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(54) LONG PERIOD FIBER BRAGG GRATINGS WRITTEN WITH ALTERNATE SIDE IR LASER ILLUMINATION

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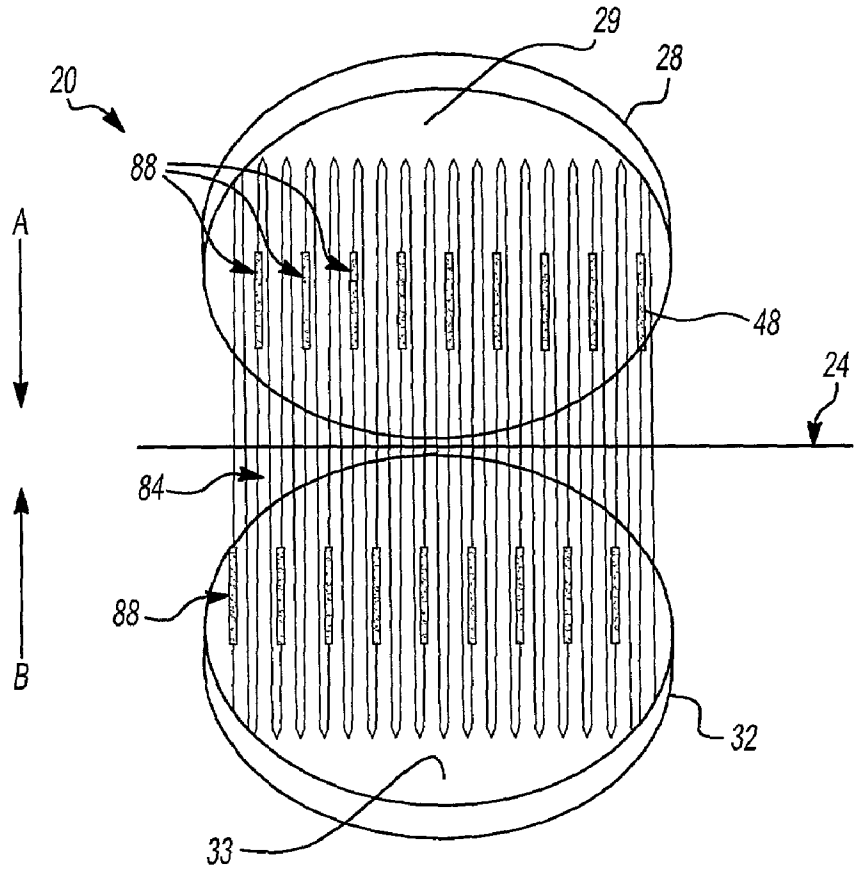
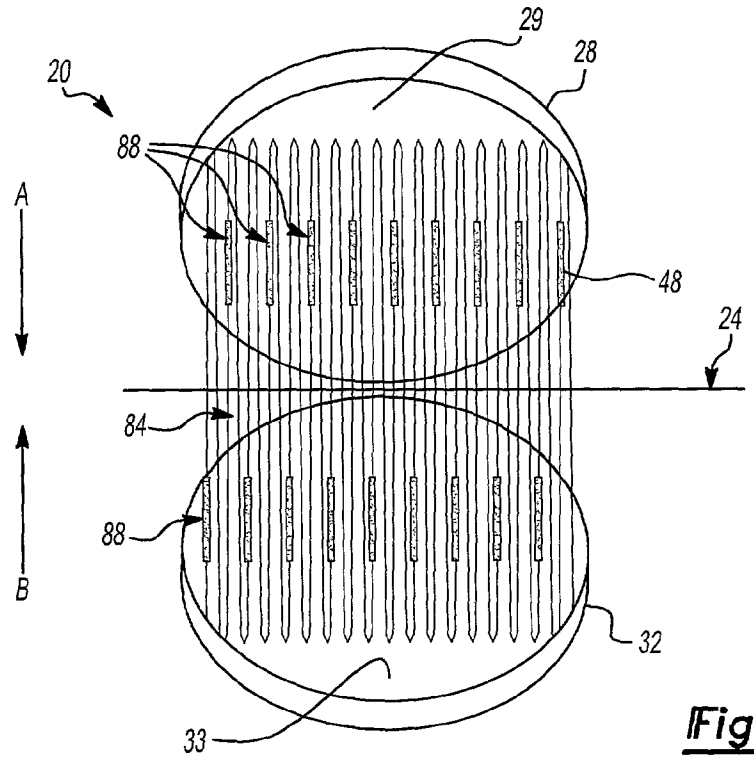
(57) **ABSTRACT**

