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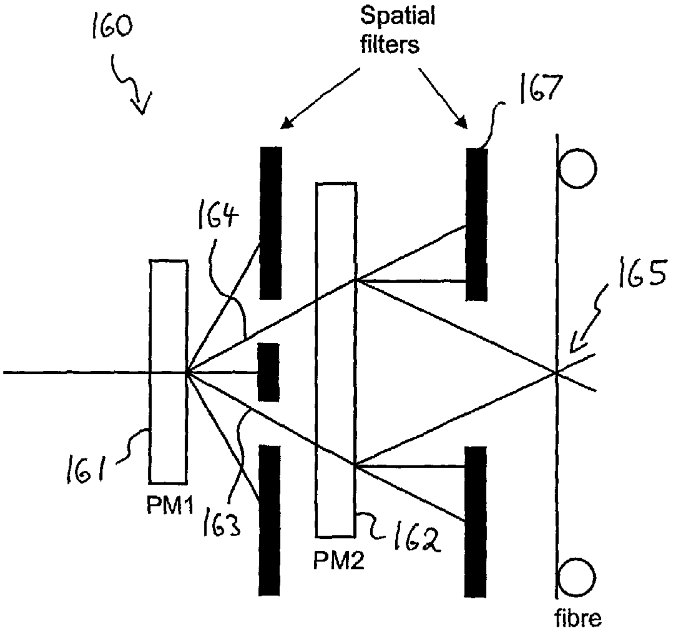
(54) Title: INTERFEROMETRIC GRATING WRITING METHOD AND APPARATUS



(57) Abstract: A method of writing a grating structure into a photosensitive waveguide, the method comprising the steps of projecting at least two coherent light beams (163, 164) onto a first phasemask (162) so as to form a first and a second series of respective diffracted order beams, and interfering at least one beam of each of the first and second series of diffracted order beams at a spatial position (165) so as to form an interference pattern substantially at said spatial position (165) for creating the grating structure through photo-induced refractive index change in the photosensitive waveguide.

Interferometric Grating Writing Method and Apparatus

Field of the invention

The present invention relates to the field of the writing of grating structures in photosensitive waveguides utilising interferometric techniques.

Background of the invention

In modern optical fibre telecommunication systems, it is becoming increasingly important to be able to form grating structures of alternating refractive indices in optical waveguides. The grating structures find many uses in the control and manipulation of dense wavelength division multiplexed (DWDM) optical fibre signals.

It is well known to write grating structures utilising the interferometric interference between two coherent light beams.

It is known to form the interferometric pattern utilising different techniques. For example, PCT Publication No. WO 97/21120 entitled "Ring interferometer configuration for writing gratings" to Ouellette et al discloses a first grating writing technique. Other techniques include the direct phasemask writing technique wherein the fibre is placed directly behind a phasemask with the grating being written as a result of the phasemask interference effects.

It is desirable to produce gratings in a high speed manner with the gratings having accurate bandpass characteristics for reflection of a particular band of interest. Further, gratings are also useful in the production of dispersion compensating components and other components in optical telecommunication systems.

In at least preferred embodiments, the present invention seeks to provide a new grating writing method and apparatus.

Summary of the invention

In the summary of invention and the claims components of the same name have been identified as e.g. "first", "second", "third" etc. This is intended to mean "first identified", "second identified", "third identified" etc. rather than being intended to define a total number of the same components in individual embodiments of the invention.

In accordance with a first aspect of the present invention there is provided a method of writing a grating structure into a photosensitive waveguide, the method comprising the steps of projecting at least two coherent light beams onto a first phasemask so as to form a first and a second series of respective diffracted order beams, and interfering at least one beam of each of the first and second series of diffracted order beams at a spatial position so as to form an interference pattern substantially at said spatial position for creating the grating structure through photo-induced refractive index changes in the photosensitive waveguide.

In one embodiment, the method further comprises the step of collimating said at least two coherent light beams before they are projected onto said first phasemask. A second phasemask and/or at least one lens and/or at least one mirror may be utilised to collimate said at least two coherent light beams.

In one embodiment the method further comprises projecting a first light beam onto a third phasemask so as to form a third series of diffracted order beams, and wherein the at least two coherent light beams comprise one pair of said third series of diffracted order beams.

The diffracted order beams utilised in the method may comprise first order and/or higher order diffracted beams.

Preferably the method further comprises blocking non-utilised diffracted order beams utilising a spatial filter.

In one embodiment said interference pattern is utilised to form an extended grating structure in a photosensitive material placed at said first spatial position and translated relative to said spatial position.

The method may further comprise the step of spatially translating the relative interrelationship between optical elements utilised in the method so as to control parameters of the written extended grating structure.

In one embodiment the method further comprises the step of separating unwanted wavelength components in the beams utilising a further spatial filter arrangement.

The method may further comprise the step of utilising a chromatic aberration of an optical lens for separating of unwanted wavelength components from the beams .

In one embodiment different wavelength components of the first and second series of diffracted order beams interfere at different locations over a region of overlap at the spatial position and the method comprises the further step of adjusting the position of the photosensitive material placed at said spatial position so as to alter the wavelength of any grating structure written.

In one embodiment the method further comprises the step of compressing one or more of the phasemasks utilised in forming the interference pattern so as to alter the wavelength of said interference pattern.

The at least two coherent beams may be orthogonally incident on the first phasemask.

In one embodiment, one or more of the at least two coherent beams are off-orthogonally incident on the first phasemask. The method may further comprises varying the angle of incidence of one or more of the at least two coherent beams on the first phasemask, so as to vary parameters in the written grating structure.

In one embodiment the angles of incidence of the at least two coherent beams on the first phasemask are the same.

In another embodiment the angles of incidence of the at least two coherent beams on the first phasemask are different.

In accordance with a second aspect of the present invention there is provided an apparatus for writing a grating structure into a photosensitive waveguide, the apparatus comprising a first phasemask, an optical arrangement for projecting at least two coherent light beams onto the first phasemask so as to form a first and a second series of respective diffracted order beams, and so as to interfering at least one beam of each of the first and second series of diffracted order beams at a spatial position so as to form an interference pattern substantially at said spatial position for creating the grating structure through photo-induced refractive index changes in the photosensitive waveguide.

The optical arrangement may comprise means for collimating said at least two coherent light beams before they are projected onto said first phasemask. In one embodiment the means for collimating comprises a second phasemask and/or at least one lens, and/or at least one mirror.

In one embodiment the optical arrangement comprises a third phasemask so as to form a third series of diffracted order beams from a light beam projected onto the third phasemask, and wherein the at least two coherent light beams comprise one pair of said third series of diffracted order beams.

The diffracted order beams utilised in the apparatus for the writing of the grating structure may comprise first order and/or higher order diffracted beams.

In one embodiment the optical arrangement comprises a spatial filter for blocking non-utilised diffracted order beams.

The apparatus may be arranged, in use, to form an extended grating structure in a photosensitive material placed at said first spatial position and translated relative to said spatial position. The apparatus may further be arranged, in use, for spatially translating the relative interrelationship between optical elements of the apparatus so as to control parameters of the written extended grating structure.

In one embodiment the optical arrangement comprises a further spatial filter arrangement for separating unwanted wavelength components in the beams utilising.

The optical arrangement may comprise an optical lens for utilising a chromatic aberration of the optical lens for separating of unwanted wavelength components from the beams.

In one embodiment the optical arrangement is disposed such that, in use, different wavelength components of the first and second series of diffracted order beams interfere at different locations over a region of overlap at the spatial position, whereby, in use, adjusting the position of the photosensitive material placed at said spatial position alters the wavelength of any grating structure written.

One or more of the phasemasks may arranged for controlled compression so as to alter, in use, the wavelength of said interference pattern.

In one embodiment the at least two coherent beams are orthogonally incident on the first phasemask.

In another embodiment one or more of the at least two coherent beams are off-orthogonally incident on the first phasemask. The optical arrangement may be arranged for varying the angle of incidence of one or more of the at least two coherent beams on the first phasemask, so as to vary parameters in the written grating structure.

The angles of incidence of the at least two coherent beams on the first phasemask may be the same.

The angles of incidence of the at least two coherent beams on the first phasemask may be different.

Brief description of the drawings

Preferred embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates a growth curve for a first exposure method for writing gratings;

Fig. 2 illustrates a measured transmission spectrum for a grating written in accordance with the arrangement of Fig. 1;

Fig. 3 illustrates a corresponding reflection spectrum;

Fig. 4 illustrates schematically a first embodiment of the present invention;

Fig. 5 is a graph of the tunability of the Bragg wavelength for an arrangement of Fig. 4;

Fig. 6 and Fig. 7 illustrate the transmission and reflection spectrums respectively for the arrangement of Fig. 4;

Fig. 8 illustrates the wavelength trajectories for the first order beam emitted from a phasemask;

Fig. 9 illustrates interference overlap regions for different wavelengths emitted from a phasemask;

Fig. 10 illustrates schematically Young's two point experiment;

Fig. 11 illustrates schematically the process of utilisation of Young's experiment in the present invention;

Fig. 12 illustrates schematically the arrangement of a second embodiment of the present invention;

Fig. 13 illustrates schematically the arrangement of a third embodiment of the present invention;

Fig. 14 illustrates schematically the arrangement of a fourth embodiment of the present invention;

Fig. 15 and Fig. 16 illustrate transmission and reflection spectra for a grating written in accordance with the arrangement of Fig. 14;

Fig. 17 and Fig. 18 illustrate transmission and reflection spectra for a translated grating written in accordance with the arrangement of Fig. 14;

Fig. 19 illustrates schematically a further embodiment of the present invention;

Fig. 20 and 21 illustrate transmission and reflective spectra for the arrangement of Fig. 19;

Fig. 22 illustrates schematically the process of utilising a small slit in front of the fibre;

Fig. 23 and Fig. 24 are transmission and reflection spectra for a grating written utilising the arrangement of Fig. 22;

Fig. 25 and Fig. 26 illustrate transmission reflection spectra for corresponding translated gratings utilising the arrangement of Fig. 22 and thereby illustrates the potential tuning range of the arrangements shown in Fig. 19;

Fig. 27 illustrates schematically a sixth embodiment of the present invention;

Fig. 28 and Fig. 29 are corresponding transmission and reflection spectra for the arrangement of Fig. 27;

Fig. 30 illustrates the growth curve for the arrangement of Fig. 27;

Fig. 31 illustrates the evolution of refractive index modulation contrast for a grating written utilising the arrangement of Fig. 27;

Fig. 32 illustrates a corresponding spectra for a grating formed by inscribing adjoining sub-gratings each formed by utilising the arrangement of Fig. 27.

Fig. 33 illustrates schematically the process of wavelength tuning;

Fig. 34 is a graph of the calculated change in Bragg wavelength when wavelength tuning an arrangement;

Fig. 35 illustrates a further seventh embodiment of the present invention;

Fig. 36 to 38 are corresponding spectra for gratings written utilising the arrangement of Fig. 35;

Fig. 39 and Fig. 40 illustrate the reflection spectrums for relaxed and compressed phasemasks respectively;

Fig. 41 illustrates a further embodiment of the present invention;

Fig. 42 illustrates the etching process suitable for use with the arrangement of Fig. 41;

Fig. 43 illustrates an alternative embodiment of the present invention.;

Fig. 44 illustrates a process of cleaning up the wavelengths emitted from a phasemask;

Fig. 45 illustrates an alternative method of forming collimated beams using a beam splitter;

Fig. 46 illustrates an alternative method of forming collimated beams using a thin reflection element;

Fig. 47 illustrates an alternative method of forming collimated beams using two light sources; and

Figure 48 illustrates a further modification to a grating writing arrangement embodying the present invention.

Detailed description of the embodiments

In the preferred embodiments, a number of techniques utilising phasemasks have been developed so as to provide for improved grating writing. The techniques have been developed so as to provide for an improved grating writing systems over and above prior art techniques.

The Direct Exposure Technique

As a point of comparison, a spot exposed grating was inscribed into a hydrogen loaded germanium-doped fibre (GF 1 from Nufern Inc.) using the direct exposure method reported on by Hill et. al. in Hill K.O., Malo B., Bilodeau F., Johnson D.C., Albert J., "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phasemask" Applied Physics Letters, 62(10), p1035, 1993. The power used was 70mW, with a beam width of approximately 0.7mm and an exposure time of 17.5 minutes from a 244nm Fre D argon ion laser (made by Coherent Scientific Inc.). The reflection curve growth is illustrated in Fig.1, with the point 2 where the growth of the reflection curve was saturated. For this experiment saturation occurred in approximately 10 minutes, and no extra growth occurred from this point on.

The spectral characteristics of this grating in reflection and transmission are illustrated for comparison purposes Fig. 2 and Fig. 3. The spectrum shows a main peak or notch 4, 5, depending on whether one is examining the reflection or transmission spectrum respectively, with a leading side lobe 6, 7. This side lobe is a typical feature of such a spot grating, originating from self-chirping of the grating as a result of the Gaussian shape of the induced average refractive index profile. This is because the beam is Gaussian in nature.

Coming through only one phasemask, the results of Fig. 2 to Fig. 3 may be considered as the best case for grating growth, without the addition of lenses to increase fluence, provided the fibre has been placed as close as possible to the mask surface. From the results, it can be seen that over a period of 10 minutes, the grating grows by around 8.3dB in transmission, and 81% in Reflection.

Imaging the phasemask period

In a first modification of the standard arrangement, an extra lens was incorporated into the arrangement. The First modified embodiment is illustrated in Fig.4. The arrangement 10 is designed to have an input light 11 concentrated by a cylindrical lens 12 projected through a phasemask 13 which provides various order output beams including zero order 14, first order 15 and second order 16. The non-first order beams e.g. 14, 16 are preferably blocked by spatial filters e.g. 18. The two first orders are concentrated by lens 20 onto a fibre 21 so that an interference pattern is formed from the two coherent first order beams at point 22.

The phasemask 13 is used as the beam splitter, with the lens 20 recombining the two $\pm 1^{st}$ orders. In this configuration, the unwanted orders are spatially filtered, improving the grating quality.

Considering the thin lens equation:

$$\frac{1}{S_i}+\frac{1}{S_0}=\frac{1}{f}$$

where f is the lens focal length (50mm for this experiment), S_i is the object distance and S_o is the image distance. When the object distance is set to twice the focal length, the image distance is equal to the object distance, i.e. $x = S_i = S_o$. This condition is achieved when $x = 2f$, and at this point, the fringe pattern formed at the interference point has a periodicity of half the phasemask period. For a phasemask with period around 1060nm, a grating with a period of half the phasemask period at around 530nm is formed, achieving a Bragg wavelength of around 1550nm.

Tuneability of the resonant wavelength can be achieved via a change in the relative phasemask and lens position. The tuneability relationship is illustrated 24 in Fig 5, and is calculated for a lens with a focal length of 50mm. This method of tuning is extremely sensitive to S_i, making it a flexible and very simple method for fabrication. Conversely this makes it more difficult to align, as can been see in Figure 5, with a small change of one millimetre giving rise to a change in Bragg wavelength of around 30nm. It is important to note that the fibre mount for fibre 21 must also be moved closer to or further from the lens to retain it's position with respect to the interference region when the phasemask to lens distance is altered.

The large tuning range with small movement of the lens 20 or phasemask 13 increases the difficulty in alignment of the apparatus. Care must be taken to set S_i to the correct value, and ideally a micrometer translated stage be used to adjust this parameter. Further, if the lens 20 is not positioned perpendicular to the incident beam, the half phasemask period may not be imaged. Additionally, if the lens 20 is positioned to one side of the zeroth order 14, i.e. off centre, one beam will impinge on the region of interference at a different angle, causing blazed gratings to be formed. Furthermore, the beam divergence introduced by the lens, and the spherical aberration of the lens can cause the region of interference to have a range of fringe periodicities, adding to the tuneability and conversely to the alignment difficulty.

Also, as a result of the lens having a short focal length to allow the 1st orders to be incident on the lens at a distance of twice the focal length, the lenses that are used may have an number approaching unity. This means beam divergence can be high. As the required orders from the phasemask are incident on the outer edges of the lens, spherical aberration can be more significant, but this may be reduced with the choice of a suitable achromatic doublet lens. The beam divergence introduced by the lens, and the spectral spread of the beam introduced by the phasemask means that tuning in the resonant wavelength can also be achieved by moving the fibre within the interference region, where the fringe period varies.

The technique of Fig 4 was used to inscribe a spot exposed grating in hydrogenated germanium doped fibre (GF 1 from Nufern Fibres Inc.) and the results plotted in Fig 6 and Fig 7 for transmission and reflection respectively. The results are shown for an incident power to the phasemask of 70mW, spot exposing (spot length equal approximately 2mm) the fibre for 20 minutes with a 244nm frequency-doubled (Fre D)) argon ion laser. The phasemask/recombining lens separation (x of Fig.4) was set to approximately 100mm, resulting in a Bragg wavelength of around 1550nm.

A grating strength of around 12.5dB in transmission 28 and 94% in reflection 29 was achieved over the 20 minute period, showing this technique is not quite as efficient as the direct exposure method results. The example grating was not inscribed with the image distance at precisely 100mm and this is clearly visible by the fundamental notch at the wavelength of around 1539nm. From the equation and based on the calculated results, the image distance must have been approximately 100.38mm (if the thin lens equation holds true for this lens). This shows the sensitivity of the technique to fibre position in the interference region.

The noise in the recorded optical power apparent in Fig.6 and Fig.7 is a result mainly of ASE noise from the tuneable semiconductor laser source used to characterise the gratings. Some additional shot and thermal noise may also affect the detector. Its effect in the reflection spectra 29 is exacerbated by the plotting of the data on a linear scale. The uncertainty in wavelength of the light used to characterise these gratings was thought to be ±0.5pm.

The additional tuning may stem from the beam divergence, which facilitates a change in period across the region of interference. As shown in Figure 8, a phasemask 30 diverges 32 the beam 31 according to the wavelength spread of the source.

This divergence can be exacerbated by the lens, with the net result, as illustrated in Fig. 9, of different parts of the beam intersecting one another at different angles 33, 34, and therefore inscribing a grating at a different period. It is of interest to note that phasemasks in this way clean up beam coherence, and can therefore be used successfully with more incoherent sources such as exciplex lasers.

With the arrangement of Fig.4, apodisation of the grating can be performed in one of two ways, depending on the method used for writing long gratings (i.e. much greater than the beam width). If the beam is scanned along the phasemask 13, a phasemask dithering technique can be utilised. This involves vibrating the mask during the scan by different amounts to smooth out the refractive index modulation at the edges of the grating. It is important to note that the lens 20 would have to be translated with the beam to keep the beam position relative to the lens constant, but additionally, the lens would have to be dithered with the mask for the same reason. This can be practically difficult. If the beam cannot be translated a subgrating technique can be implemented. This requires an interferometrically controlled translation stage, and allows for the fibre only to be translated, releasing the requirements on moving the lens.

The techniques of Fig.4 means that strong gratings are possible to fabricate using this method. There are few optical elements, and the only main source of loss would be from power diffracted into unwanted orders by the mask. Fluence can be decreased by the dispersion of the beam, leading to an expanded spot size for the same power. This can be corrected by inserting a cylindrical lens 12 with a focal length of 150mm into the beam path, decreasing the spot size in the vertical direction.

The system of Fig.4 is simple and flexible. However, care must be taken in alignment of the lens as this will ultimately affect Bragg wavelength and grating quality. The large tuning range is advantageous for selecting resonant wavelength and chirped gratings, but also increases the demand for good alignment, especially if low bandwidth gratings are required.

Rather than recombining the beams straight from the beam splitter, a collimation of these beams before their recombination may make it easier to align the system and allow separate external modulation of the beams if required. This can be achieved using techniques outlined below. The collimation retains the advantages of using phasemasks with regard to their coherence improvements, and keeps the system compact, robust and flexible in tuneable range. This is not achieved by prior art techniques. The techniques of the preferred embodiment incorporate the principles behind Young's double slit experiment.

In Young's experiment, as illustrated schematically in Fig.10, light from source 35 is fed through two points 37 in screen 36. The light emanating from two point sources 37 interferes to give a fringe pattern 38.

As illustrated in Fig.11, in a first method incorporating the principles of this experiment, the phasemask 39 splits the beam in a similar way to the double slit creating a fringe pattern 39 that is then imaged 44 by lenses 42, 43. This idea of Fig.11 may be used (albeit in a loose interpretation) to develop a technique whereby light from the two point sources is collimated 39 so that the fringe pattern 44 is allowed to be imaged away from the splitting element 39.

An example of an arrangement formed in accordance with the principles of Fig.11 is shown in Fig. 12. The input beam 50 projects through phasemask 51 and then is collimated by lenses 52, 53. Lens 52 acts as the collimator, acting on the ±1st orders from the phasemask 51.

Lens 52 recombines these collimated orders, forming a fringe pattern at the plane where the fibre 54 is placed.

