. 10** illustrates apparatus for performing a fifth recording method in accordance with the invention;

[0039] **FIG. 11** illustrates first and second component interference patterns for recording the grating;

[0040] **FIG. 12** is a schematic illustration of the combination of the intensities of the first and second component interference patterns;

[0041] **FIG. 13** is an enlarged view of the pattern shown in **FIG. 12**, adjacent the end **20a**;

[0042] **FIG. 14** is an enlarged view of the pattern shown in **FIG. 12**, for the central region **19**;

[0043] **FIG. 15** is a graph of the wavelength response of the apodised grating recorded by the method of the invention, in reflection along the optical fibre;

[0044] **FIG. 16** illustrates an apparatus for performing a sixth method according to the present invention;

[0045] **FIG. 17** is a graph of the reflectivity of a grating formed according to the present invention with the actual and predicted reflectivity of a prior art grating for comparison;

[0046] **FIG. 18** is a graph showing the delay of a grating formed according to the present invention with the actual and predicted reflectivity of a prior art grating for comparison; and

[0047] **FIG. 19** is a schematic block diagram of a communications system employing gratings made according to the present invention.

DETAILED DESCRIPTION

[0048] A first example of a grating formation method in accordance with the invention will now described with reference to **FIG. 5**. The method can be considered as a modification of the method described with reference to **FIG. 1**, in which like parts are marked with the same reference numbers. The two interfering beams **3**, **4**, which, in **FIG. 5** are shown to have a given width, interfere in region **7** to form an interference pattern which is recorded in the optical fibre **8** in the manner generally as previously described. The laser **1**, beam splitter **2** and mirrors **5**, **6** have been omitted from **FIG. 5** in order to simplify the drawing.

[0049] In accordance with the invention, first and second component interference patterns are produced and individually recorded in the fibre so as to produce the apodisation of the grating. The component grating patterns have slightly different spatial periodicities, chosen so that their combined effect is to suppress the side lobes in the wavelength response of the recorded grating, as will be explained more fully hereinafter.

[0050] In **FIG. 5**, the first component interference pattern is recorded in the fibre by producing interference between beam **4** and beam **3** shown in dotted outline. Thereafter, a transparent wedge **15** placed in the beam **3** in order to introduce a progressive phase shift in the wavefront of the beam across its width. This interferes with the beam **4** to produce a second component interference pattern. There is a progressive small increase in spacing between the successive peaks and troughs of the second interference pattern in comparison with the first pattern and this will be explained in more detail hereinafter with reference to **FIG. 11**. Thus, the second, slightly different pattern is recorded in the fibre **8**, overlying the first pattern formed by the beams **3a**, **4**. In order to form the second component pattern, the beam **3** may need to be shifted to the position **3b** shown in **FIG. 5** in order to produce the correct overlying alignment of the first and second component patterns.

[0051] Referring now to **FIG. 11**, this shows the amplitude of the first and second component interference patterns **16**, **17** that are produced. The first pattern **16** is shown in dotted outline whereas the second pattern **17** is shown as a solid line. **FIG. 11** shows the component patterns at three positions across the width of the interference pattern **7**, namely at the left side 7_l the centre 7_c and the right side 7_r. The second component pattern **17** has a slightly different periodicity from the pattern **16** due to the phase shift introduced by the wedge **15**. In the central region 7_c, the patterns overlie one another, but due to their different periodicities, they become progressively out of phase towards the side edges of the interference pattern so that in positions 7_l and 7_r the patterns are out of registry, as shown in **FIG. 11**.