A method of optical fiber manufacture involves the writing of a grating on the fiber using a laser. A first laser beam is directed on a first locality of the fiber having a circumference. A second laser beam is then directed on a second locality circumferentially displaced from the first locality. The first laser beam may be the second laser beam. In this way, a grating is formed on the fiber. The fiber may have a core and a cladding layer. The fiber may also comprise two gratings to form an interferometer.

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28
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A
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24
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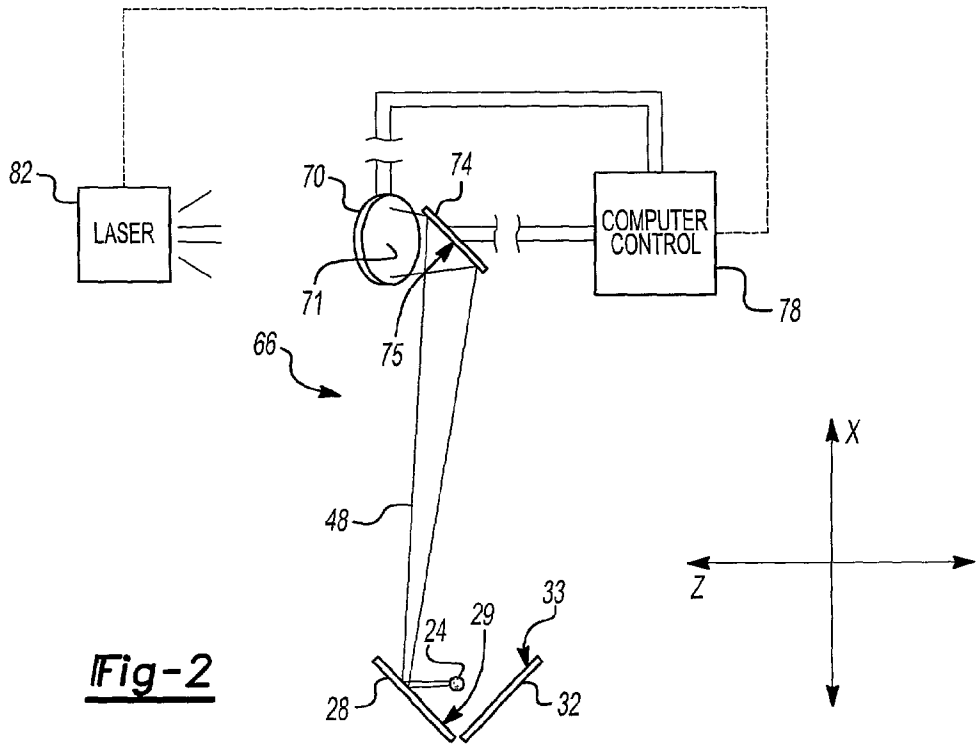
88
B
32
33

Fig-1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78
66
75
48
X
Z
33
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24
28
32