The setup allows tuneability by changing the value of the beam separation (D) or a change in the focal length of lens 52. The approximate relationship between grating period and these parameters is:

$$\Lambda_g \approx \frac{f_2 \lambda_{uv}}{D}$$

So, for a required grating period of around 500nm, with lens 53 having a focal length of 25mm, the beam separation to achieve this would be 12mm.

Effects of a spherical aberration for the above setup can be lessened, as the collimating lens is closer to the phasemask for this case (one focal length away as opposed to two focal lengths for design of Fig. 4). Even still, aberration of the lenses is a concern, although this may be made much less important by using achromatic doublet (aspheric) lenses whose aberration is suppressed.

Adjusting D in Fig. 12 is not accomplished without complication for the above design, because changing the spacing between the phasemask and lens 1 (52) would cause the lens to be a distance not equal to its focal length and thus the beams would not longer be collimated. This would mean they approach lens 2 at some incident angle, and the beams would not intersect at the focal length of lens 2.

However, there is another way of achieving the desired outcome. This is illustrated with reference to Fig.13 which illustrates a double phasemask collimator 60. In the arrangement 60 of Fig.13, a second phasemask 61 is used as the collimating element. This phasemask 61 can be of the same period as the first phasemask 62, thus by nature collimating the beam. The arrangement 60 removes the effects of spherical aberration associated with the collimating lens, and reduces restrictions on the position of the optics used. Again, spatial filtering 64 can be performed in between the splitting and recombining elements to improve grating quality.

A change in the beam separation can be achieved via altering the distances between the phasemasks without complication, as long as they are both kept parallel and perpendicular to the beam.

The tuning range for this configuration was examined mathematically and the mathematical relationship between beam separation and Bragg wavelength was thought to be:

$$\frac{d\lambda_B}{dD}=\frac{n_{eff}\lambda_{uv}}{\frac{D^2}{50}\sqrt{1+\frac{D^2}{2500}}}$$

Where D is the collimated beam separation, n_{eff} is the effective refractive index of the fibre core, and λuv is the writing wavelength.

Two different methods may be used to increase the strength of gratings inscribed using the arrangement 60 of Fig.13. Separate lenses placed in each beam path could be used to increase the spot size at the writing point, increasing the number of refractive index modulations in the fibre, and thus the grating strength. Otherwise stronger gratings may be fabricated by making them longer via beam translation or consecutive subgrating inscription. However, beam translation may not work with this method, as there is no change in the beams to induce a situation where fringes are formed as the beam moves along the fibre. It is important to note that if the beam was translated along the first phasemask 62, the lens 65 would ideally have to be translated as well to ensure consistent alignment and minimise the effects of aberration. This also places restrictions on the smoothness of travel of the translation stage, as vibrations introduced to the lens can cause the fringes to be smeared. Again, for apodised gratings, phasemask 1 (62) and the lens 65 would require dithering, placing a practical challenge on the using this method for writing gratings where the beam is translated across the apparatus. Apodisation via adjusting the subgrating overlap may be a more suitable method for use with this technique.

The arrangement of Fig.13 is easier to align than that previously mentioned as it can be done in a more stepwise manner, and the position of the lens 65 is not as critical to Bragg wavelength. However it still should have the beams centred and symmetric with respect to the optical elements 65 and it is still very important that each element be perpendicular to the beams in the interests of grating quality.

The arrangement does show some promise in terms of tuneability and chirping of gratings.

The Three Phase Mask Technique

A further arrangement is illustrated 70 in Fig.14. A phasemask 71 was used in place of the lens to interfere the writing beam for this technique. Removing all lenses from the design means that the effects of spherical aberration are removed, and beam divergence is drastically reduced (only the inherent divergence of the laser beam remains). Separation of the splitting and recombining elements mean that the many unwanted orders associated with this method can be spatially filtered of e.g. 72, 73.

Alignment is made simple because each phasemask 71, 74, 75 can be aligned separately, and the distance from one another is not critical, the limiting factor being that the beam separation is less than the phasemask length. For collimation the period of phasemask 2 (75) is preferably equal to that of phasemask 1 (74) and they are preferably parallel. Phase mask 3 (71) can be of any period required to obtain the desired Bragg wavelength.

Tuneability can be accomplished in different ways. A first method is to use a lens in front of the phasemask to tune the resonant wavelength via magnification of the fringe period. Alternatively, a lens positioned in each beam path could be used to converge the two collimated beams, although this may lead to small spot sizes. Even still, this technique could be used to provide a tuneable range to this method. Furthermore, described below is a technique for tuning the Bragg Wavelength by compressing the silica mask structure. The last mask could be compressed in this way to change its period and thus the wavelength at which it writes gratings. This is another alternative for adding flexibility to the arrangement of Fig.14.

Apodisation could be performed via the dither technique. The first phasemask 74 or last phasemask 71 could be vibrated to smear out the fringes and thus the photo-induced refractive index modulation in the fibre core. Alternatively, Stubbe's method of adjusting the overlap between two adjacent subgrating footprints could be used.

One draw-back of this three-phasemask interferometer is the wastage of power that is diffracted into other unnecessary orders. Consider a set of three very well made phasemasks with 45% of the incident intensity transmitted in each of the $\pm1^{st}$ orders. At the writing point, each of the writing beams will have a total of 9.11% of the original incoming intensity. In an example arrangement constructed in accordance with Fig.14, with the laser impinged on the first phasemask 74, and at the writing point 77, the optical power values were 74mW (original power) and 6mW (writing power). This represents a considerable loss of writing power, being only 8.12% of the power from the laser, and an inefficient use of the available UV light used to inscribe these gratings.

The fluence may be improved through the use of lenses to focus the beams more onto the fibre, without making the spot size too small, but this will not replace the power that is lost to unnecessary orders. Example results were obtained using the arrangement for Fig.14. The experiment was set up using phasemasks with a period of 1085nm for the splitting and collimating elements, and a 1075nm diffraction grating to recombine the beams. Continuous wave light at 244nm and 75mW was launched into the apparatus for 2 hours, photo-inducing a spot grating in hydrogenated GF 1 fibre. The results for reflection and transmission are shown in Fig.15 and Fig.16 respectively.

A translated grating was then written into a sample of hydrogenated GF 1, using a power of 75mW. The beam 78 only was moved over the stationary system 70. The grating was 20mm long, with the beam moved over this region of the fibre at 0.1mm/min. The results in transmission and reflection can be seen in Fig.17 and Fig.18 respectively.

Another method of fabricating a translated grating was then attempted. The first two phasemasks 74, 75 of Fig. 14 were moved with the beam. This passed the two collimated beams across the final phasemask. From the results of Fig.15 to Fig.18, one can see that both types (spot and translated) of grating were successfully fabricated. The spot grating shows the typical side lobe structure 80-84 as a result of no apodisation being applied to the system. The heights of the side lobes 80-84 are different, most likely due to quadratic chirp from the Gaussian nature of the beam. Because the beam is Gaussian, the photo-induced effective index is also Gaussian, thus a small range of resonant wavelengths are reflected across the grating. This makes the side lobe strength asymmetric. The fact that the dips between the side lobes and fundamental do not return to the baseline e.g. 86 is an indication of a linear chirp applied to the writing process, resulting from a misaligned system.

The translated grating exhibited a rough spectrum (Fig.17, Fig.18) originating possibly from a number of sources. Primarily, and stemming from the results obtained from the spot grating, the misaligned system may have contributed to such a rough spectrum. Secondarily, phase information introduced to the beam by the first mask is effected by the subsequent masks, introducing phase shifts into the induced grating structure. The phase shifts exhibit themselves as notches within the grating spectra, adding to the roughness of the spectra.

The wastage of power exhibited by the arrangement of Fig.14 is seen in a low fluence impinging on the fibre core at the writing point.

Lens Collimation

To increase the optical power incident on the fibre core for grating writing purposes, a lens was installed in place of the second phasemask in the previous system. The resulting arrangement is illustrated schematically in Fig.19. With the lens 91 placed a distance equal to it focal length away from the 1st beam-splitting mask 92, the ±1 orders will be collimated as seen in the thin lens equation by making Si equal to f.

$$\frac{1}{f} + \frac{1}{S_0} = \frac{1}{f}$$

$$\therefore S_0 = \infty$$

This configuration results in the space between the lens and second (recombining) phasemask 94 being much greater than the focal length of the lens. Spatial filters 96-98 may be positioned within the system because of the separation of splitting and recombining elements, thereby improving the grating quality.

In an example setup arranged in accordance with Fig.19, the period of both phasemasks 92, 94 was 1085nm, with a lens of 25mm focal length. Due to the distance between the lens and phasemask 94 being much greater than the lens' focal length, beam divergence was significant giving a spot size at the writing point of approximately 4mm.

A spot grating was inscribed into hydrogenated GF 1 fibre for 90 minutes at a power from the laser of 70mW. The results are shown in Fig. 20 for transmission and Fig.21 for reflection. Gaussian distribution overall show a grating was fabricated, but the fact that it took 90 minutes to inscribe a grating that was 10dB strong in transmission suggests that this method is also inefficient in its use of power.

One observation is that no side lobes show up in reflection (a result of beam shape), with only the leading lobe 99 visible in transmission. This is most likely that the index modulations were inscribed at an angle to the fibre axis, that is the grating is blazed, and the loss in transmission does not show as a peak in reflection due to coupling of the fundamental mode to radiation modes. Furthermore the absence of any other side lobes from both spectra may be because lens aberration smooths the edges of the Gaussian beam to some other function, apodising the spot further and lowering side lobes.

To increase the strength of the gratings, translated gratings were then created. Firstly the beam, lens 91 and spatial filters 97, 96 were moved, keeping all other elements stationary. Due to the stage using a stepper motor, mechanical vibrations were introduced into the system that vibrated the lens and smeared out fringes that may have formed. This problem can be solved with a translation stage with smoother movement.

Next only the second phasemask 94 and fibre mount (not shown) were translated. This too provided low quality results. The new beam profile (caused by the effect of lens aberration) was smearing out fringes as the beams moved across the fibre, as shown schematically in Fig. 22. A 1mm slit 100 was placed in the region just before the beams hit the fibre 102.

A spot grating was then fabricated successfully, using 70mW and hydrogenated GF 1 fibre and exposed for 120 minutes. The resulting transmission and reflection spectra are illustrated in Fig. 23 and Fig. 24 respectively.

The slit 100 (Fig. 22) acts to limit the grating length. The gratings fabricated with the slit 100 (Fig. 22) in place are weaker, as visible by the lower strength gratings fabricated over a longer exposure time than without the slit (compare Figures 20, 21 and 23, 24).

Additionally, the grating structure is more like what is expected with side lobes 105, 106 clearly present in the spectrum. This may be because the slit 100 (Fig. 22) has spatially filtered the smoothed sides of the beam profile to give a more abrupt change in intensity at the beam edge, so that the effective index drops of more rapidly at the edges and cavity effects reveal themselves in the spectral behaviour (see Fig.24 inset). Thus, a new way of apodisation has been shown here, that is apodisation via the change in beam profile. The alignment is seen to be good, with little linear chirp as can be seen by the gaps e.g. 108 (Fig. 24) between side lobes in the reflection spectrum reaching the baseline. Furthermore the spectrum exhibits very little quadratic chirp (due to a flatter top on the beam profile).

Next, the iteration in the system was retained and phasemask 2 (94 of Fig.19) and the fibre mount holding fibre 95 translated to examine the effect of changing the beam profile. A 10mm long portion of hydrogen-loaded GF 1 fibre was scanned at 0.05mm/min with a power of 80mW, by scanning the collimated beams across the second mask 94. No result was achieved.

This may be due to the 2 collimated beams being incident on different parts of the mask, relative to the surface relief pattern. Phase correlation is therefore not locked between two points on the phasemask and thus the two beams, leading to smearing of the index modulations. Again, this may also be due to no phase change between the beams as they translate, thus the entire spot grating moves along, smearing itself out. Fabrication of long gratings may still be accomplished via inscription of adjoining spot gratings.

Alignment of this technique is simple for all components but the fibre holder, because the significant beam divergence creates a variation in fringe period across the region of interference. However, this also gives the method a large tuning range. To examine this tuning range, the slit 100 (Fig. 22) was removed and two spot gratings were written at different points in the fibre. At each point the fibre was moved to one of the two extremities in the interference region, to reveal the change in fringe period across the region of interference. Each grating was inscribed into hydrogenated GF1 with a 70mW laser for 90 minutes. The results are illustrated in Fig. 25 and Fig. 26 for transmission and reflection respectively and show that, over a distance of 2.78mm, the resonant wavelength changed from 1560.03nm to 1611.62nm, a range of 51.59nm. This may be expressed as a chirp of 18.56nm/mm. This is a very large chirp, making potentially compact broadband grating dispersion compensators.

The beam divergence can be calculated determining the change in fringe period over the region. The change in Bragg wavelength of 51.59nm equates to a change in the fringe period of 17.67nm. Thus the beam divergence is 6.36nm/mm or an angle of 1.82×10^{-4} degrees.

The arrangement of Fig.19 could therefore be used to fabricated chirped gratings by placing the fibre 95 at a slight angle to the second phasemask 94, keeping it within the region of interference, but with a continuous chirp along the exposed area of the fibre. The only impediments to this idea are that this technique fabricates only very weak gratings. Step-chirped gratings using Stubbe's method would be trivial to inscribe with a precise translation stage.

As alluded to before, the tuneability of this method makes it suitable for inscribing large bandwidth gratings, but also makes it difficult to fabricated low bandwidth gratings. This problem may be reduced using an achromatic doublet lens instead of a conventional convex lens, minimising beam divergence and thus the region of interference.

There are some points that warrant mentioning from examination of the results in Fig. 25 and Fig.26. The ripple 110 in the transmission spectrum is thought to be an artefact of the characterisation process only, and is not a feature of the gratings. The two gratings were fabricated under the same conditions, however they are different strengths 111, 112 because the first grating shrunk during the inscription process of the second grating. This may be due to spurious UV light decreasing the index modulation depth of the first grating.

To increase the fluence incident on the fibre core, the elements were brought closer to one another, attempting to get the fibre as close to the focus point from the collimating lens as practical. The arrangement can be then as illustrated in Fig. 27. With this arrangement, the spot size was decreased down to approximately 0.5mm, with the fibre 120 about 50mm from the lens 121 (focal length is 25mm). In addition, to increase the fluence a long focal length (150mm) cylindrical lens 122 was placed in front of the first phasemask 123. This optical element focused the beam in the vertical-direction, increasing the intensity without affecting the beam width at the fibre.

A spot grating was then written into a sample of hydrogen loaded GF1 at 80mW for 10 minutes. The results illustrated for transmission in Fig. 28 and reflection in Fig.29 show that the fluence was increased drastically, with >10dB gratings inscribed within a 10-minute period. This is comparable to the result using direct writing shown earlier in Fig. 2 and Fig. 3.

This is a substantial improvement, and the spectra of Fig. 28 and Fig. 29 show a symmetric structure for the fundamental peak, dip and side lobes. The growth of a grating inscribed under the same conditions was then examined with the results shown in Fig. 30 and Fig. 31. The grating strength in transmission and through wavelength was recorded every minute for a 20 minute period, and plotted in Fig. 30. From this information, the refractive index modulation depth and induced average refractive index can be calculated, and thus the refractive index modulation contrast can be determined, as shown in Fig. 31.

The calculation of average index is based on the approximation that a change in the Bragg wavelength of 1nm corresponds to a change in the average index of 10^{-3}. The calculation of the refractive index modulation, Δn, is a two step process. Firstly, the coupling coefficient, *k*, is found via the equation:

$$\kappa = \frac{\tan^{-1}\sqrt{T}}{L}$$

Where T is the grating strength in transmission (as a fraction), and L is the grating length. The coupling coefficient is then related to the modulation depth by:

$$\kappa = \frac{\pi \Delta n}{\lambda}$$

Where λ is the Bragg wavelength at the point where the coupling coefficient is being calculated. Both of Fig. 30 and Fig. 31 concur that the grating growth has reached saturation at around 16 minutes. The curve showing evolution in fringe contrast shows that it starts at around 10 minutes.

With the arrangement of Fig. 27, a translated grating was attempted yet again by moving the second phasemask 124 and fibre mount (not shown) with poor results. Stubbe's method of writing long gratings by use of adjoining subgratings was more successful. Assuming a spot size of around 0.5mm, three gratings were written next to one another. The writing conditions were kept the same at 80mW for 10 minutes in the same hydrogenated GF1 fibre. The results are illustrated in Fig. 32 and show a grating much larger than a single grating, with the resulting strength after all three gratings were inscribed of approximately 33dB (with around 10dB for one grating). The dips in the spectrum are from phase shifts introduced by the inaccuracy in position of the translation stage. A similar result was achieved using a system with a longer focal length lens as the collimating element.

Another way of imprinting these subgratings would be to chop or modulate the beam at such a rate that subgrating periods overlap neatly with no smearing of the refractive index modulation.

The inability to get a result for the situation where the collimated beams are moved across the second (recombining) mask (124 of Fig.27) may be due to the difference in phase information of the two beams when they move across different points of the surface relief pattern. The reason why results are obtained for spot gratings is that phase information with movement of the beam across the phasemask does not enter the situation.

A different method of tuning (illustrated with reference to Fig. 33) was also considered for use with this system. If the distance between the first phasemask 130 and collimating lens is changed 131 from the focal length, the beams are no longer collimated. They will either diverge or converge, depending on whether the lens 131 is positioned within its focal length from phasemask 1 (130) or outside its focal length respectively. This means that the beams impinge on the second phasemask 137 at an angle. This has two effects. Firstly it changes the angle at which the beams interfere 138 and therefore the grating period and Bragg wavelength. Secondly, it changes the intensities in each diffracted order. The second effect will be as little as a few percent, thus another means for tuneability in resonant wavelength can be devised.

Measurements were taken of the image distance (S_i), the beam separation leaving the second phasemask (d), and the distance between the phasemask surface and the point of beam interference 138, where the fibre would be placed (F). The Bragg wavelength at which the system set to these parameters would inscribe a grating was calculated and plotted in Fig.34. This was done for two points, with a third provided from experimental data taken for the collimated beam. As the results show the separation between phasemask 130 and the collimating lens 131 has a significant impact on resonant wavelength, with a range of over 500nm being possible for a change in lens position of 5mm. The results were determined through the use of geometry, the thin lens equation and

$$\Lambda_{pm} = \frac{m\lambda_{uv}}{\sin\frac{\theta_m}{2} - \sin\theta_i} \quad \text{(with m=1, and } \lambda_{uv} = 244\text{nm)}$$

Apodisation can be performed by one of two ways with this system. If the apparatus 130 could be kept still while the beam 139, collimating lens 131 and spatial filters, e.g. 140, were moved, then either phasemask 130, 137 could be dithered to achieve and apodised structure. However, if the first phasemask 130 was vibrated, so too would the lens 131 need to be to keep the beam position relative to the lens 134 constant. This may be practically difficult, with the lens 134 needed to be simultaneously moved with the beam 139, and vibrated with the first phasemask 130. Dithering the second mask 137 would be the better option. Apodisation via change in the overlap between two consecutive subgratings can also be achieved, if the subgrating method is employed.

The arrangement of Fig.33 is flexible and able to produce large bandwidth chirped gratings. If using the subgrating method, the arrangement can include an interferometrically controlled translation stage. The arrangement provides a number of advantages to interferometric techniques outlined in the introduction. The main advantages of the arrangement are that it is compact, the potential tuning range is very large and not limited by physical space, and that the alignment is straightforward (although very sensitive if low bandwidth gratings are required). When compared to non-phasemask interferometers, the equality in path length is also a major advantage.

Mirror Collimation

As an alternative to beam collimation via a lens or phasemask, a two-mirror configuration such as that shown in Fig.35 can be constructed. The arrangement 145 removes the effects of increased beam divergence, asymmetric incidence on the lens surface and spherical aberration. The two mirrors 146, 147, anti-reflection coated for 244nm light, were positioned so that the beams were collimated 148, 149, and incident on the centres of the mirrors. The cylindrical lens 150 was retained to increase the fluence to the fibre. Alignment is still simple using this arrangement, the most time consuming part being ensuring the beams are collimated. Again, the separation of splitting and recombining elements ensures spatial filtering can be employed to block unwanted orders.

Using the arrangement 145, a spot grating was written into hydrogenated GF1 at 80mW for 20 minutes, then another 5mm away in the same fibre. The resulting grating structure was measured (Fig. 36). Subsequently, a translated grating was written and the results measured as shown in Fig. 37 and Fig. 38. The results show a small amount of quadratic and linear chirp applied to the grating, however this is typical. The extra side lobe structure 160 visible on the low wavelength side (approximately 1570nm) of the fundamental 160 peak in the transmission spectrum is anomalous and appears to be an effect of the index modulations not being perpendicular to the fibre axis, thereby blazing the fibre. Its presence in transmission and not reflection leads one to think this may be so. It would therefore be due to coupling of the light from the forward propagating mode into a radiation mode and therefore out of the fibre. This indicates the incident angles of each beam with respect to the fibre were not equal in the example.