[0052] It will be understood that the combination of the intensities corresponding to the two amplitude patterns **16**, **17** shown in **FIG. 11** is recorded in the photosensitive waveguide **8** (**FIG. 5**) as variations in the refractive index of the waveguide. The resultant combined intensity pattern produced by the component amplitude patterns **16**, **17** is shown in **FIG. 12** and consists of a spatially periodic

function having an envelope **18**. The value of the cyclic spatial intensity variations for the function shown in **FIG. 12** is highest in a central region **19** of the function and progressively decreases towards the opposite ends **20a, 20b** in the direction z along the waveguide. A more detailed view of the intensity function of **FIG. 12** adjacent the end **20a** is shown in **FIG. 13** and a more detailed view of the region **19** is shown in **FIG. 14**. The refractive index grating produced by this intensity pattern is thus apodised as a result of the shape of the envelope **18**. Furthermore, the shape of the envelope **18** has the advantage that the average intensity remains constant along the length z so that n_{eff} is substantially constant along the length of the grating, which minimises side lobes in the grating characteristics produced by chirp that was described previously with reference to **FIG. 4A**.

[0053] A more detailed discussion of the function shown in FIGS. 12 to 14 will now be given. The spatially periodic amplitude of the first and second component interference patterns **16, 17** in the direction z will be referred to as $A_1(z)$ and $A_2(z)$, and the resultant intensity pattern I(z) shown in **FIG. 12** can be written as the sum of the squares of the intensity patterns, i.e.

$$I(z) = \frac{K}{2}(A_1^2 + A_2^2) \tag{1}$$

[0054] where K is a constant.

[0055] Each of amplitudes $A_1(z)$ and $A_2(z)$ can be represented as a spatial cosine function, i.e.

$$A \sim \cos \beta z$$

[0056] where the period Λ of the diffraction grating pattern is given by:

$$\Lambda = 2\pi/\beta$$

$$\text{Thus } A_1 = p \cos \beta_1 z \tag{2}$$

$$\text{and } A_2 = q \cos \beta_2 z \tag{3}$$

[0057] where p and q are constants.

[0058] From equations (1), (2) and (3), it follows that

$$I(z) = K/2 \ (p^2 \cos^2 \beta_1 z + q^2 \cos^2 \beta_2 z)$$

[0059] where K is a constant

[0060] which can be written as

$$I(z) = K/2 \ (P^2 \cos^2 \beta_1 z + Q^2 \cos^2 \beta_2 z) \tag{4}$$

[0061] where P and Q are constants. For the purpose of simplicity in the following analysis, P and Q are assumed to be of value 1.

[0062] The form of equation (4) will now be considered in detail by way of example at the end of point **20a** and in the central region **19** in order to explain the refractive index variations that are recorded in the waveguide as a grating pattern.

[0063] In the central region **19**, the two component patterns **16** and **17** are substantially in phase, with the same spatial periodicity, so that in region **19** $\beta_1 = \beta_2 = \beta$. *Thus, equation (4) reduces to*

$$I_{(19)} = \frac{1}{2}(\cos^2 \beta z + \cos^2 \beta z)$$

$$\text{i.e. } I_{(19)} = \cos^2 \beta z$$

[0064] It can be shown that over one spatial period of the pattern i.e. $\beta = 0 \rightarrow 2\pi$, the inensity $I_{(19)}$ has an average value $<I_{(19)}> = \frac{1}{2}$ in the arbitrary units of this analysis.

[0065] Considering now the end point **20a** of the envelope **18**, the patterns **16, 17** are arranged to become progressively out of phase from the in-phase condition in region **20**, so that at the opposite ends of the envelope, e.g. at end point **20a**, the patterns are 90° out of phase, i.e. $\beta_1 = \beta_2 + \pi/2 = \beta$. Thus, at the end point **20a**, equation (4) reduces to:

$$I_{20} = 1/2 \ (\cos^2 \beta^2 + \cos^2(\beta z + \pi/2))$$

$$= 1/2(\cos^2 \beta z + \sin^2 \beta z)$$

$$= 1/2 \ (\text{in the arbitrary units of this analysis})$$

[0066] It will be therefore understood from the foregoing, and from an inspection of **FIG. 12**, that the average intensity is constant along the z dimension of the envelope **18**, shown as line **21**. Thus n_{eff} as recorded in the fibre **8**, is constant along its length, which avoids chirp that would arise if n_{eff} were to vary.