Fig-2

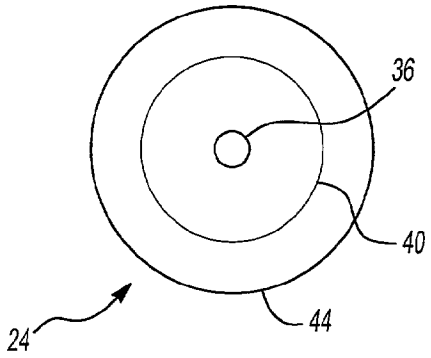


Fig-1A

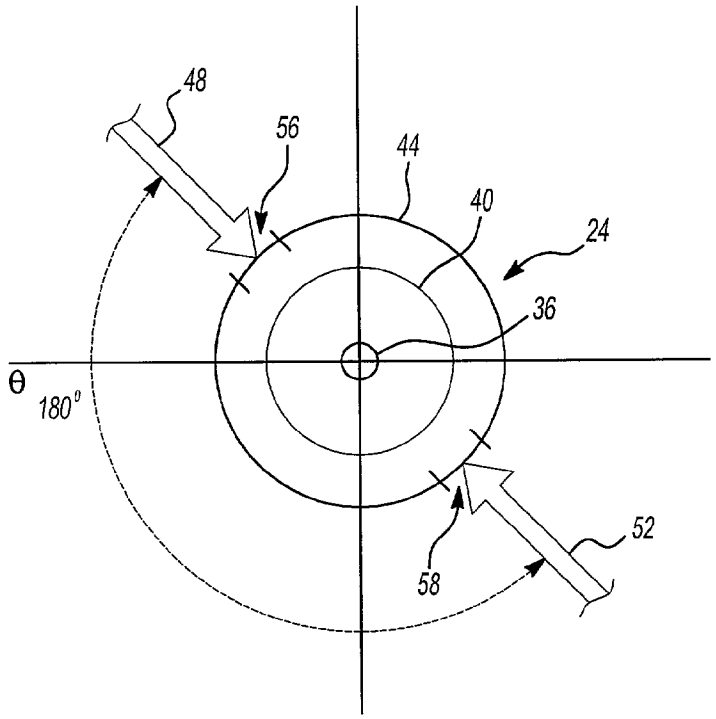


Fig-1B

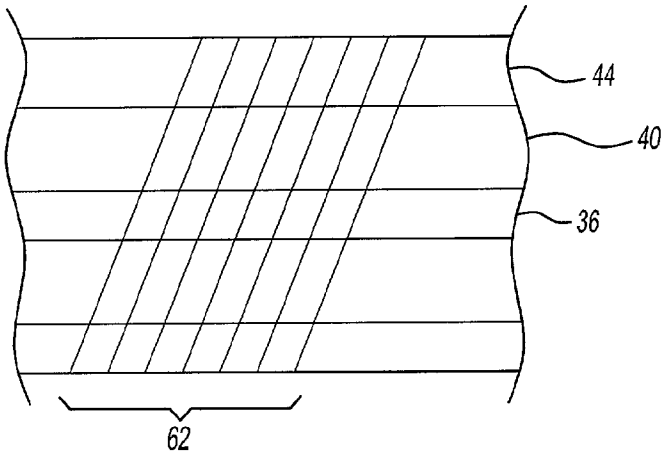


Fig-1C

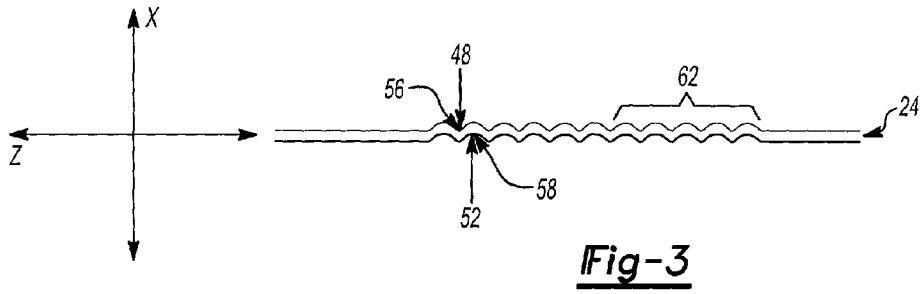


Fig-3

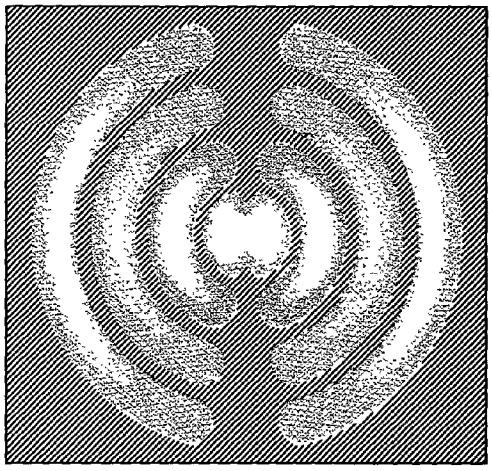
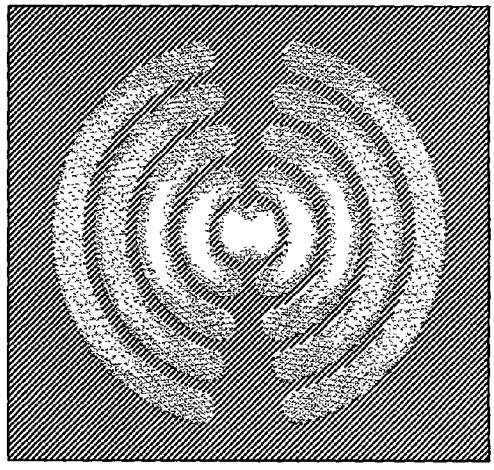