This result suggests that as the beam moves across the first phasemask 154 it imparts the phase information that is required to add index modulations as the writing beams traverse the fibre. If the beams receive phase information separately from different points of the mask, no grating will be inscribed into the fibre. However, if the beams receive phase information from the same point (as they move across the first mask) there is a direct correlation between the phases of the two beams and a grating is successfully written into the fibre.

Furthermore, these results suggest that it is the path length difference induced in interferometers that inscribes the fringe pattern into fibres when the beam is translated. When the collimated beams were scanned across the final mask, poor results may have been achieved because the path length difference of either beam did not change. The fact that the incident angle of each beam was different could mean the second phasemask was placed not perpendicular to the collimated beams, leading to mismatch in the phase of each beam. On the other hand, when the beam was scanned across the first mask, the point at which each diffracted beam was incident on its respective collimating mirror changed. This may induce a path length difference between the beams, and therefore an index modulation imprinted along the fibre, one fringe at a time.

Apodisation can be accomplished via dithering of the first (154) or last (152) phasemask. If using the subgrating method, the overlap of each consecutive subgrating could be adjusted to achieve the same end.

In the same way that the collimating lens 131 in the system of Fig. 33 can be moved to tune the Bragg wavelength, the collimating mirrors 146, 147 may be rotated here to change the beam angle incident on phasemask 2 (152).

The aforementioned methods for inscribing fibre Bragg gratings provide for being able to fabricate devices flexibly with apodised and chirped structures at selected wavelengths.

Tuneability via Phase Mask Compression

In relation to the aforementioned techniques, further tuned changes in Bragg wavelength can be achieved by compressing the phasemask. A phasemask diffracts the light into orders at angles associated with the period of the surface relief structure by the previously seen relation:

$$\Lambda_{pm} = \frac{m\lambda_{uv}}{\sin\frac{\theta_m}{2} - \sin\theta_i}$$

Pure silica, of which phasemasks are made, will compress by approximately 4% before fracturing. That is the maximum change in the phasemask period can be given by:

$$\frac{d\Lambda_{pm}}{\Lambda} = 0.04$$

By differentiating the equation relating phasemask period to diffraction angle, assuming m=1 and $\theta = 0$, the changed in the half angle of diffraction $d(\frac{\theta_m}{2})$ from 4% compression of a phasemask with a relaxed period of 1064nm (writes at 1533m) is determined to be approximately $9.42\text{x}10^{-3}$ degrees. This is too small to measure accurately; therefore gratings must be written to verify the validity of this method for tuning the resonant wavelength.

Accordingly, to the relation between Bragg wavelength and phasemask period, the change in the resonant wavelength would also be a maximum of 4%. Therefore, for a phasemask with a period of 1064nm, the tuning range would be 62.14nm.

In order to illustrate the aforementioned process, spot granting were written into hydrogenated GF 1 fibre using 70mW, with the phasemask in both a relaxed and compressed state. The results are illustrated in Fig. 39 for the relaxed state and Fig. 40 for the compressed state.

The results were taken in reflection, due to very weak gratings fabricated using non-ideal apparatus and a phasemask with a high zero order. As the phasemask was compressed for the first time, a stress concentration brought on by a curved edge on the compressive mount causes a crack to form in the glass that extended across the lower portion of the mask. This did not affect the region of the mask being used. However, it may have allowed for a relaxation in the compressive force that was being applied. The poor grating shape was a result of a phasemask with a high zero order, and restrictions in alignment accuracy due to the compressive feature of the apparatus. However, by using a compression arrangement a significant cost saving may be achieved as a new grating for each wavelength would not be required.

Two Phase Mask Interferometers

Fig. 41 illustrates a further relatively simple design of a two phasemask interferometer. It is a relatively simple design, involving only two phasemasks 161, 162 positioned parallel to one other. The two first orders 163, 164 are incident on an appropriately designed second phasemask 162, which recombines the orders 165 onto the output plane, where the fibre is positioned. The separation of recombining and splitting elements allow spatial filtering of unwanted orders e.g. 167.

The second phasemask 162 must be made longer than the first (as its length will limit the length of gratings able to be inscribed), and designed to accept the incoming light at an incident angle, and still maximise the intensity into the ±1st orders. Advantageously, it has a suitable period and the surface structure is of a particular depth. The period should be half that of the first phasemask 161, e.g. if the first mask has a period of 1064nm, the second should have a period of 532nm. Fabrication of such a mask with a low zeroth order and high ±1st orders is likely to add significantly to the cost of the mask due to the custom technical requirements. Additionally, the etch depth of the grooves is ideally optimised to increase the intensity in the wanted orders. The incident angle from the first phasemask, if it has a period of 1064nm is 13.26°. Using Snell's law,

$$n_i \sin\,\theta_i = n_t \sin\,\theta_t$$

With $n_i=1$, $\theta_i=13.26°$ and $n_t=1.455$, the transmitted angle is 9.14°. For an incident angle of 0°, the optimum depth is given by

$$d = \frac{\lambda_{uv}}{2(n_{SiO_2} - 1)}$$

and would be 268.13nm. However, as illustrated in Fig. 42, the incident angle of the input order 170 to the etch pattern is 9.14°, so the etch depth d should be altered. Using basic trigonometric arguments, the etch depth d should be 264.73nm.

Of course, a specific etch depth away from that of the standard UV wavelengths increases the cost.

Tuneability can be performed via phasemask compression on the second mask 162 of Fig. 41, as could apodisation, with the piezo-electric transducer vibrating the second mask 162. Another possible method of tuneability would be to use a lens or lenses to diverge the beam, in a similar way to the arrangement shown in Fig. 14. Alignment is also simplified, with only the two phasemask elements 161, 162 that are normally simple to align.

Translation can be performed in a similar manner to the three phasemask system of Fig. 14, where both gratings remain stationary, while the beam and spatial filters move across them. The arrangement of Fig. 41 is simple, compact and flexible, as well as blocking unwanted orders. This technique also works well with an extended, incoherent source, introducing the possibility of compact and cheap grating fabrication systems for portable and non-laboratory applications. However, the costs involved in the design and fabrication of the second phasemask 162 may increase overall cost.

Further modifications are possible. For example, in Fig. 43, there is illustrated a further modified embodiment wherein there is provided a wide beam from an Excimer laser or the like. Two side beams 182, 183 are formed on either side of blocking element 184. These two beams separately strike phasemask 185 and form order beams 186 to 189. The two beams 187, 188 interfere in the area 195 so as to from a grating structure on fiber 194. The other order beams 186, 189 are blocked by filters 190, 191.

In Fig. 45 there is shown the production of a pair of collimated beams using a beam splitter 210 such as a prism or semi-transparent mirror and mirrors 211 to form the collimated beams 212, 213.

A further alternative particularly suitable for use with long range coherence lasers is shown in Fig. 46 which uses a reflection element 220 having parallel front 221 and back 222 surfaces. The front surface is reflection coated to give 50 % reflection of the incident light signal. The incident light signal is partially reflected by each of the front 221 and back 222 surfaces of the reflection element to form a pair of collimated beams. The thickness of the reflection element and the angle of incidence are chosen to give the desired beam separation.

Fig. 47 shows the use of two lasers 230, 231 to produce two collimated beams 232, 233 that are projected onto a phasemask 235 to create an interference pattern at a spatial position 236.

In the arrangements before described, filters can be used to clean the collimation of the phasemask beams. An example of the arrangement is illustrated 200 in Fig. 44 wherein a input light 201 strikes a phasemask 202 emitting two order beams 203, 204. Each order beams will consist of a range of wavelengths, from λ_1 to λ_N. The order beams can be "clean up" by utilising two screens 205, 206, each containing a slot to let through only the light of interest. In this way, unwanted frequencies can be blocked from interfering to form grating structures.

The use of collimated beams in forming an interferometric pattern provides practical benefits in inscribing grating structures into photosensitive waveguides. The insertion and alignment of optical elements into the straight line system is simplified, in particular where phasemasks are employed for producing the collimated beams, as no tilting is required. Further, because the waveguide is isolated from the recombination phasemask, degradation of the phasemask due to the presence of extraneous material on the waveguide is reduced.

Tunability is made straight forward through the positioning of the waveguide, lens and spatial filters. The tasks of providing tuning and recombination to form the interference pattern can be separated into distinct optical components thus providing the system with greater flexibility. The separation of these tasks also allows vibrations in one region, for example in the first phasemask, to be isolated from the recombination optics such that the inscribed grating structure is minimally affected. The end result is a relatively compact unit having a useful tuneable range of operation.

In the arrangements described above, the two beams projected on to the re-combining phasemask were described as orthogonally incident on that phasemask. However, it is noted that the present invention is not limited to such embodiments, but also extends to the use of off-orthogonally angle of incidence. In the latter case, additional flexibility can be obtained for the writing of grating structures, as will now be described with reference to Figure 48.

In Figure 48, the recombining phasemask 300 has been rotated (angle α). Accordingly, the two coherent writing beams 302, 304 are incident on the phasemask 300 under an angle α with respect to the normal of the phasemask 300. As a result, the interference pattern 306 in the region of overlap 308 is also angled with respect to an optical fibre 310 positioned parallel to the initially un-rotated phasemask. Accordingly, such a setup can be used to write blazed gratings in the optical fibre 310.

It is noted that the same effect can be achieved by rotating the pair of beams 302, 304, instead of, or in addition to rotating the phasemask 300. It is further noted that writing of blazed gratings is also possible without rotating either the phasemask nor the writing beams, where the fibre is moved/rotated instead, as will be appreciated by a person skilled in the art. The arrangement described above with reference to Figure 48 may provide the advantage of easier control of the relative angles.

Where the angles of incidence of both writing beams with respect to the phasemask are the same, the period of the interference pattern and thus the written grating structure will remain constant. If, in different embodiments, the angles of incidence for the writing beams are adjusted to be different from each other, the period will be changed, thus providing a further degree of flexibility.

It will be understood that the invention disclosed and defined in the various embodiments disclosed herein extends to all alternative combinations of two or more of the individual features mentioned or evident from the text or drawings. All of these different combinations constitute various alternative aspects of the invention.

The foregoing describes embodiments of the present invention and modifications, obvious to those skilled in the art can be made thereto, without departing from the scope of the present invention.

Throughout the specification, except where the context requires otherwise due to express language or necessary implication the word "comprising" and variants thereof is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

Claims:

1. A method of writing a grating structure into a photosensitive waveguide, the method comprising the steps of:

- projecting at least two coherent light beams onto a first phasemask so as to form a first and a second series of respective diffracted order beams, and

- interfering at least one beam of each of the first and second series of diffracted order beams at a spatial position so as to form an interference pattern substantially at said spatial position for creating the grating structure through photo-induced refractive index changes in the photosensitive waveguide.

2. A method as claimed in claim 1 further comprising the step of:

- collimating said at least two coherent light beams before they are projected onto said first phasemask.

3. A method as claimed in claim 2 wherein a second phasemask and/or at least one lens and/or at least one mirror are utilised to collimate said at least two coherent light beams.

4. A method as claimed in any previous claim wherein the method further comprises projecting a first light beam onto a third phasemask so as to form a third series of diffracted order beams, and wherein the at least two coherent light beams comprise one pair of said third series of diffracted order beams.

5. A method as claimed in any previous claim wherein the diffracted order beams utilised in the method comprise first order and/or higher order diffracted beams.

6. A method as claimed in any previous claim wherein the method further comprises blocking non-utilised diffracted order beams utilising a spatial filter.

7. A method as claimed in any previous claim wherein said interference pattern is utilised to form an extended grating structure in a photosensitive material placed at said first spatial position and translated relative to said spatial position.

8. A method as claimed in claim 7 further comprising the step of spatially translating the relative interrelationship between optical elements utilised in the method so as to control parameters of the written extended grating structure.

9. A method as claimed in any previous claim wherein the method further comprises the step of separating unwanted wavelength components in the beams utilising a further spatial filter arrangement.

10. A method as claimed in any previous claim, wherein the method further comprises the step of utilising a chromatic aberration of an optical lens for separating of unwanted wavelength components from the beams .

11. A method as claimed in any previous claim wherein different wavelength components of the first and second series of diffracted order beams interfere at different locations over a region of overlap at the spatial position and the method comprises the further step of adjusting the position of the photosensitive material placed at said spatial position so as to alter the wavelength of any grating structure written.

12. A method as claimed in any previous claim further comprising the step of compressing one or more of the phasemasks utilised in forming the interference pattern so as to alter the wavelength of said interference pattern.

13. A method as claimed in any previous claim, wherein the at least two coherent beams are orthogonally incident on the first phasemask.

14. A method as claimed in any one of claims 1 to 12, wherein one or more of the at least two coherent beams are off-orthogonally incident on the first phasemask.

15. A method as claimed in claim 14, wherein the method further comprises varying the angle of incidence of one or more of the at least two coherent beams on the first phasemask, so as to vary parameters in the written grating structure.

16. A method as claimed in claims 14 or 15, wherein the angles of incidence of the at least two coherent beams on the first phasemask are the same.

17. A method as claimed in claims 14 or 15, wherein the angles of incidence of the at least two coherent beams on the first phasemask are different.

18. An apparatus for writing a grating structure into a photosensitive waveguide, the apparatus comprising:

- a first phasemask,

- an optical arrangement for projecting at least two coherent light beams onto the first phasemask so as to form a first and a second series of respective diffracted order beams, and so as to interfering at least one beam of each of the first and second series of diffracted order beams at a spatial position so as to form an interference pattern substantially at said spatial position for creating the grating structure through photo-induced refractive index changes in the photosensitive waveguide.

19. An apparatus as claimed in claim 18 wherein the optical arrangement comprises means for collimating said at least two coherent light beams before they are projected onto said first phasemask.

20. An apparatus as claimed in claim 19 wherein the means for collimating comprises a second phasemask and/or at least one lens and/or at least one mirror.

21. An apparatus as claimed in any one of claims 18 to 20 wherein the optical arrangement comprises a third phasemask so as to form a third series of diffracted order beams from a light beam projected onto the third phasemask, and wherein the at least two coherent light beams comprise one pair of said third series of diffracted order beams.

22. An apparatus as claimed in any one of claims 18 to 21 wherein the diffracted order beams utilised in the apparatus for the writing of the grating structure comprise first order and/or higher order diffracted beams.

23. An apparatus as claimed in any one of claims 18 to 22 wherein the optical arrangement comprises a spatial filter for blocking non-utilised diffracted order beams.

24. An apparatus as claimed in any one of claims 18 to 23 wherein the apparatus is arranged, in use, to form an extended grating structure in a photosensitive material placed at said first spatial position and translated relative to said spatial position.

25. An apparatus as claimed in claim 24 wherein the apparatus is further arranged, in use, for spatially translating the relative interrelationship between optical elements of the apparatus so as to control parameters of the written extended grating structure.

26. An apparatus as claimed in any one of claims 18 to 25 wherein the optical arrangement comprises a further spatial filter arrangement for separating unwanted wavelength components in the beams utilising.

27. An apparatus as claimed in any one of claims 18 to 16 wherein the optical arrangement comprises an optical lens for utilising a chromatic aberration of the optical lens for separating of unwanted wavelength components from the beams .

28. An apparatus as claimed in any one of claims 18 to 27 wherein the optical arrangement is disposed such that, in use, different wavelength components of the first and second series of diffracted order beams interfere at different locations over a region of overlap at the spatial position, whereby, in use, adjusting the position of the photosensitive material placed at said spatial position alters the wavelength of any grating structure written.

29. An apparatus as claimed in any one of claims 18 to 28 wherein one or more of the phasemasks are arranged for controlled compression so as to alter, in use, the wavelength of said interference pattern.

30. An apparatus as claimed in any one of claims 18 to 29 wherein the at least two coherent beams are orthogonally incident on the first phasemask.

31. An apparatus as claimed in any one of claims 18 to 29, wherein one or more of the at least two coherent beams are off-orthogonally incident on the first phasemask.

32. An apparatus as claimed in claim 31, wherein the optical arrangement is arranged for varying the angle of incidence of one or more of the at least two coherent beams on the first phasemask, so as to vary parameters in the written grating structure.

33. An apparatus as claimed in claims 31 or 32, wherein the angles of incidence of the at least two coherent beams on the first phasemask are the same.

34. An apparatus as claimed in claims 31 or 32, wherein the angles of incidence of the at least two coherent beams on the first phasemask are different.

35. A method substantially as herein before described with reference to any of Fig. 4 to 47 of the accompany drawings.

36. An apparatus substantially as herein before described with reference to any of Fig. 4 to 47 of the accompany drawings.

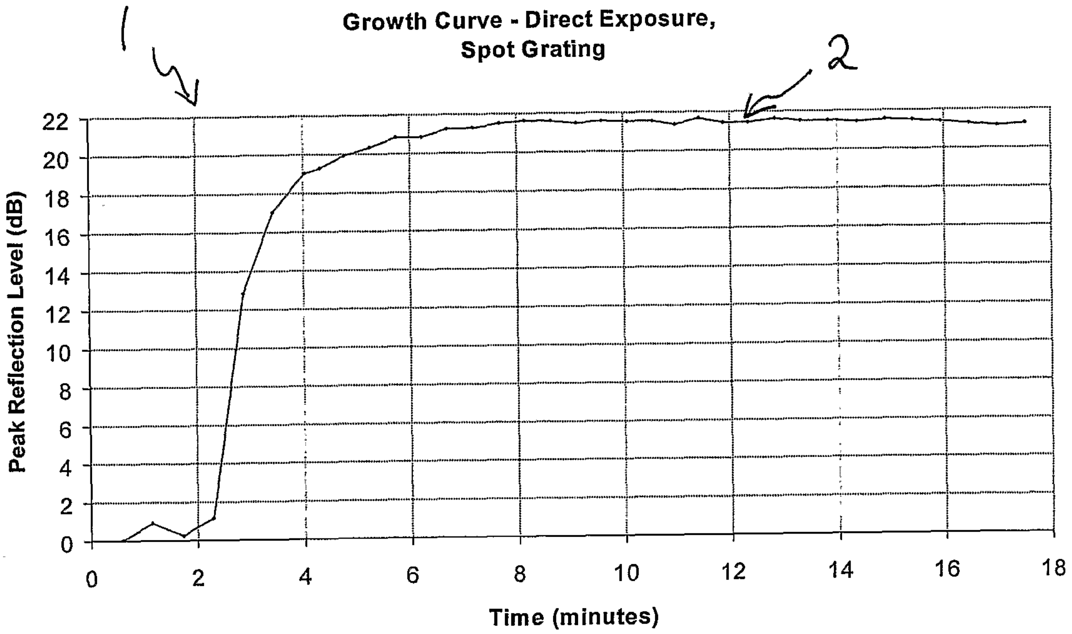

1
2
Growth Curve - Direct Exposure, Spot Grating
Peak Reflection Level (dB)
0
2
4
6
8
10
12
14
16
18
20
22
Time (minutes)
0
2
4
6
8
10
12
14
16
18