[0067] In an example of a grating recorded in a germanium doped photosensitive fibre **8**, u.v. light from a laser operating c.w.~100 mw at a wavelength of 244 nm produced the first interference pattern **16** in region **7** of **FIG. 5**, of a length z=4-6 mm and a transverse dimension of 40 μm. The spatial period of the interference pattern was of the order of 1 μm. Then, the wedge **15** was inserted into beam **3** in order to produce the second pattern **17**. The wedge was made of SiO₂ with a refractive index n=1.46, and a wedge angle of 5" of arc. The second pattern **17** was spatially in phase with the first pattern in the central region **19** and the relative spatial phase of the patterns progressively increased outwardly from the central region **19** towards the ends **20a, 20b** where the phase difference was $\pi/2$. The optical fibre consisted of a silica fibre with an outside diameter of 125 μm, codoped with Ge/B to provide a core of 4 μm diameter. The exposure time for each component pattern was approximately ten minutes.

[0068] The resultant spectral characteristic of the apodised grating recorded in the fibre **8** is shown in **FIG. 15**, as trace **23**. For comparison purposes, the wavelength characteristic for a grating produced by only one of the patterns **16** or **17** is shown as trace **22**, from which the suppression of the side lobes produced by the apodisation can be clearly seen. The characteristics shown in **FIG. 15** were determined by launching relatively broadband laser radiation along the core of the fibre **8** and measuring the spectral response of the radiation reflected by grating, using conventional techniques.

[0069] Referring now to **FIG. 6**, the second method of recording an apodised grating in accordance with the invention will now be described. This can be considered as a modification of the method described with reference to **FIG. 5**. In the method of **FIG. 6**, the beams **3, 4** produce interference in region **7**, in the manner described previously. The first interference pattern is recorded in the fibre **8** when

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it is in position A so that the fibre is in position 8_1. Thereafter, the fibre is moved through a small angle e.g. ~3° for a pattern of length z=4 mm, and the second pattern is recorded, whilst the fibre is in position B, lying along line 8_2 shown in dotted outline. The plane in which the fibre is rotated may lie within the beams **3, 4** or may be transverse to the beams, for example in a horizontal plane for the configuration shown in **FIG. 6**.

[0070] Thus, by the method described with reference to **FIG. 6**, the first and second component interference patterns are formed in relation to the fibre **8**, which are recorded therein so as to produce a combined pattern in which the fibre grating is apodised.

[0071] A third method in accordance with the invention will now be described with reference to **FIG. 7**. In this example, the beams **3** and **4** are directed to the fibre **8** as before, and the fibre is subjected to different levels of longitudinal stress. Piezoelectric devices **22, 23** are attached to opposite ends of the fibre **8**. The beams **3, 4** produce an interference pattern in region **7**.

[0072] Firstly, the fibre is subject to a first relatively low level of stress, during which the piezoelectric devices **22, 23** are unenergized. A first component grating pattern is recorded in the fibre during this period. Thereafter, the devices **22, 23** are energized so that the fibre is stretched by a small amount corresponding to a period A of the interference pattern. The interference pattern formed in region **7** is then recorded again as a second component pattern in the fibre **8**, with the level of stretching being maintained during exposure for the second pattern. Thereafter, when the exposure is completed, the fibre is released from the piezoelectric devices **22, 23**. When the stretching is released, the spatial periodicity of the second pattern becomes slightly compressed as a result of the release of the fibre stress, so that the second pattern has a slightly smaller periodicity than the first pattern. The patterns are arranged so that they are spatially in phase in their central regions, and are b **90°** out of phase at the opposite ends, so the resulting combination of the first and second patterns recorded during the first and second exposures of the fibre, produces an apodised grating.