Fig-4A

Fig-4B



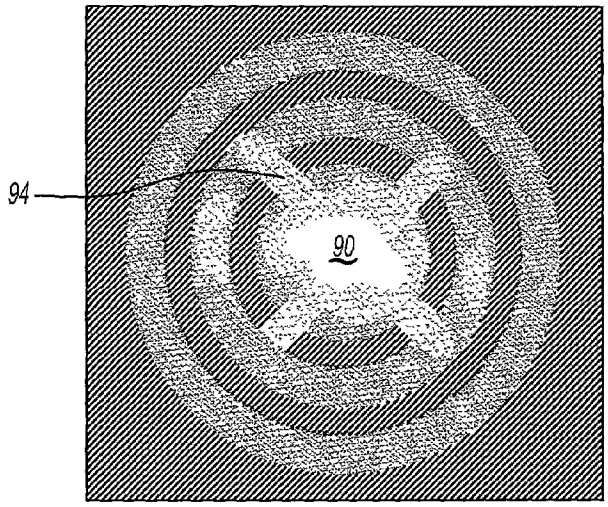


Fig-5

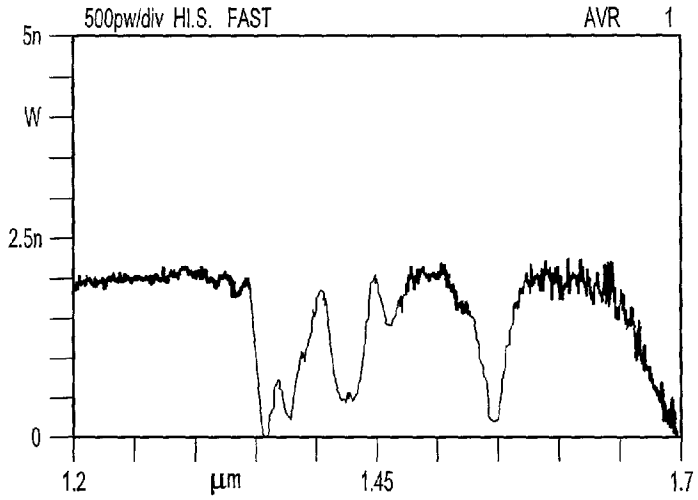


Fig-6

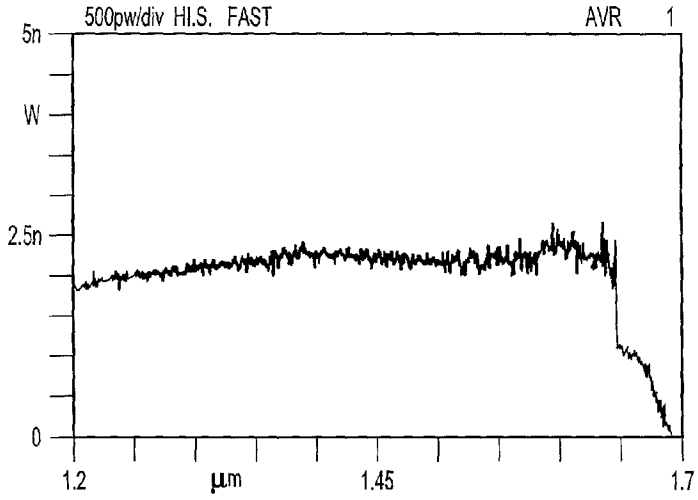


Fig-7