Figure 1

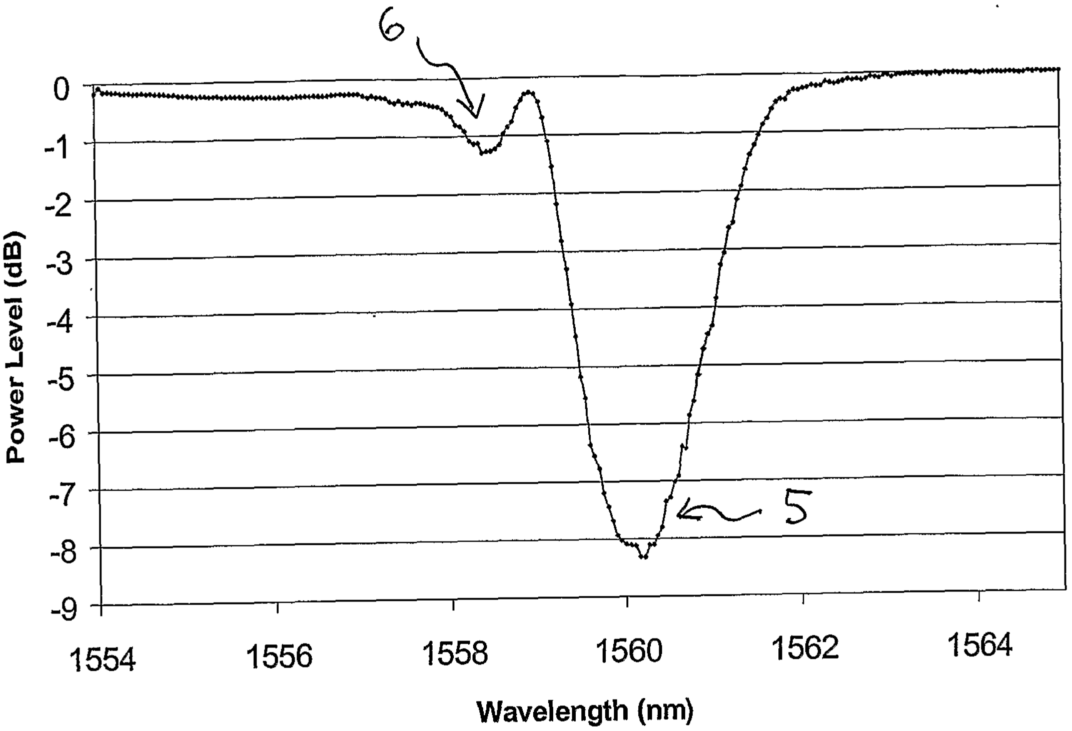


Figure 2

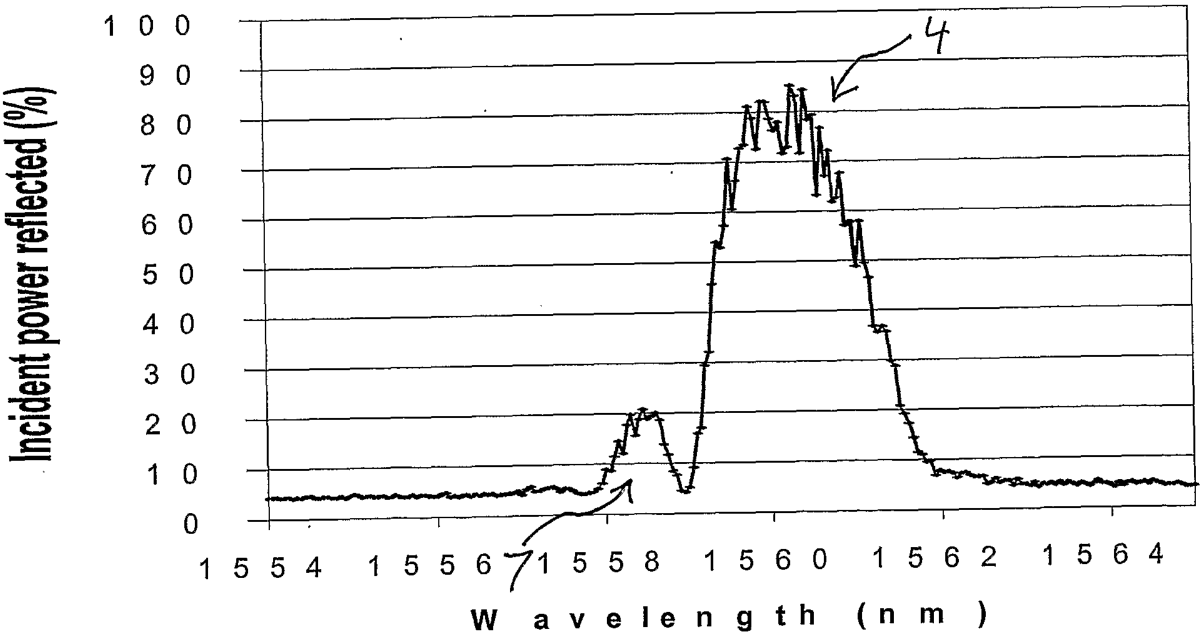


Figure 3

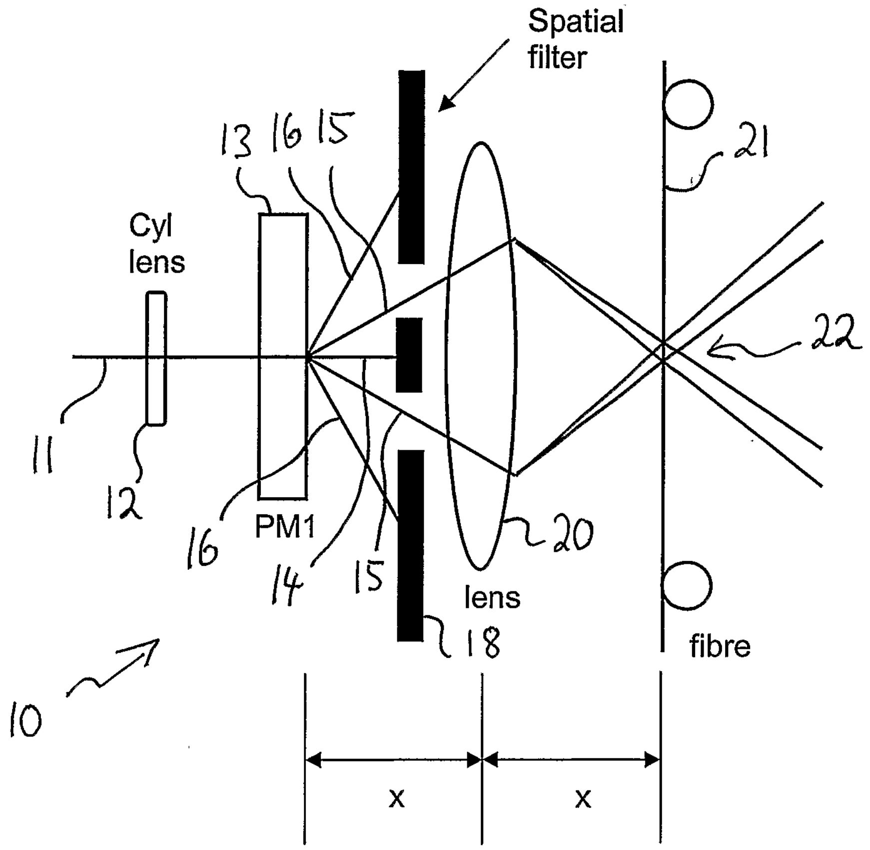


Figure 4

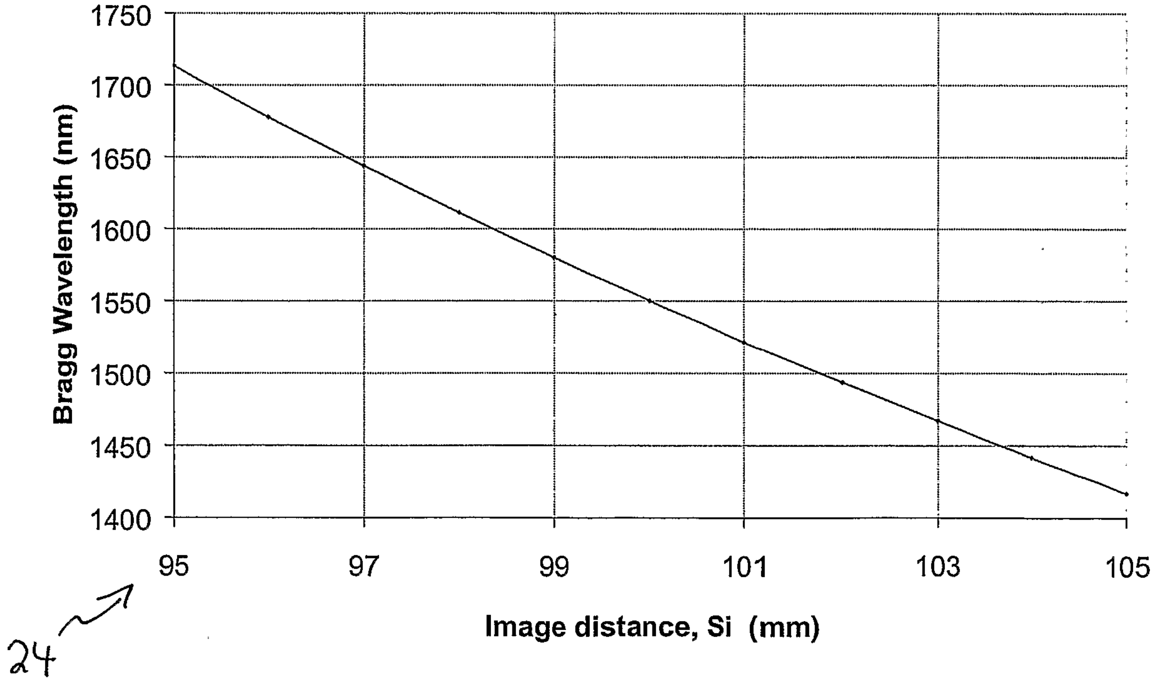


Figure 5

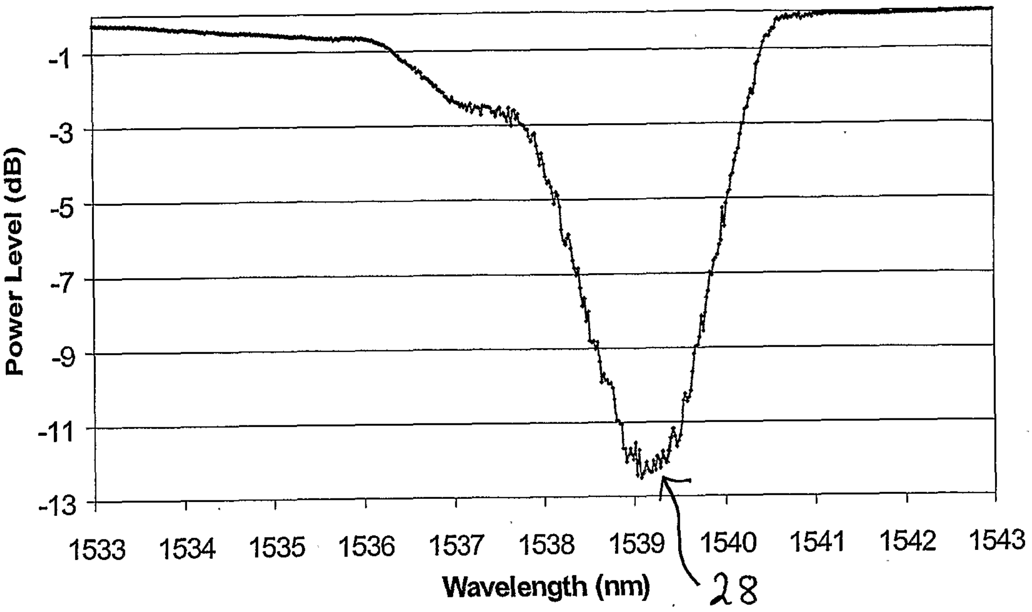


Figure 6

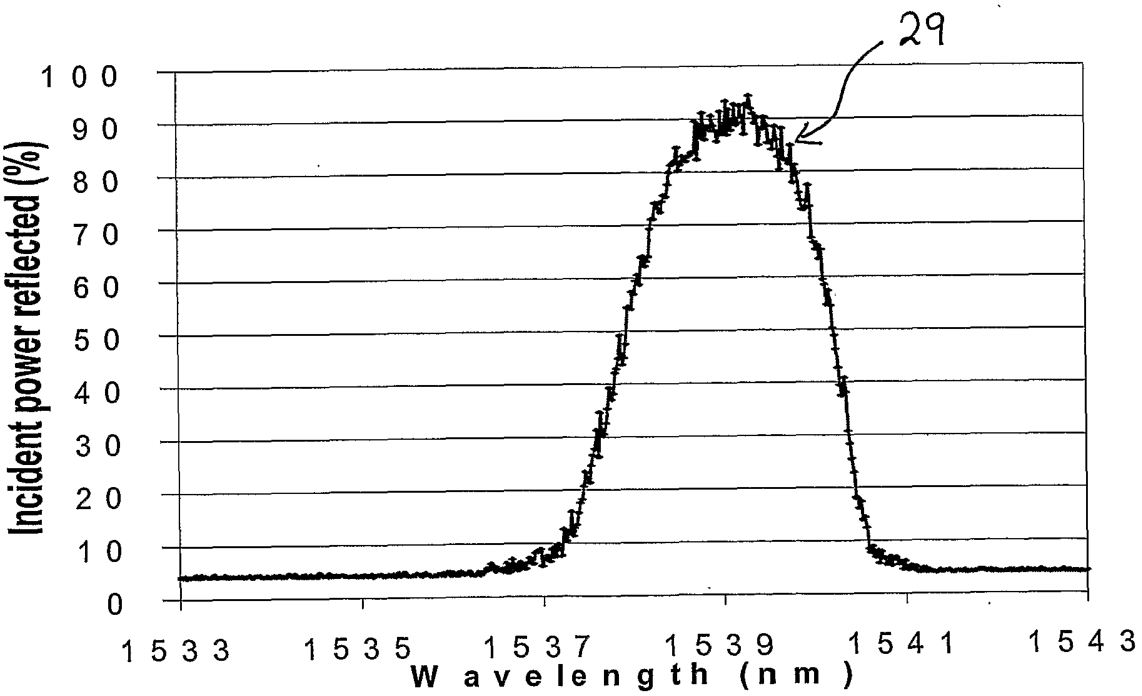


Figure 7

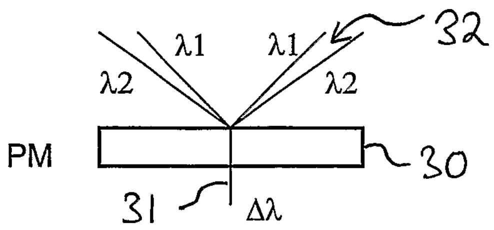


Figure 8

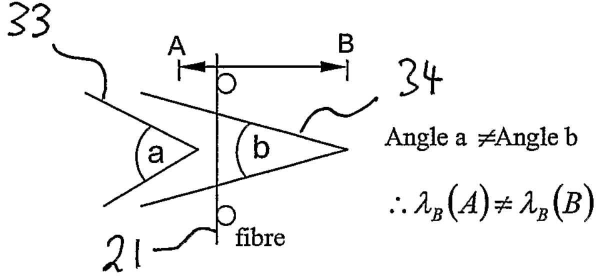


Figure 9

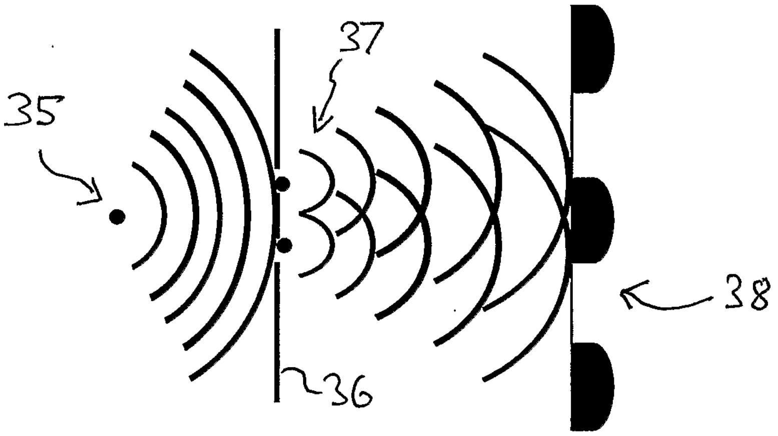


Figure 10

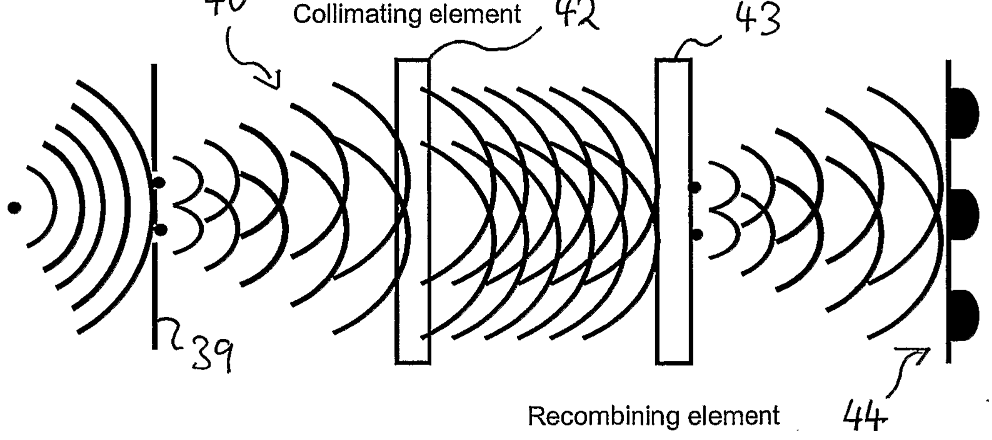


Figure 11

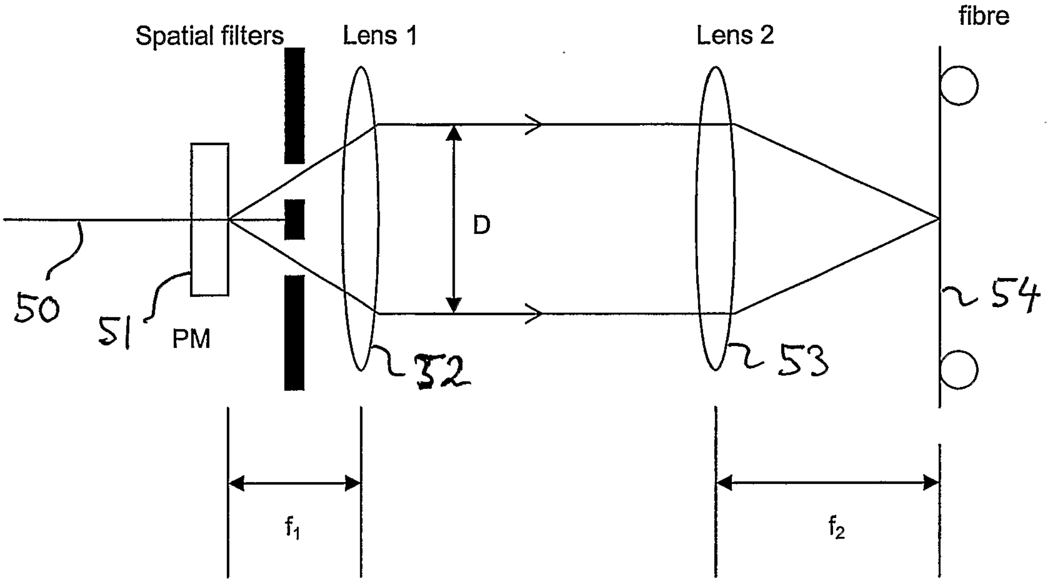