[0073] In a modification the piezo electric devices **22, 23** are driven by an oscillator (not shown) e.g. at a frequency of about 5 Hz, during the exposure, which may take several minutes. This results in the desired apodised pattern.

[0074] In the examples of the method according to the invention described so far, the first and second component patterns have been recorded sequentially. However, it is possible to achieve simultaneous recording of the patterns and an example will now be described with reference to **FIG. 8**.

[0075] Light from a laser source **24** is directed through a phase mask **25**, which acts as a beam splitter, so as to form two phase coherent beams **26, 27** which pass through respective reflective corner cubes **28, 29** so as to be reflected back on paths **30, 31** to mirrors **32, 33**. The mirrors are adjusted so as to reflect the beams along paths **34, 35** which converge at an angle θ upon the photosensitive optical fibre **8**. The spectral content of the output of the laser **24** is shown schematically in **FIG. 9** and consists of a narrow Gaussian distribution of wavelengths with a peak wavelength λ_{max}. The two beams **34, 35** interfere and produce an interference

pattern in the region **7** of the fibre. The interference pattern can be considered as a superposition of patterns produced at each of the component wavelengths that makes up the distribution shown in **FIG. 9**. It can be shown that the resulting superposition gives rise to an apodised grating pattern recorded in the fibre.

[0076] A fifth example of a method according to the invention will now be described with reference to **FIG. 10**. In this example, two holographic phase mask patterns are used to record the first and second component patterns in the fibre **8**. The phase mask patterns may be formed one overlying the other in the same phase mask, and, in **FIG. 10**, the first and second component patterns are shown as patterns P1 and P2 formed in a phase mask **36**. An optical system **37** shown schematically, is operable to focus a beam of light either onto the pattern P1 or the pattern P2 and cast a corresponding holographic reference pattern onto optical fibre **8**. The optical system **37** thus, records interference patterns derived holographically from the patterns P1, P2 sequentially in the fibre and the result of the two component patterns, when recorded, is to produce a grating which exhibits apodisation.

[0077] In a modification, the patterns P1 and P2 may be recorded side by side in the mask **36**, and the mask is moved between exposures to align the patterns with the optical source **37** and the fibre **8**. In another modification, a single phase mask pattern P1 is used and the fibre **8** or the phase mask **36** is stretched to produce the second component pattern to be recorded in the fibre. Also instead of stretching, the phase mask can be compressed to alter the periodicity of the pattern P1 so as to provide the second component pattern to be recorded in the optical fibre. The compression technique can also be applied to the optical medium. Although an optical fibre cannot easily be longitudinally compressed, the compression technique is particularly useful for recording apodised gratings in planar waveguides, which cannot readily be stretched but can be longitudinally compressed.

[0078] A sixth example of the invention will now be described with reference to **FIG. 16** in which the fibre **8** is placed immediately behind phase mask **36** and held in chucks in assemblies **39, 40** that include piezoelectric actuators that correspond to the actuators **22, 23** shown in **FIG. 7**. The phase mask **36** is formed from silica, etched by a standard e-beam technique, with a 100 mm long step-chirped grating with a chirp of 0.75 nm. The grating comprises 200 sections, each 0.5 mm in length, mimicking a near continuous chirp. A beam **41** of UV radiation at 244 nm wavelength is scanned across the phase mask **36** to imprint the grating in the fibre **8**. The UV radiation is produced by an intra-cavity frequency-doubled argon ion laser **42**.

[0079] The phase mask **36** is positioned symmetrically between the chucks **39, 40** so that the centre of the grating experiences zero stretch. The piezo electric actuators are driven by an oscillator **43** at about 5 Hz by a triangular ramp signal ensuring that the fibre **8** at the ends of the phase-mask **36** experiences a stretch amounting to approximately half the period of the grating at those points. In order to achieve a satisfactory symmetric half-period stretch for a given length of grating, the following should be satisfied:

$$f > \frac{v}{w}$$

[0080] where f is the frequency of the stretching of the waveguide, v is the scanning speed of the beam and w is the diameter of the beam spot.