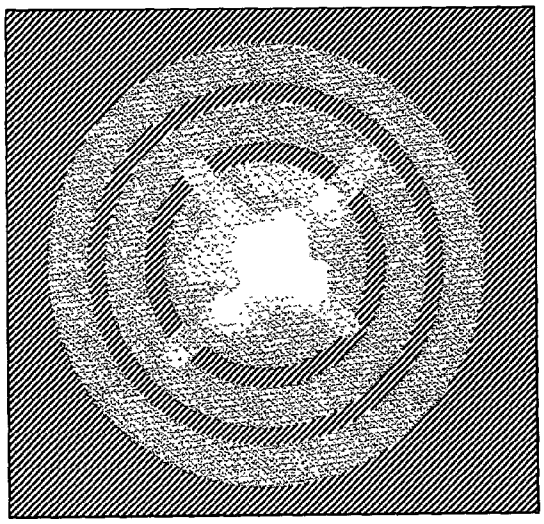


Fig-8

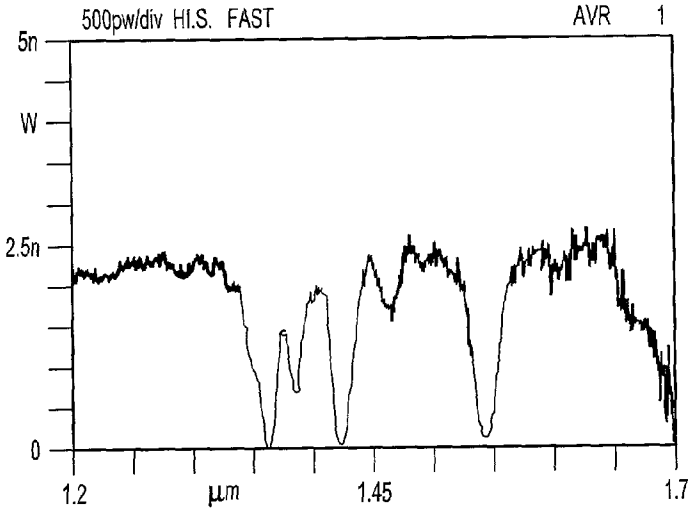


Fig-9

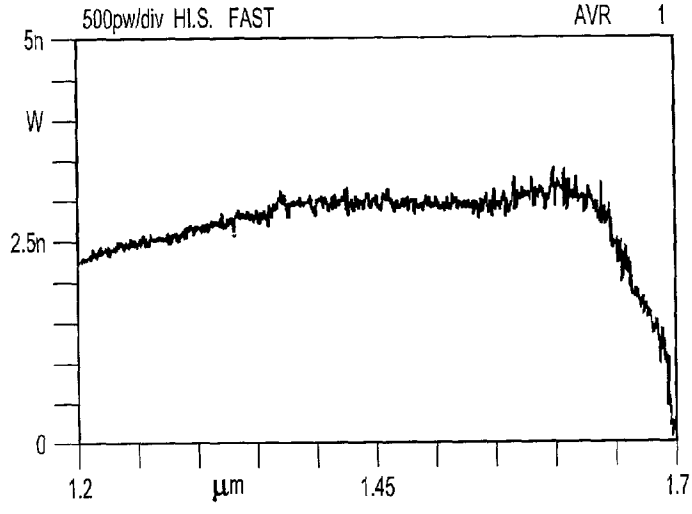


Fig-10

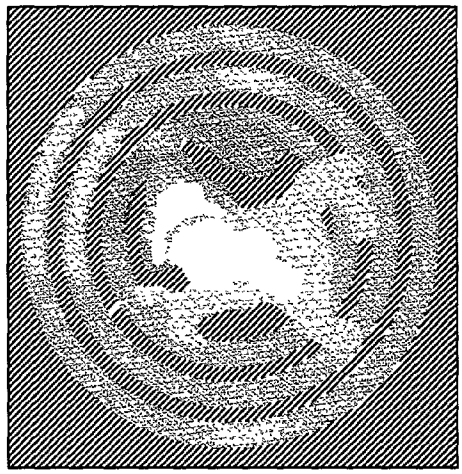