Figure 12

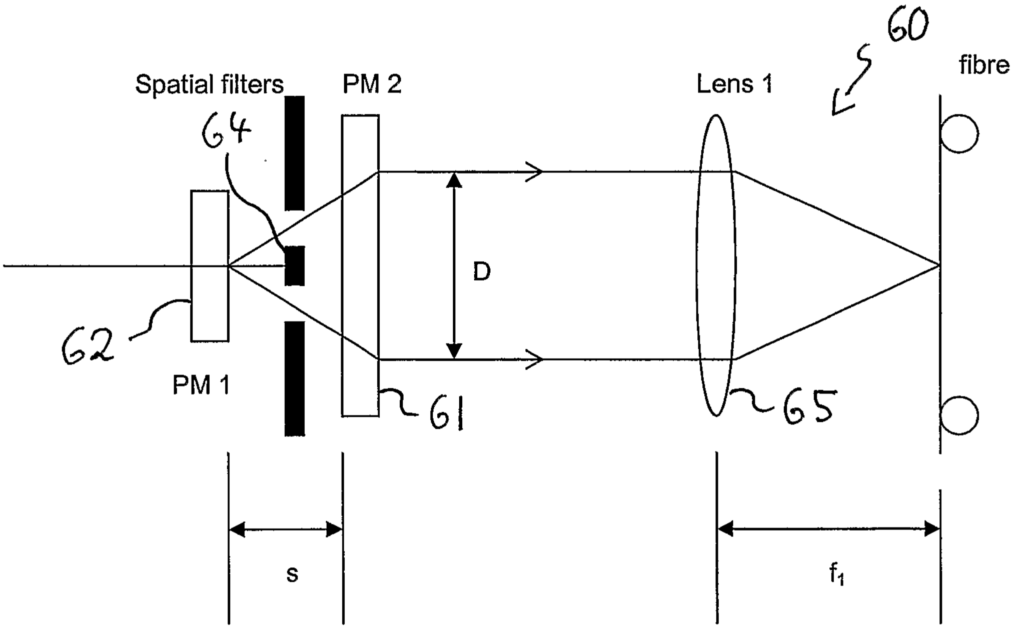


Figure 13

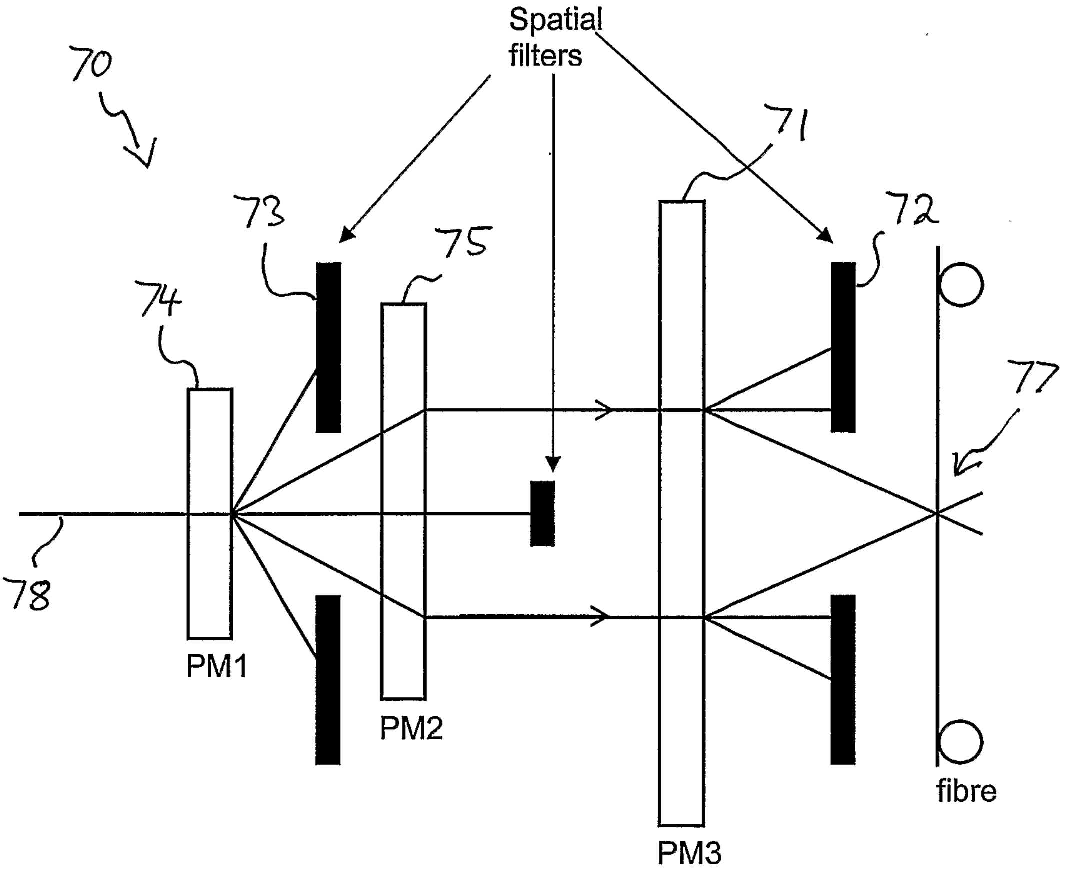


Figure 14

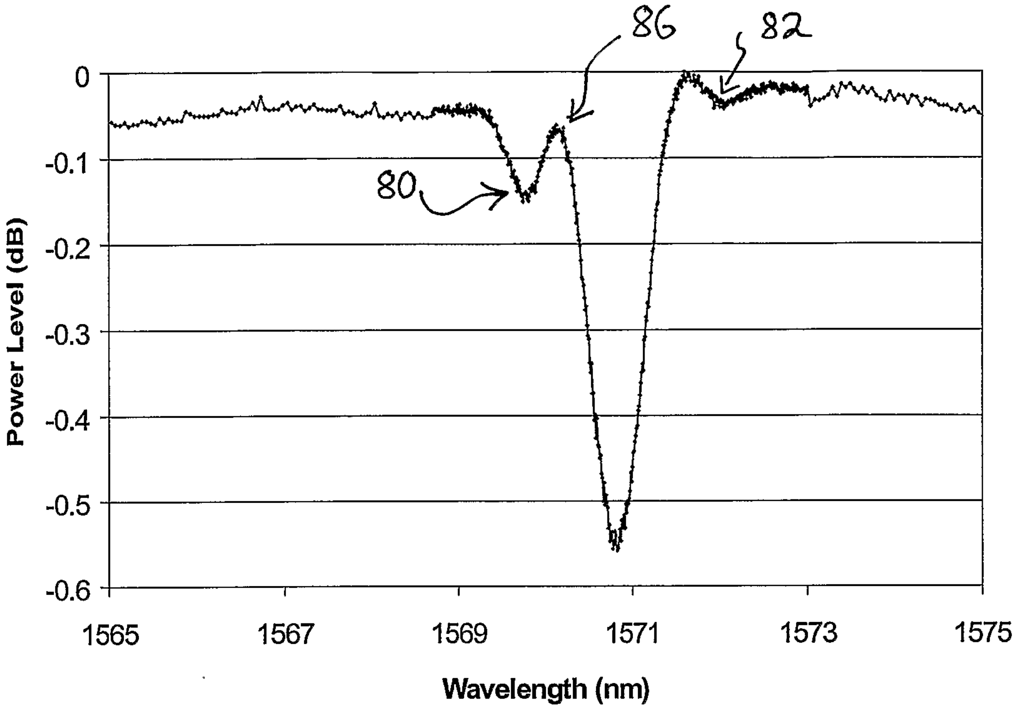


Figure 15

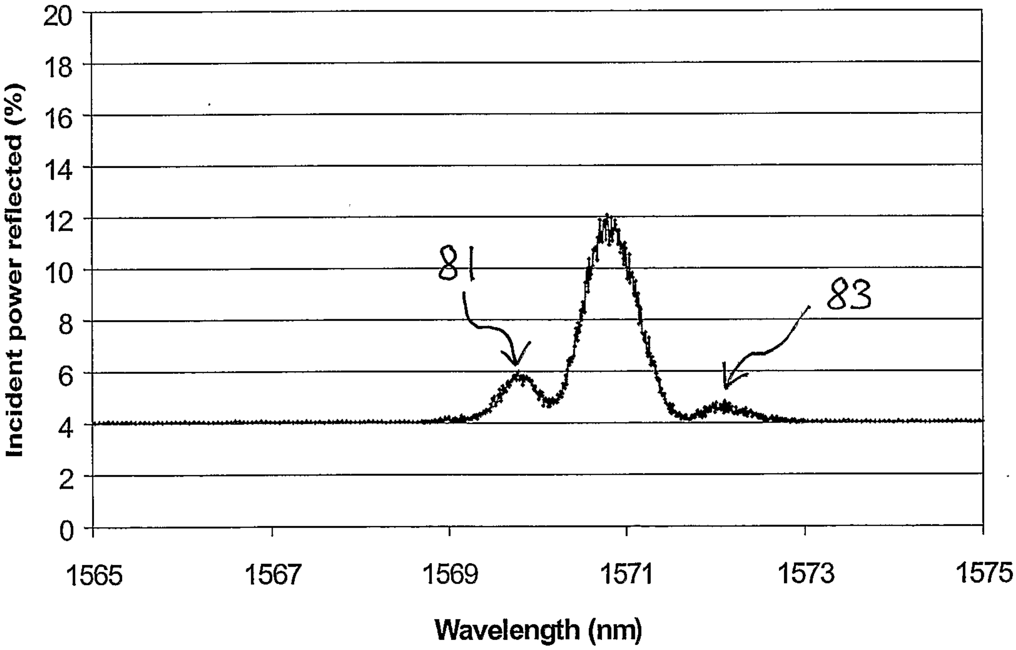


Figure 16

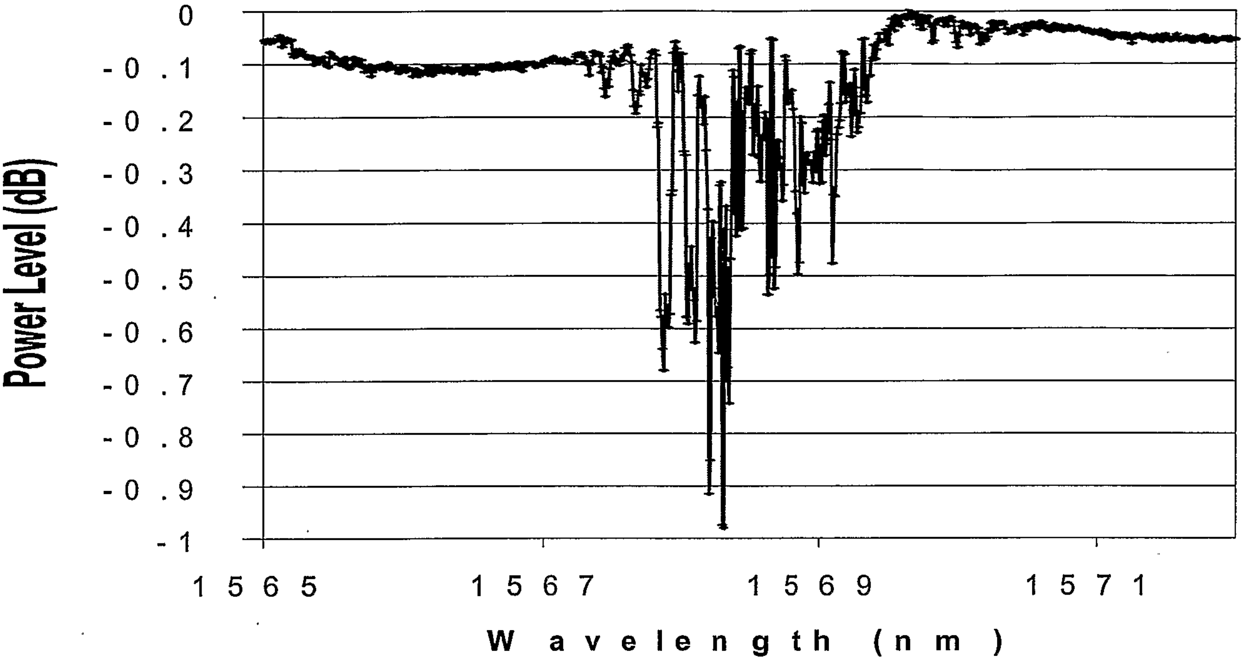


Figure 17

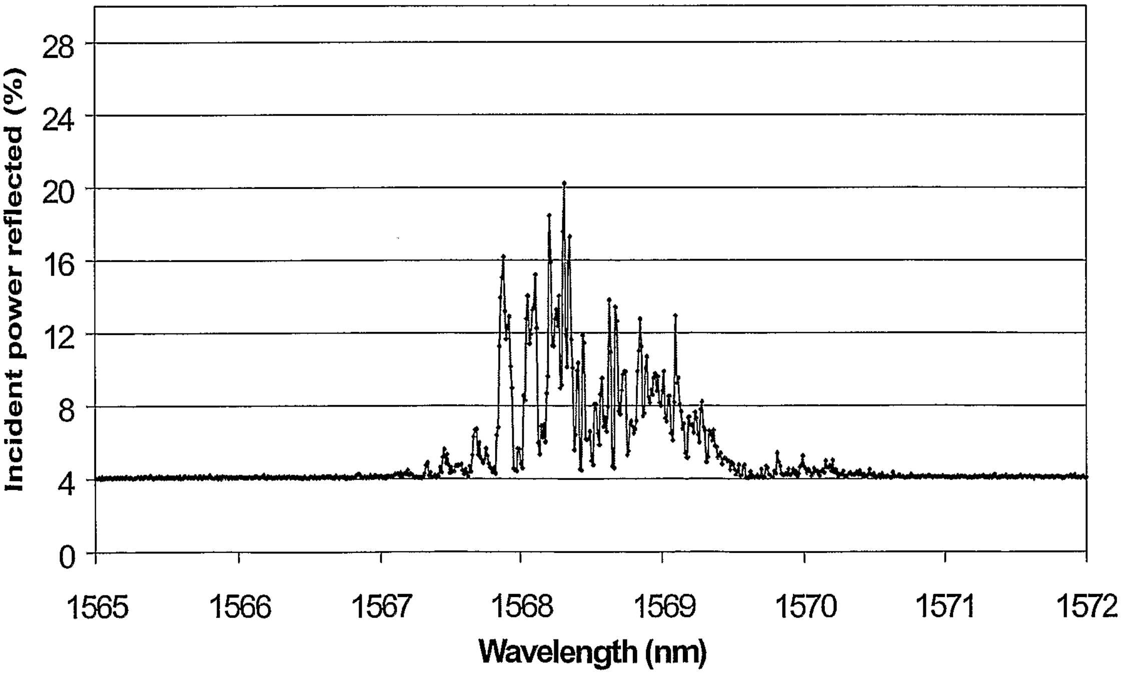


Figure 18

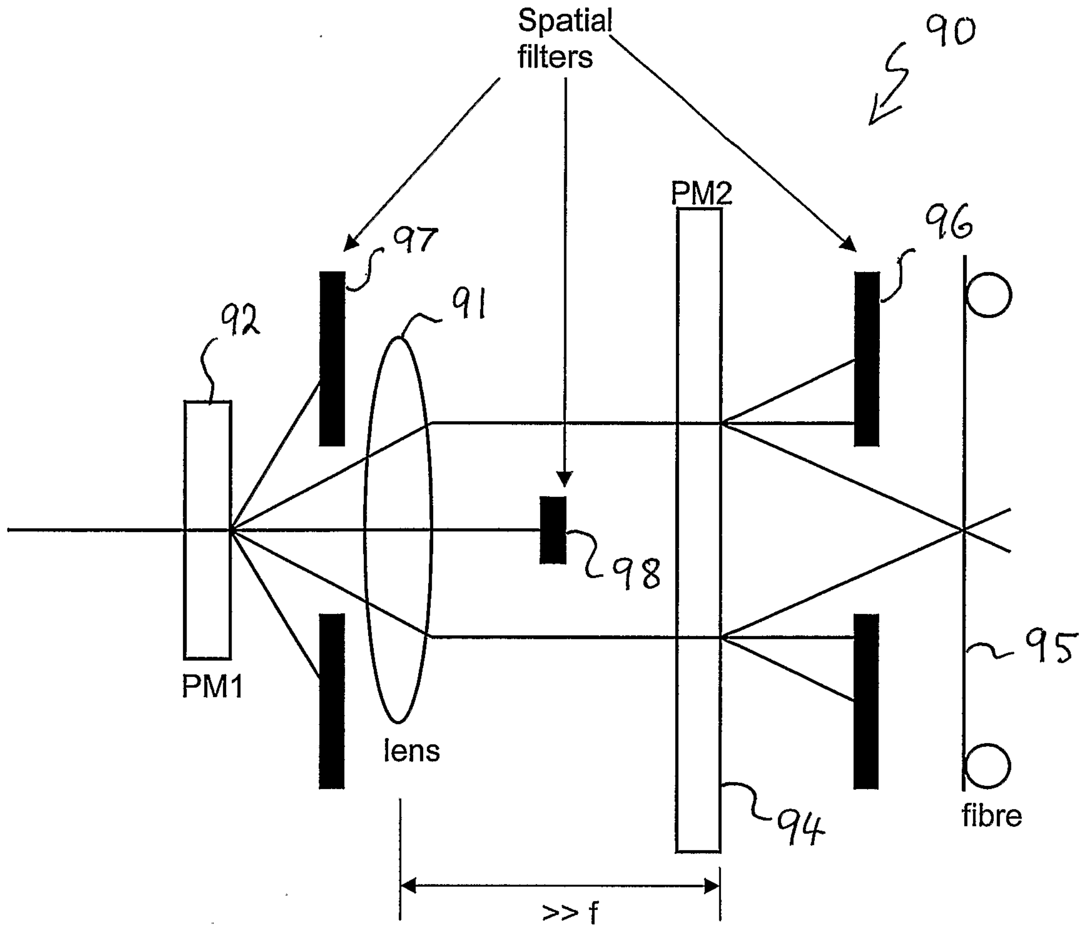


Figure 19

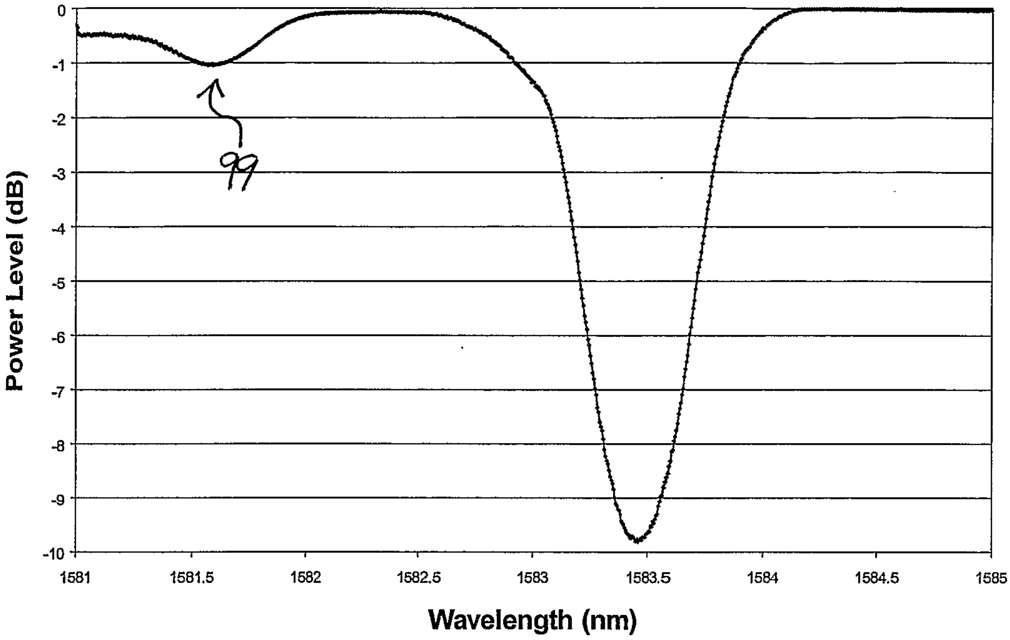


Figure 20

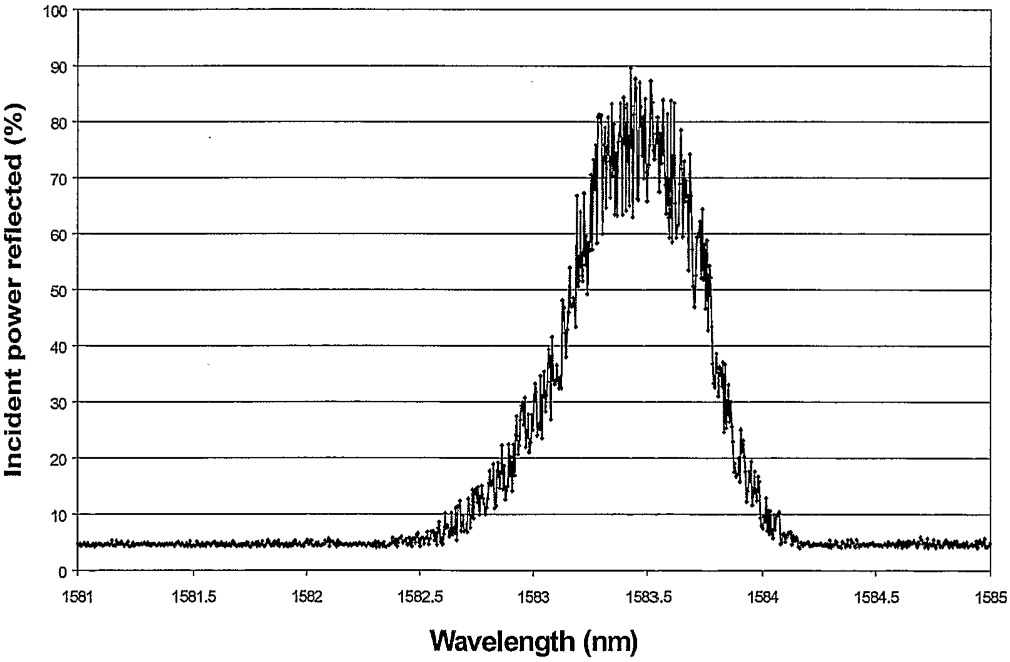


Figure 21

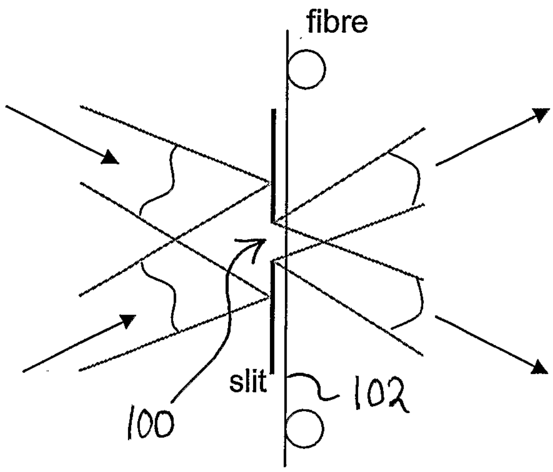


Figure 22

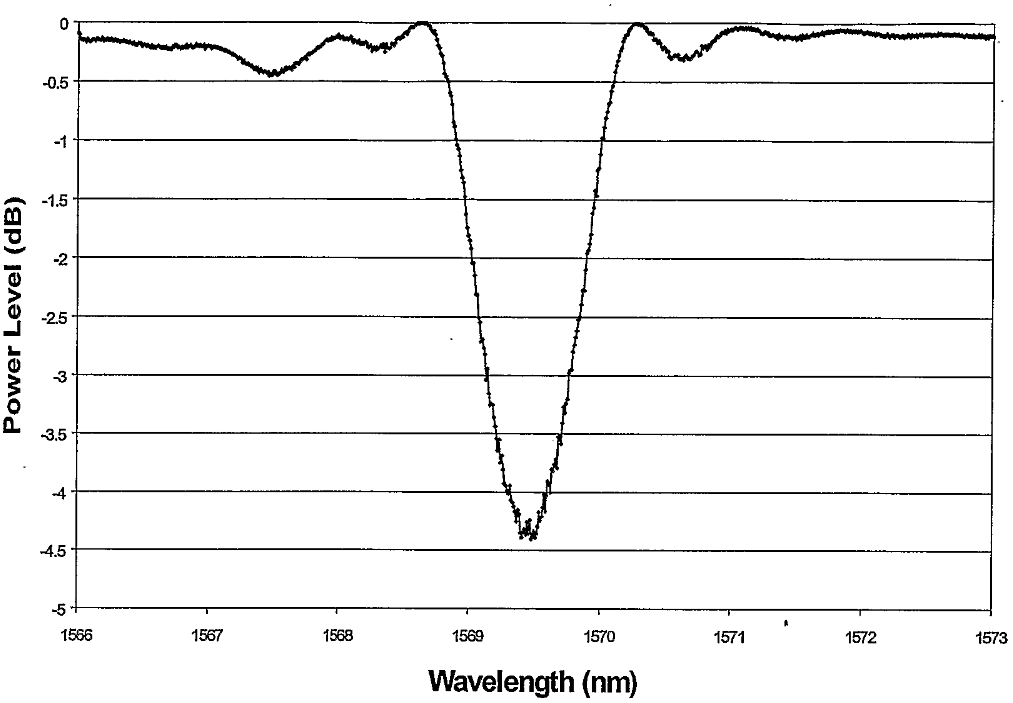