[0081] It is to be understood that this process can be repeated on the same fibre at different, substantially contiguous locations with the same phase mask to produce a long grating, in which case apodisation by stretching will be applied asymmetrically at the ends of the long pattern. To achieve this, the fibre may be stretched by means of one of the piezoelectric devices only.

[0082] Alternatively, phase masks with different spatial periodicities can be used to produce a chirped pattern. The recorded patterns can be matched at their junctions by the apodisation process.

[0083] FIGS. 17 and 18 show respectively the reflectivity and delay of a chirp grating made according to the sixth example of the present invention, in comparison with a theoretical prediction produced by means of a computer simulation and the actual performance of a corresponding unapodised grating.

[0084] Referring to FIG. 19, a WDM system which makes use of apodised grating filters made in accordance with the invention will now be described. A link in an optical communication system comprises a WDM multiplexer 44 and an optical amplifier 45 at a transmitter station. The output of the amplifier 44 is directed to a 120 km length of optical waveguide 46. At a receiver station, an amplifier 47 receives and amplifies optical signals from the waveguide 46 and outputs them to a first port or an optical circulator 48. A second port of the optical circulator 48 is coupled to a bidirectional demultiplexer/multiplexer 49. A third port of the optical circulator 48 is coupled to an optical receiver 50. The demultiplexer/multiplexer 15 is also coupled to four chirp filters 51,52,53,54. Each of the chirp filters 51, . . . , 54 was made by the method described with reference to FIG. 16 and are adapted for compensating for dispersion of signals at respectively 1548 nm, 1552 nm, 1557 nm and 1562 nm. The dispersion parameter of the chirp filters 51, . . . , 54 is 1600 p nm¹. The operating bandwidth of the chirp filters is ~3 nm, allowing them to be used over a temperature excursion of ±10° C.

[0085] At the transmitter station, optical signals at 1548 nm, 1552 nm, 1557 nm and 1562 nm are combined and applied to the amplifier 45 by the multiplexer 44. The amplifier 45 amplifies the multiplexed signals and launches them into the waveguide 46. During their passage along the waveguide, the optical signals become dispersed.

[0086] At the receiver station, the multiplexed signals are boosted by the amplifier 47 and fed to the optical circulator 48 which feeds them from its second port to the demultiplexer/multiplexer 49. The demultiplexer/multiplexer 49 distributes the component signals of the multiplex signal to the chirp filters 51, . . . , 54 which reflect the applied signals in such a manner as to compensate for the dispersion occurring in the waveguide 46. The compensated optical

signals are then recombined by the demultiplexer/multiplexer 49 and fed back to the circulator 48 which outputs them at its third port. Finally, the compensated optical signals are received by the optical receiver 50. With the system of FIG. 19, using data rates in the region of 10 Gb s⁻¹, a total bit-rate x distance product of 4.8 Tb s⁻¹ km has been achieved. Also over 24 dB of cross-channel isolation has been measured.

[0087] Many modifications and variations to the described examples falling within the scope of the claimed invention are possible. For example, gratings formed by the method of the invention may be used in devices other than optical filters. The grating need not be recorded in an optical fibre; it can be recorded in other forms of optical waveguide such as a planar waveguide, or in a bulk optical medium that is not necessarily configured as a waveguide. Also, the grating need not necessarily be of a narrow elongate structure as previously described. The waveguide elements could be disposed as concentric circles, ellipses or other similar shapes, such that the length of the grating extends radially outwardly of the recorded pattern

1. A method of recording an apodised refractive index grating in a photosensitive optical medium with a pattern of optical radiation, that comprises producing a plurality of spatially periodic component optical patterns for recording a sequence of elements that form the grating, with a relative spatial phase which varies along the sequence in such a manner as to result in apodisation of the grating recorded in the optical medium.

2. A method according to claim 1 wherein the effective refractive index (n_{eff}) of the optical medium is substantially constant along the recorded grating.

3. A method according to claim 1 or 2 wherein said relative phase progressively changes in directions away from an intermediate region of the component patterns towards the ends thereof.

4. A method according to claim 3 wherein the component patterns have zero relative spatial phase in the intermediate region.

5. A method according to claim 4 wherein the component patterns have a relative phase of ±π/2 in respect to the spatial periodicity of the patterns, at opposite ends thereof.

6. A method according to claim 3, 4, or 5, wherein the intermediate region is disposed centrally of the component patterns.

7. A method according to any preceding claim wherein the component patterns are formed sequentially.

8. A method according to any preceding claim wherein the component patterns are optical interference patterns.

9. A method according to claim 8 including causing beams of optical radiation to interfere to produce a first of the component interference patterns, and thereafter introducing a phase shift across the width of at least one of said beams, so as to form a second of the component interference patterns.

10. A method according to claim 8 including introducing a wedge of optically transparent material into one of said beams so as to produce said phase shift for said second component interference pattern.

11. A method according to claims 1 to 10 including forming an interference pattern, arranging the optical medium in a first disposition relative to said interference pattern so as to provide the first component interference

pattern to be recorded in the medium, and thereafter arranging the medium in a second disposition relative to the interference pattern so as to provide the a second component interference pattern to be recorded in the medium.

12. A method according to claim 11 including rotating the optical medium relative to the interference pattern between the first and second dispositions.

13. A method according to claim 11 including altering the length of the optical medium in order to achieve said first and second dispositions.

14. A method according to claim 13 including stretching the medium.

15. A method according to claim 13 or 14 including stretching the optical medium cyclically

16. A method according to claim 13, 14 or **15** including stretching the medium from one end only of the recorded pattern.

17. A method according to claim 13 including compressing the medium.

18. A method according to **13, 14, 15** or **16** including repeatedly recording the pattern along the medium

19. A method according to any one of claim 13 to **18** wherein the pattern is provided from a phase mask.

20. A method according to claim 19 including altering the length of the phase mask so as to produce the component patterns.

21. A method according to claim 19 wherein the optical medium is stretched symmetrically about the centre of the resultant grating.

22. A method according to claim 19 wherein a beam of said radiation is scanned along the phase-mask and the optical medium is cyclically stretched such that the condition:

$$f > \frac{v}{w}$$

is met, where f is the frequency of stretching, v is the scanning speed of the beam and w is the diameter of the beam spot.

23. A method according to any one of claims 1 to 6 wherein the component patterns are formed concurrently.

24. A method according to claim 23 wherein beams of optical radiation are caused to interfere to produce said component patterns, said beams having a predetermined spectral content whereby light at different wavelengths interferes to produce said patterns.

25. A method according to any one of claims 1 to 6 wherein a phase mask that includes first and second mask patterns, is placed adjacent to the waveguide and light is directed through the phase mask so as to produce the component patterns to be recorded in the optical medium in the waveguide.

26. A method according to claim 25 including selectively illuminating the mask patterns in the phase mask sequentially.

27. A method according to any preceding claim including recording the refractive index grating in an optical waveguide that is photosensitive to the optical radiation.

28. A method according to claim 27 wherein the waveguide comprises an optical fibre.

29. A waveguide including an apodised refractive index grating formed by a method according to any preceding claim.

30. An optical chirp filter comprising a grating which is a composite of a first component grating and a second component grating, the phase difference between the first and second component gratings increasing from the centre of the said grating to produce apodisation thereof.

31. An optical wavelength division multiplexed communications system comprising a transmitting station and a receiving station coupled by an optical waveguide, the receiving station including a plurality of chirp filters according to claim 27, each filter being arranged to compensate for dispersion of an optical signal in a different WDM channel received from the waveguide.

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