Figure 23

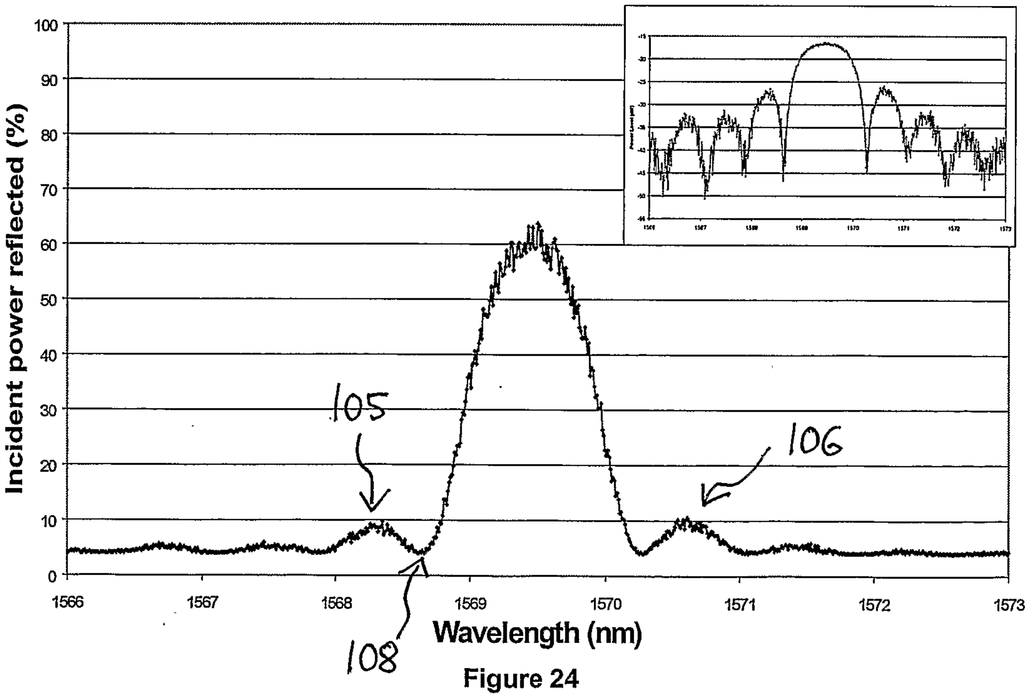


Figure 24

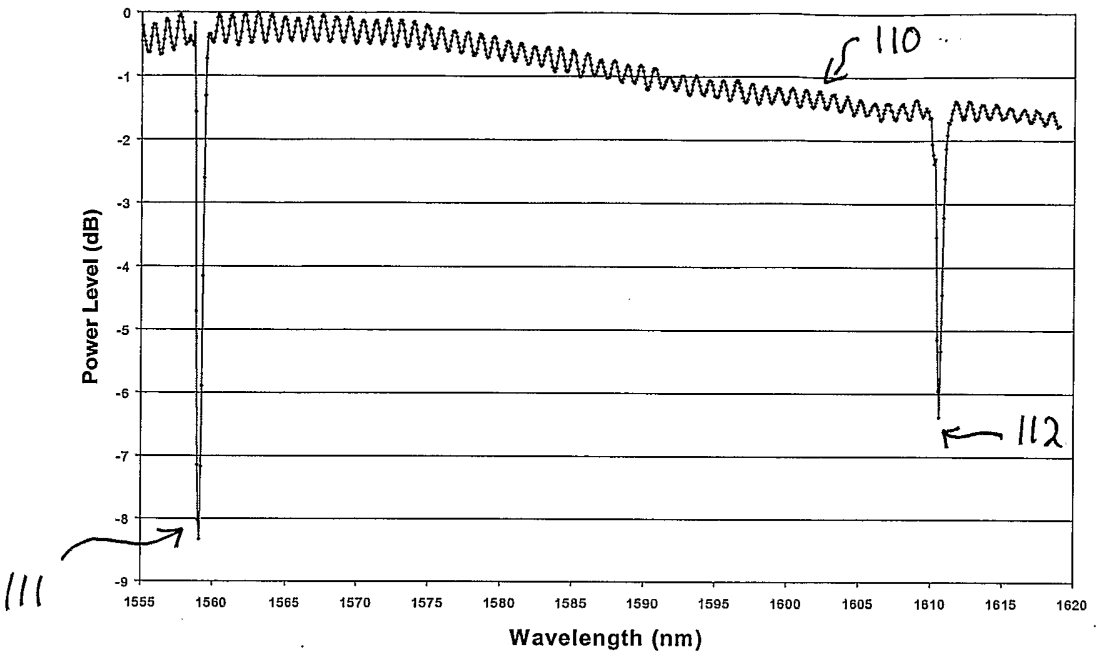


Figure 25

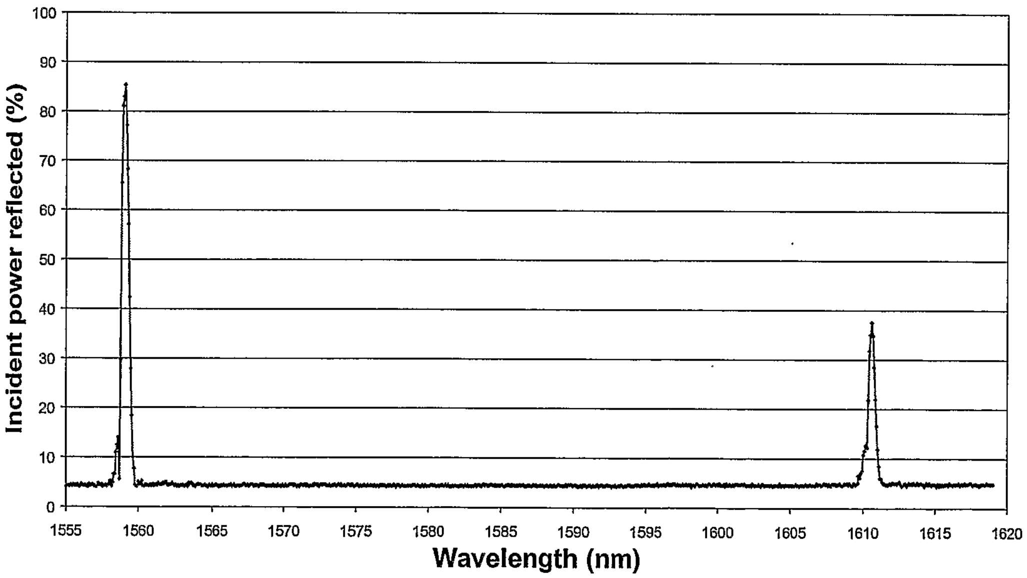


Figure 26

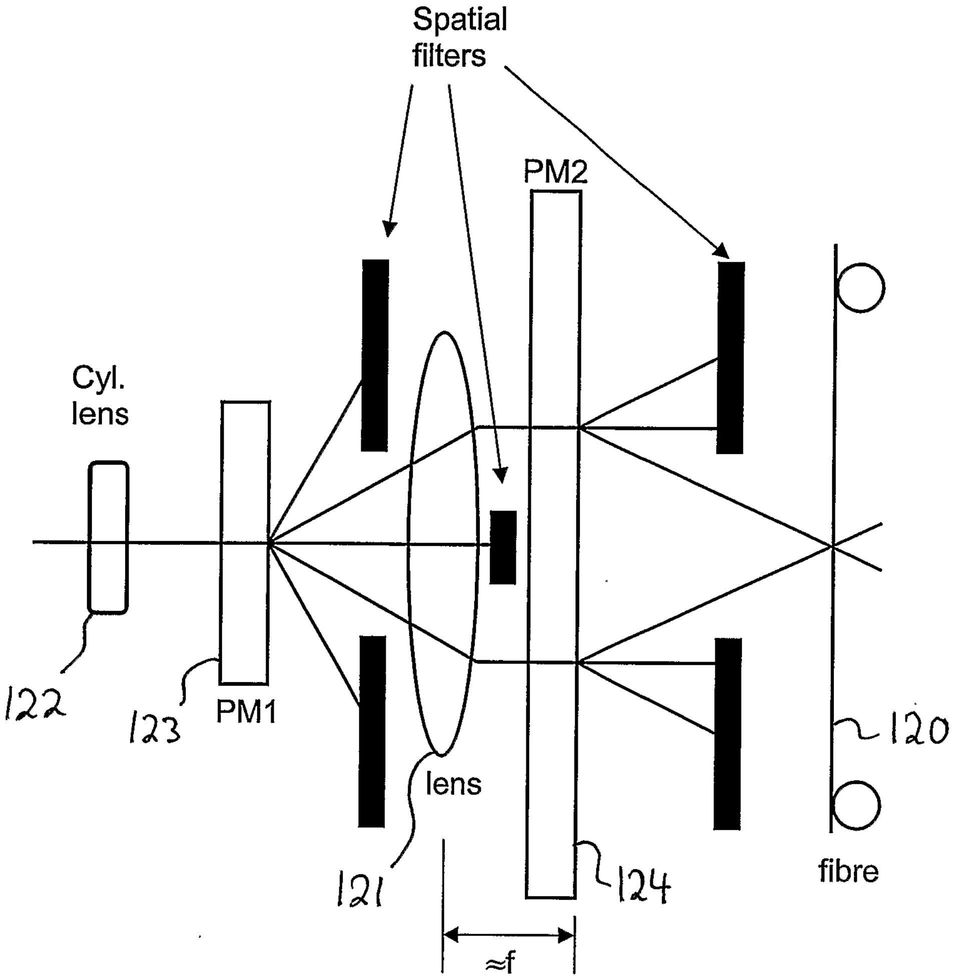

Spatial filters
PM2
Cyl. lens
122
123
PM1
lens
121
124
120
fibre
≈f

Figure 27

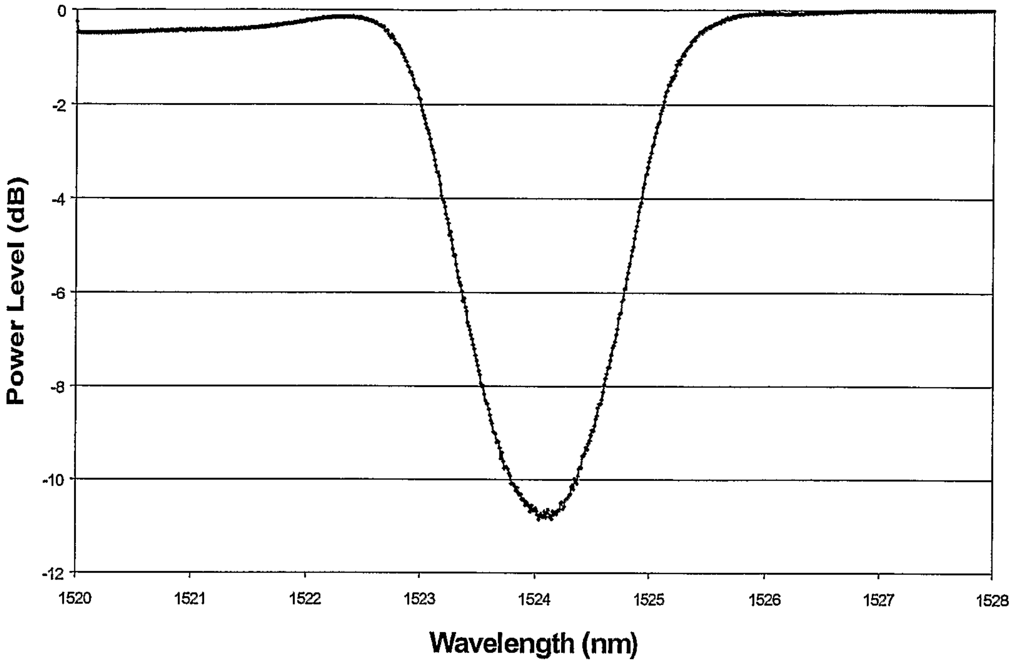
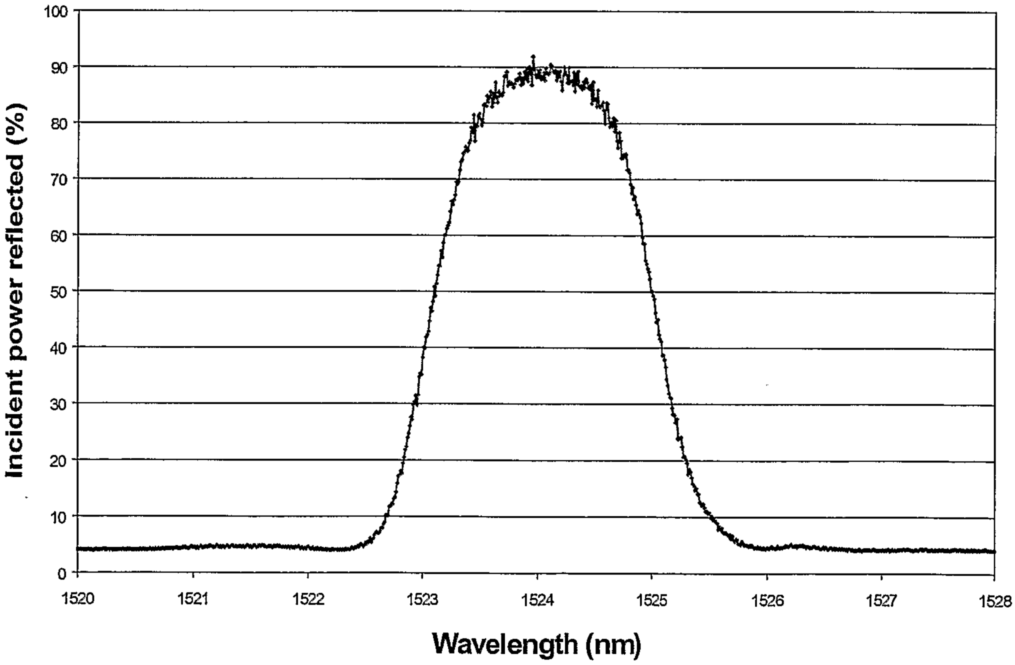


Figure 28



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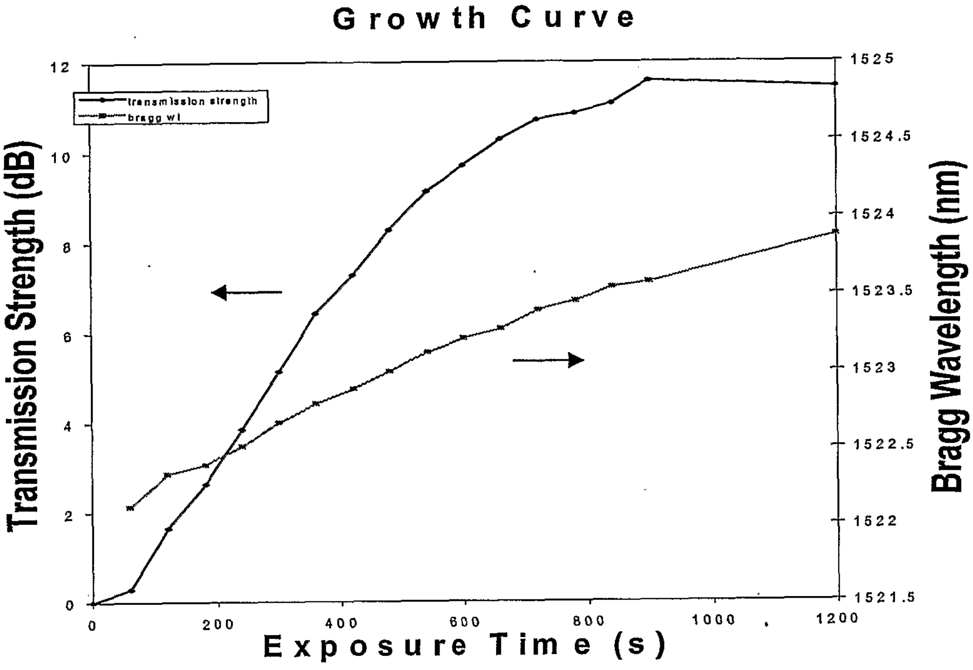

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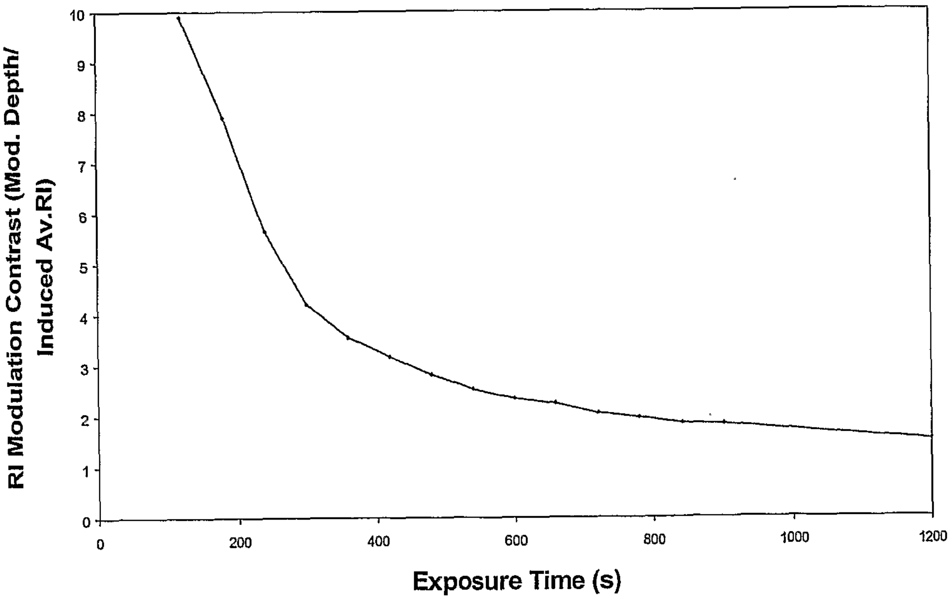

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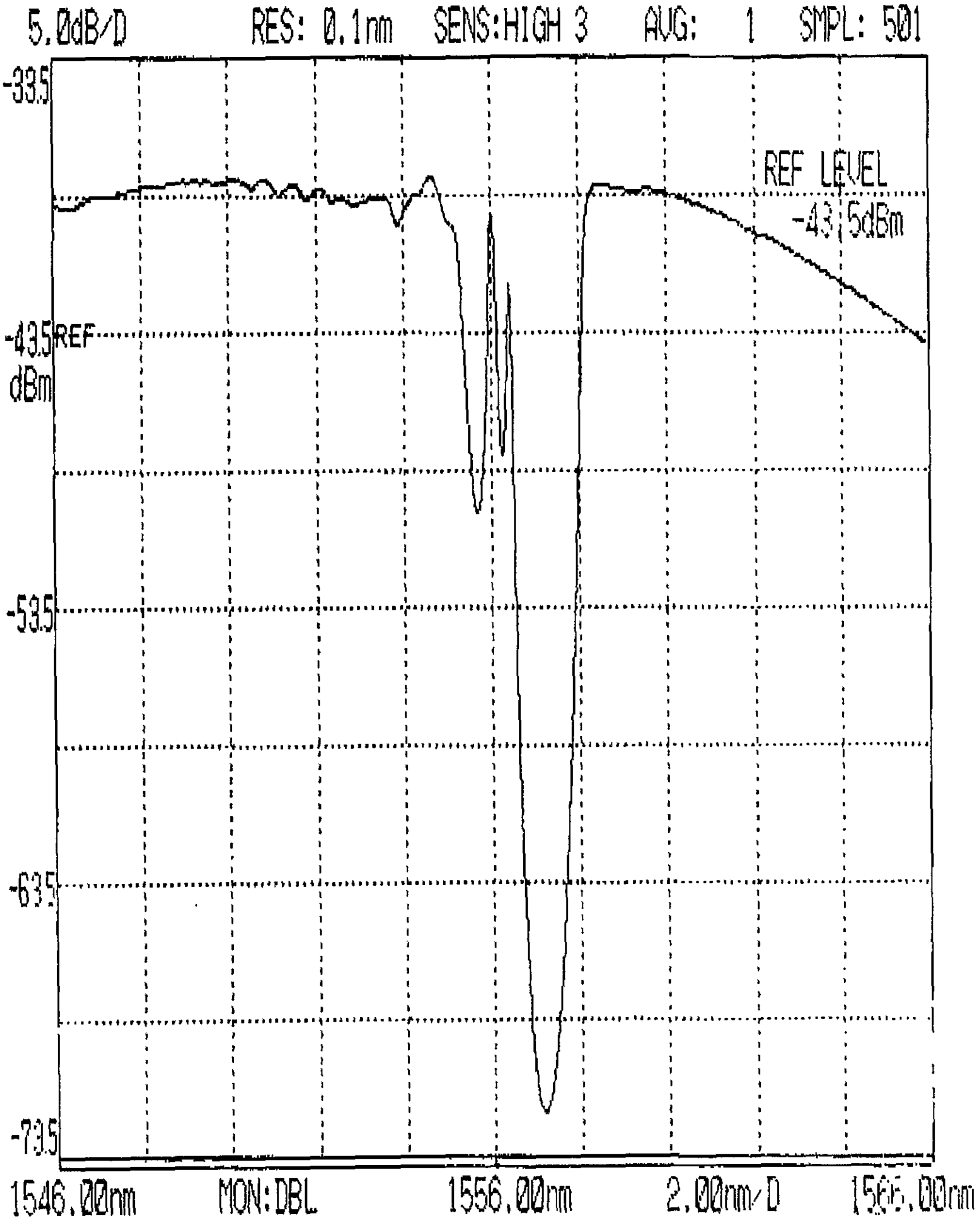
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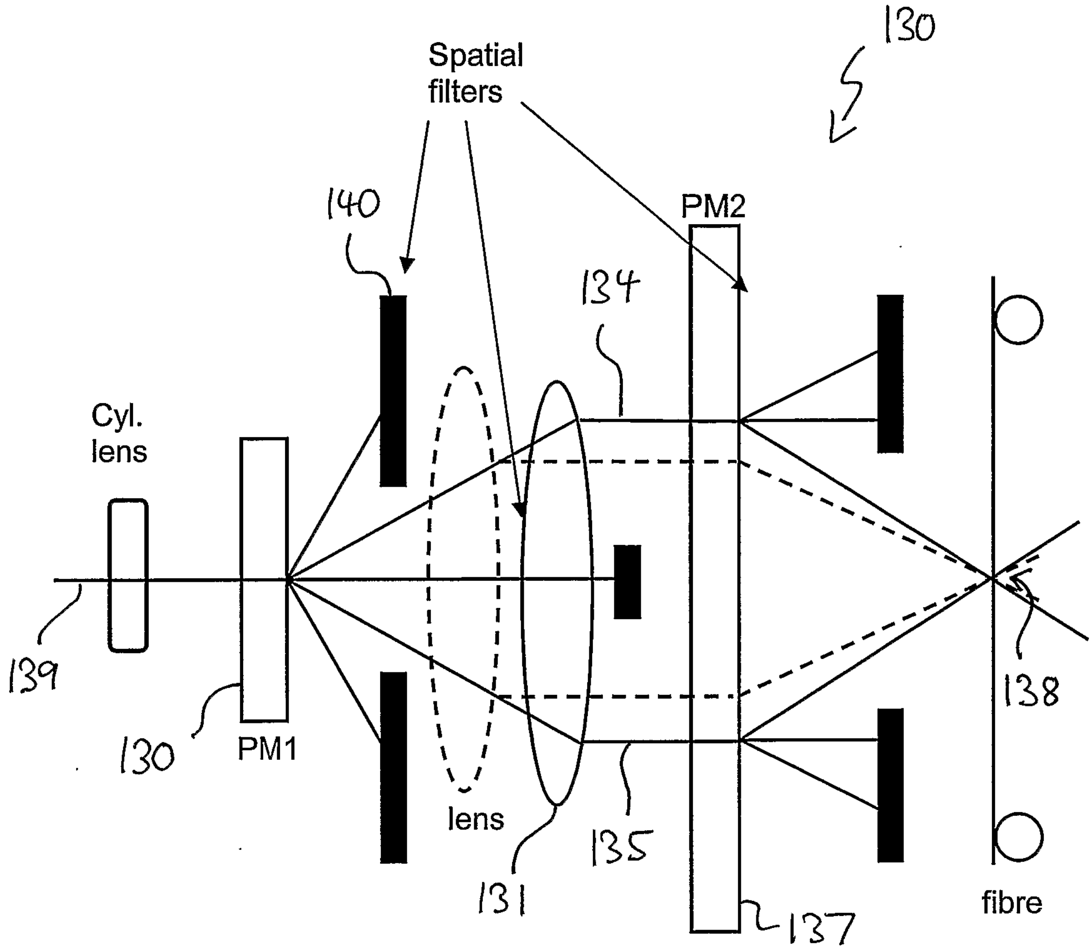
RES: 0.1nm
SENS:HIGH 3
AVG: 1
SMPL: 501
-33.5
REF LEVEL
-43.5dBm
-43.5 REF
dBm
-53.5
-63.5
-73.5
1546.00nm
MON:DBL
1556.00nm
2.00nm/D
1566.00nm

Figure 32


Spatial filters
130
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PM2
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Cyl. lens
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130
PM1
lens
131
135
137
138
fibre

Figure 33

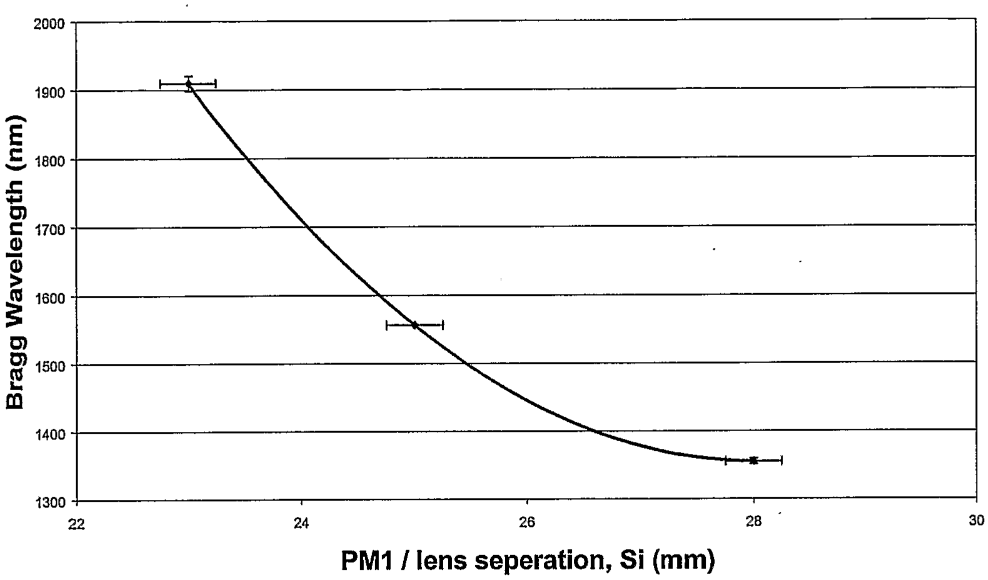


Figure 34

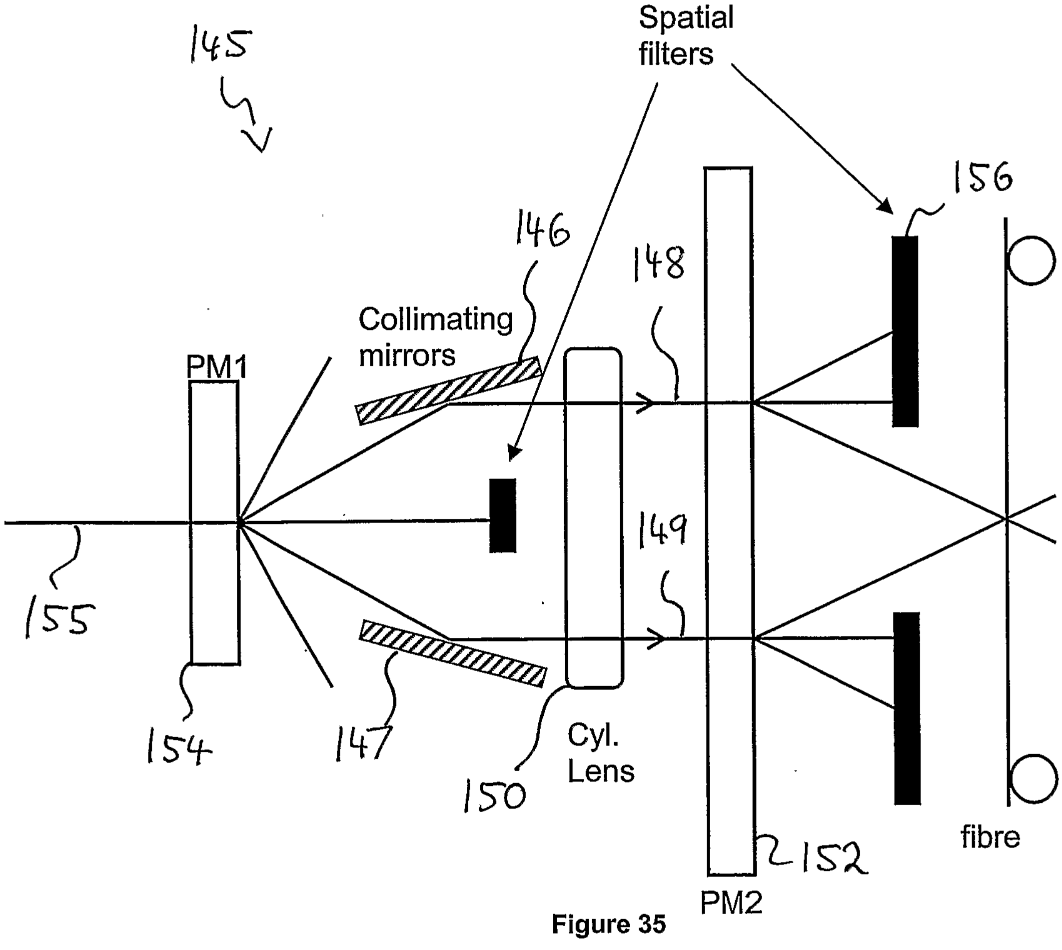
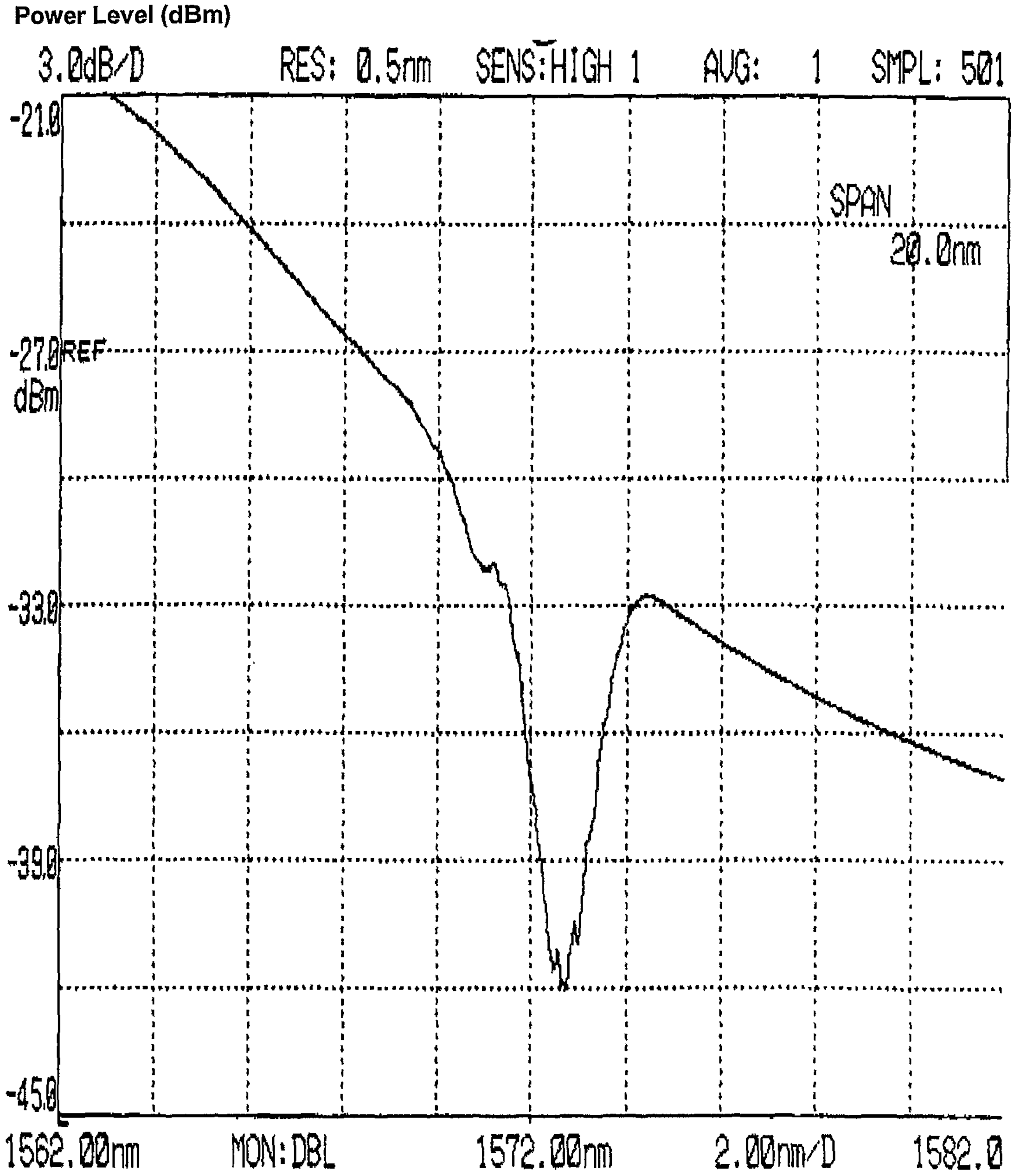


Figure 35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RES: 0.5nm
SENS:HIGH 1
AVG: 1
SMPL: 501
-21.0
-27.0
REF
dBm
-33.0
-39.0
-45.0
SPAN
20.0nm
1562.00nm
MON:DBL
1572.00nm
2.00nm/D
1582.0
Wavelength (nm)

Figure 36

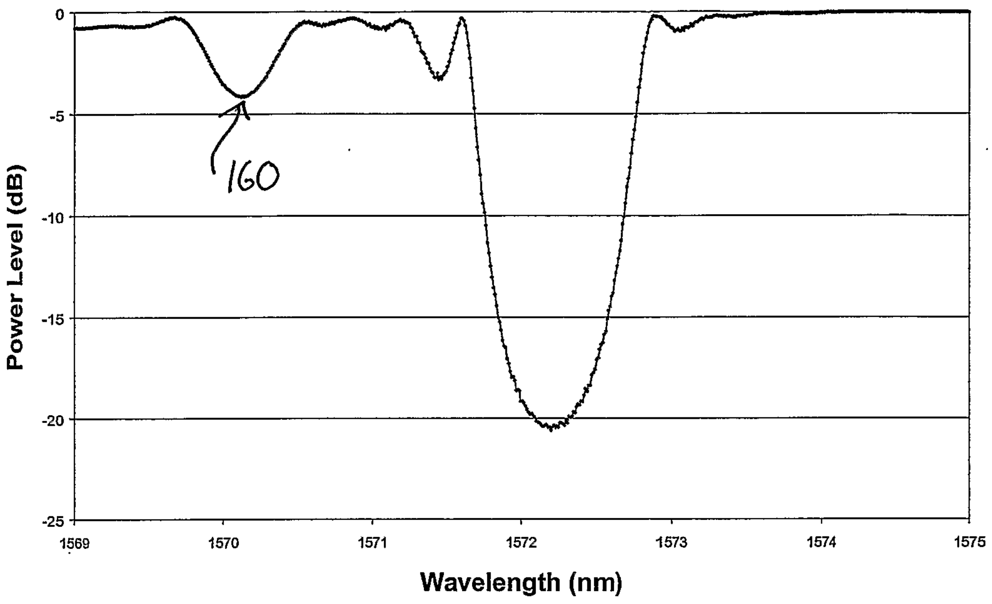


Figure 37

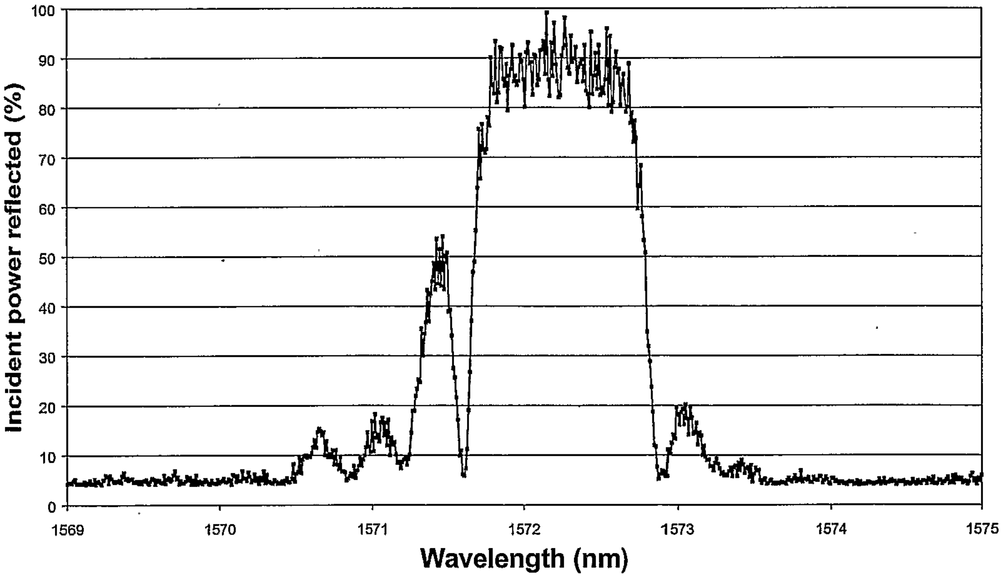


Figure 38

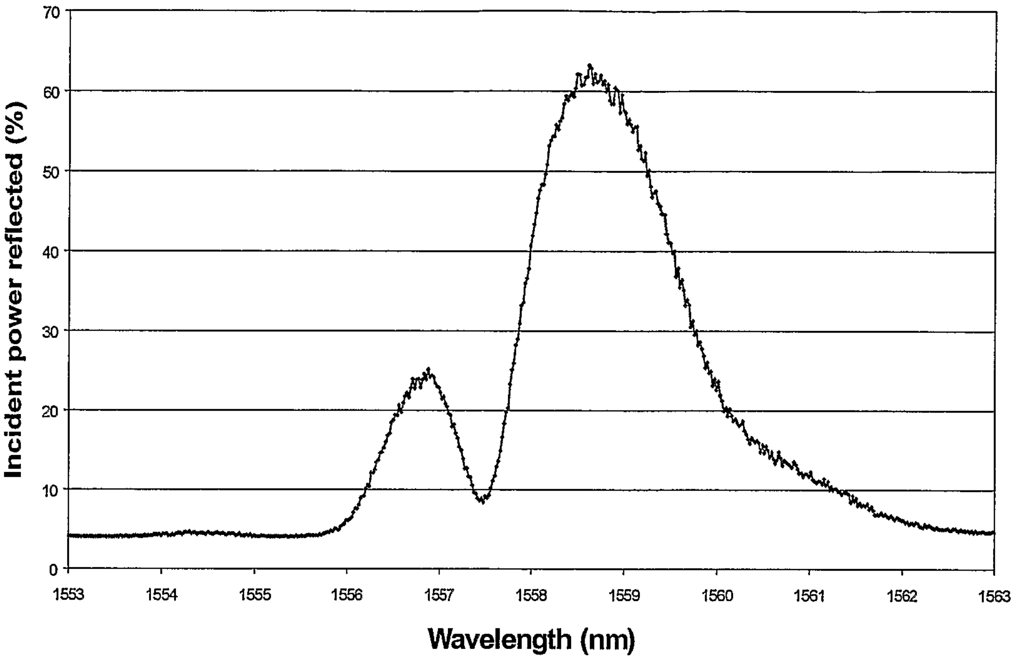
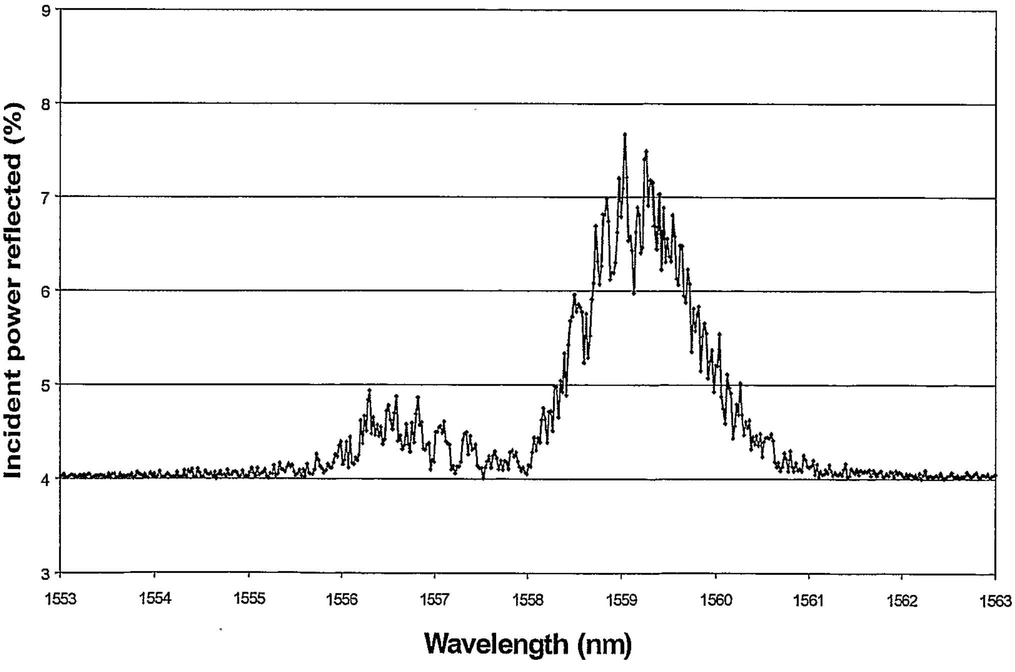


Figure 39



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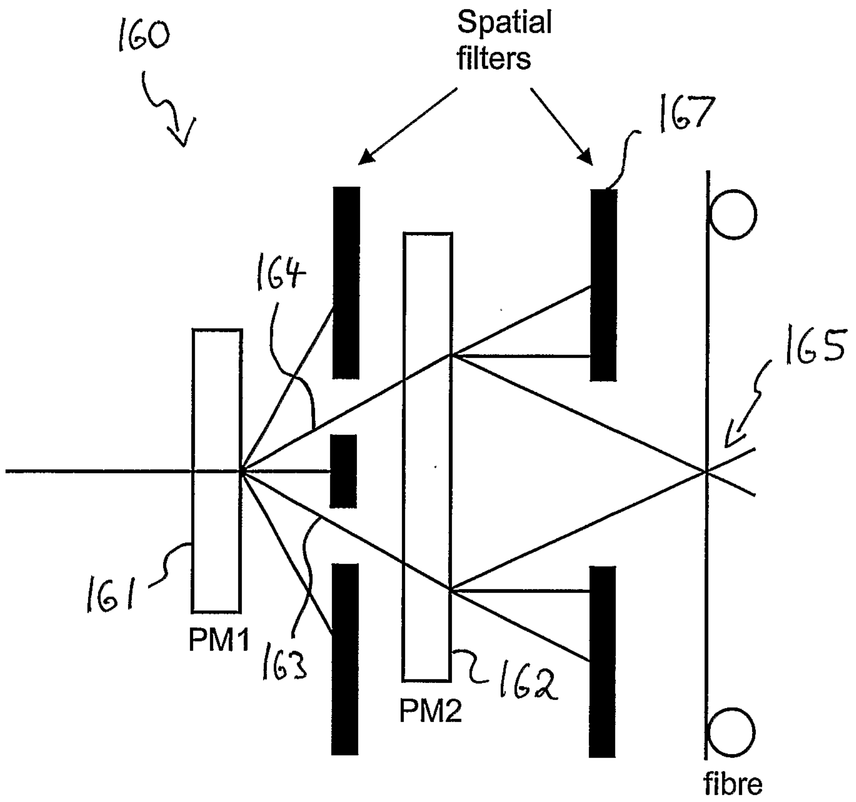


Figure 41

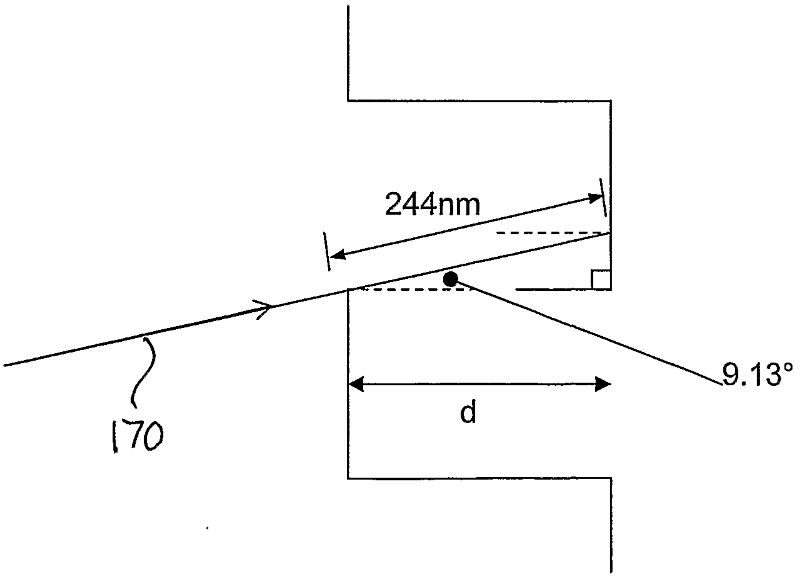


Figure 42

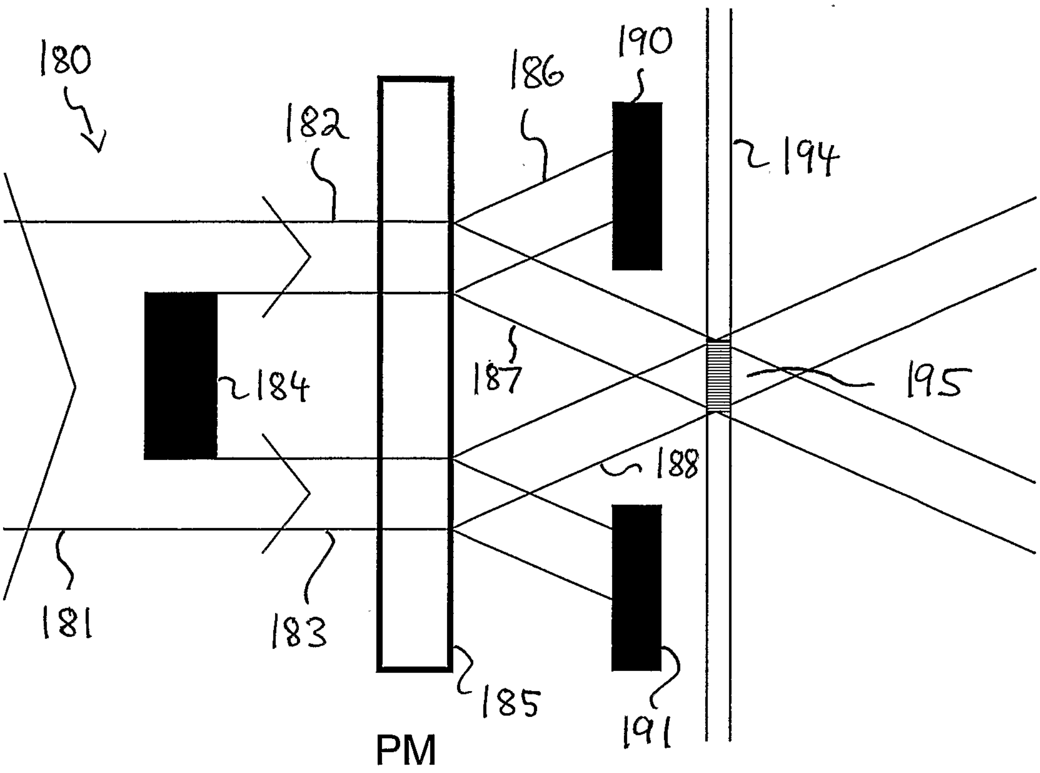
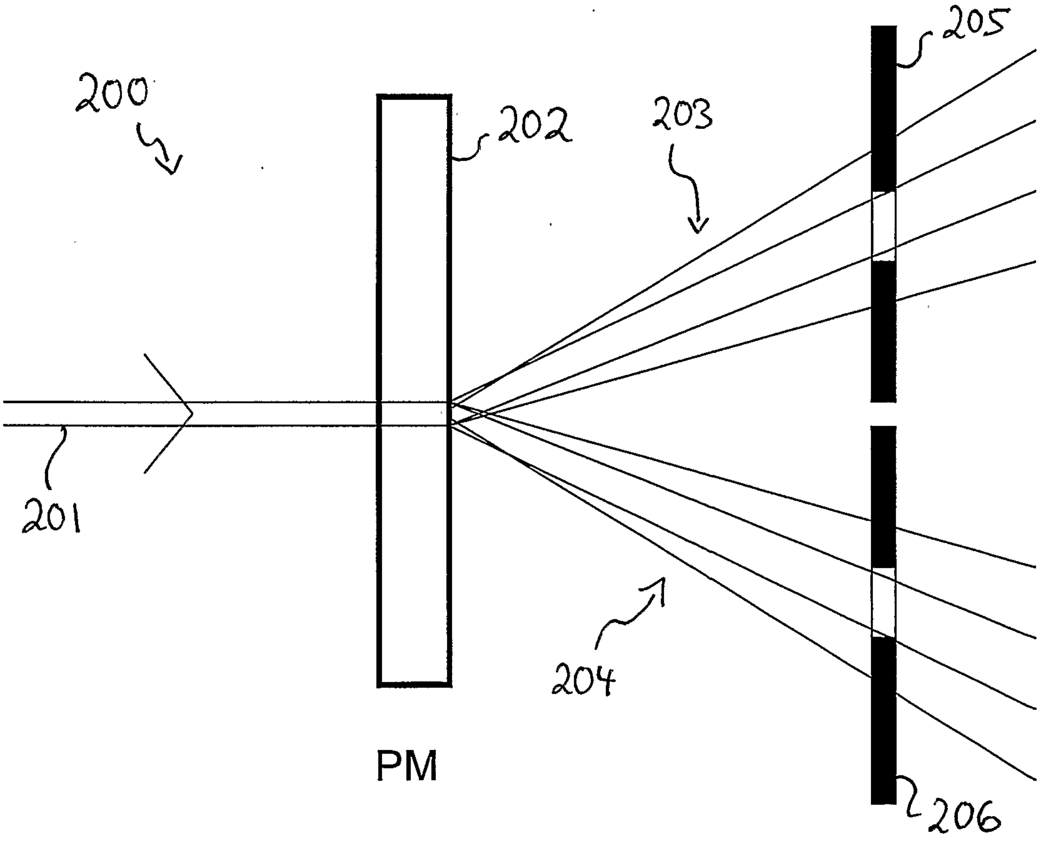


Figure 43



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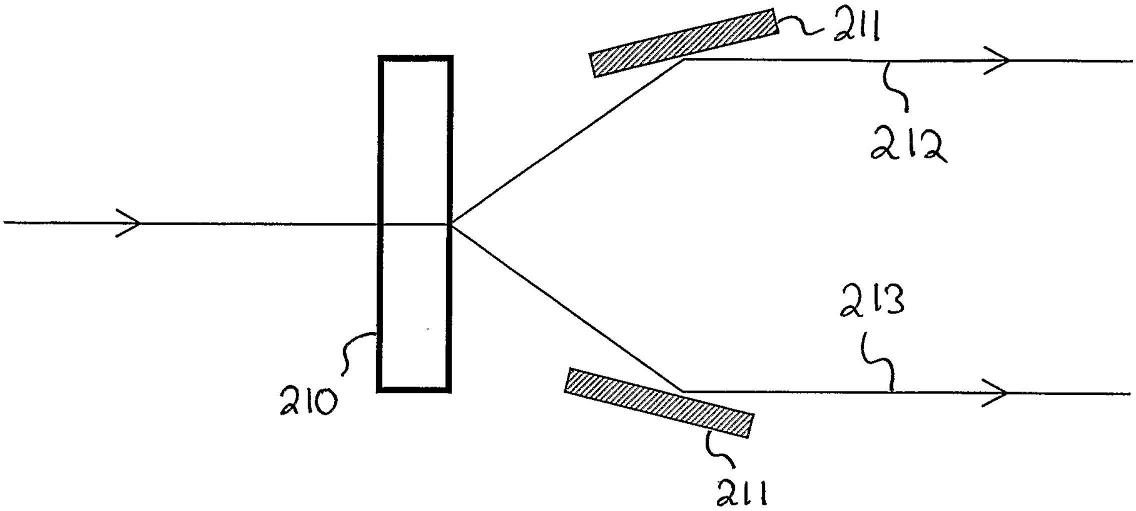
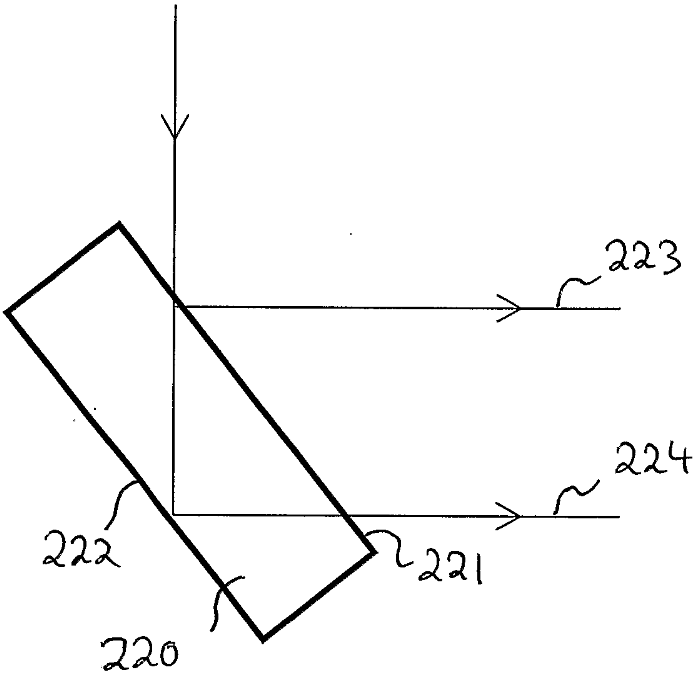


Figure 45



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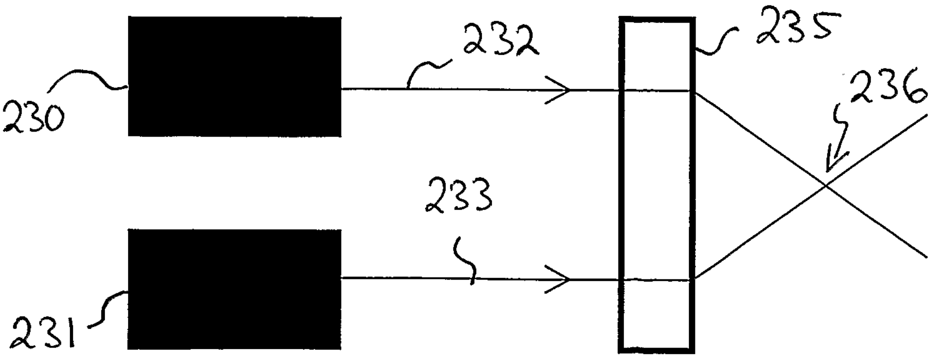

Figure 47

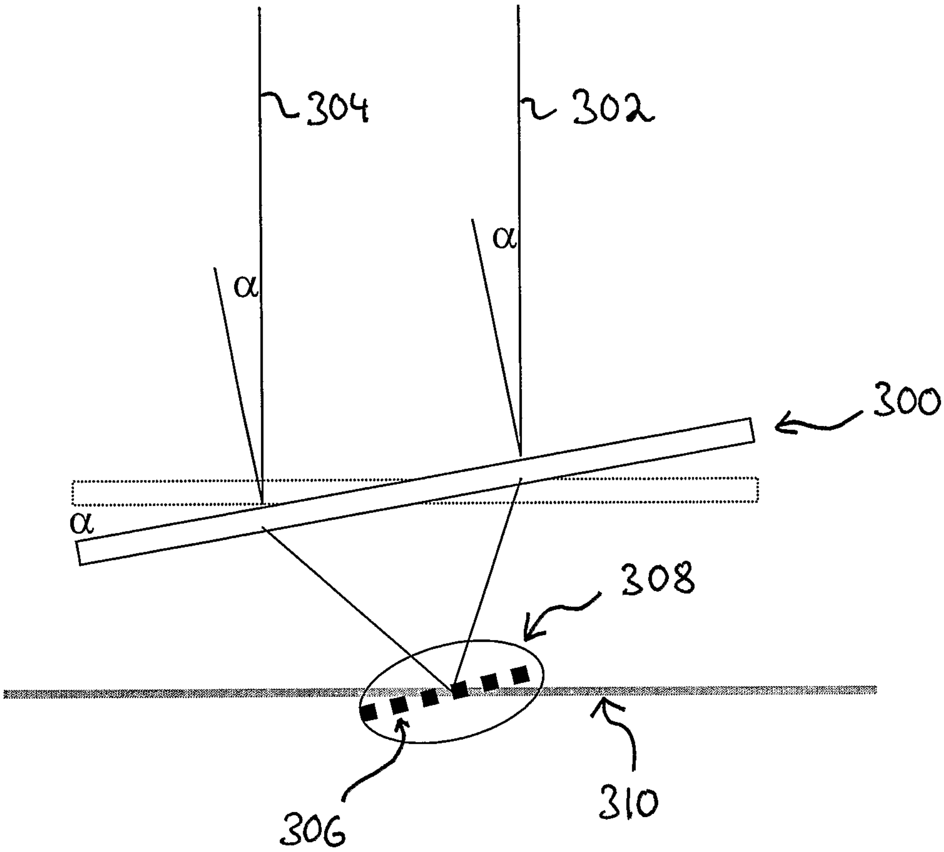

Figure 48

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU03/00637

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. ^{7}: G02B 6/34, 6/16, G01B 9/02

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)

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 practicable, search terms used)
DWPI: keywords [grating?, interfer+; phase mask?; lens+, focus+, collimat+]; [grating?, interfer+; mask?; order?]; G02B 5/-, 6/- & keywords [grating?; interfer+; collimat+]

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2329484 A (NORTHERN TELECOM LIMITED) 24 March 1999 Page 5 lines 5-29, page 6 lines 7-14, figure 2, claim 4	1-3, 5-8, 13, 16, 18-20, 22-25, 30, 33
P, X	US 6437886 B (TREPANIER *et al.*) 20 August 2002 Col. 6 line 4 - col. 7 line 53, Example 1, figures 1 & 8, claims 1 & 16	1-3, 5-8, 13-20, 22-25, 30-34
A	WO 01/44845 A (UNIVERSITY OF SOUTHAMPTON) 21 June 2001 Abstract, figure 2	1-36

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

"A"	document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 23 June 2003	Date of mailing of the international search report 27 JUN 2003
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer **IRINA TALANINA** Telephone No : (02) 6283 2203

C (Continuation).	**DOCUMENTS CONSIDERED TO BE RELEVANT**	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99/22256 A (PIRELLI CAVI E SISTEMI S.P.A.) 6 May 1999 Abstract, figure 1	1-36

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU03/00637

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
GB	2329484	CA	2247744	EP	903597	US	6310996
US	6437886	CA	2305070				
WO	200144845	AU	200118729	CA	2394399	EP	1238297
WO	9922256	AU	95519/98	BR	9813267	CA	2307189
		EP	1025457	NZ	504184	US	6549705

END OF ANNEX