Fig-11

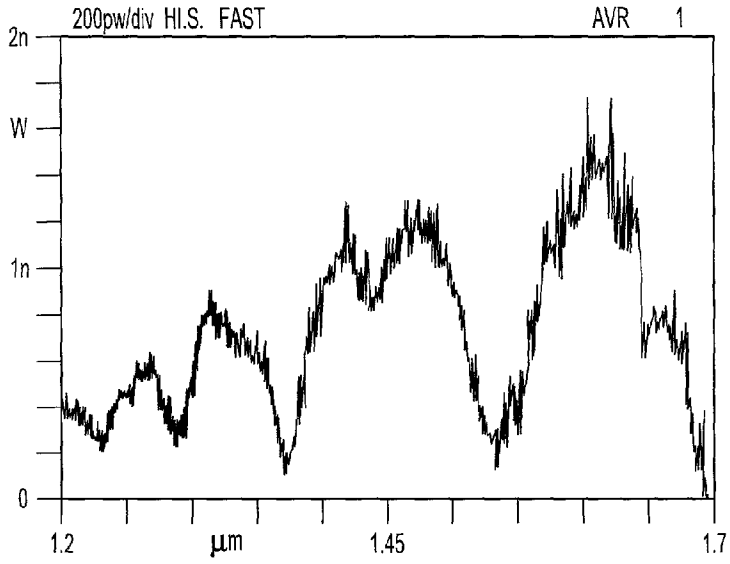


Fig-12

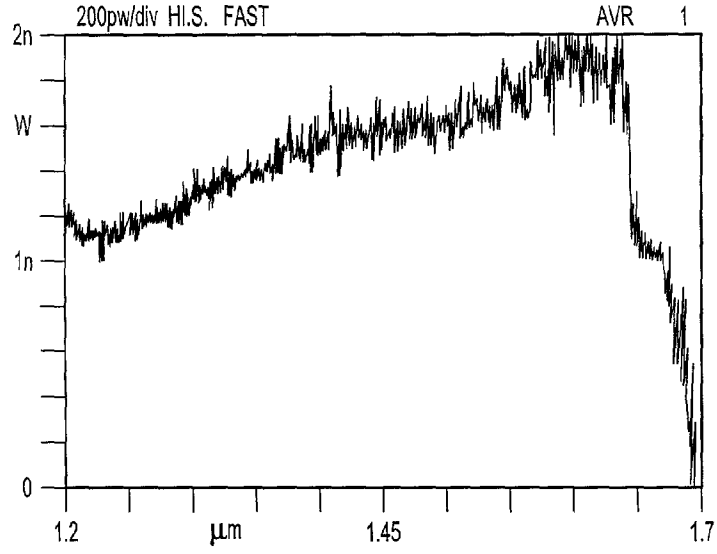


Fig-13

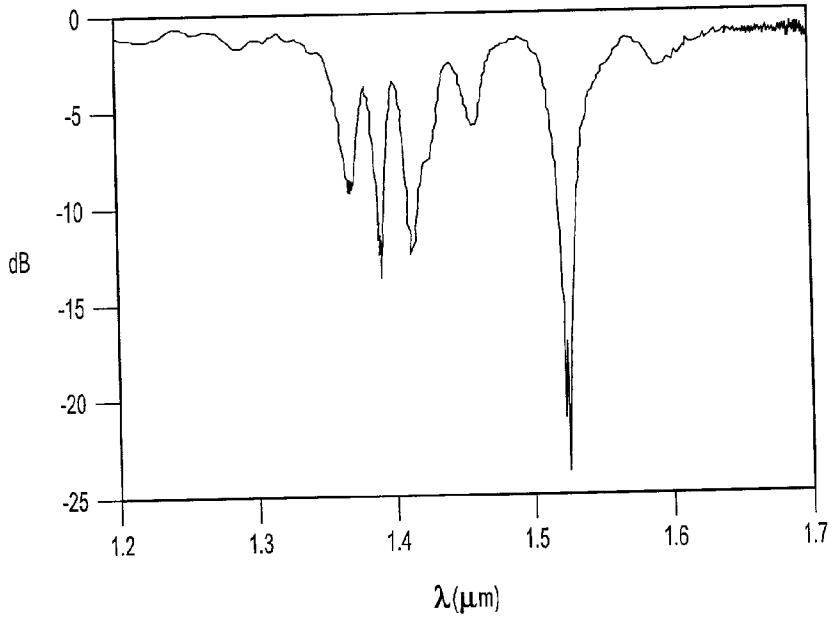


Fig-14

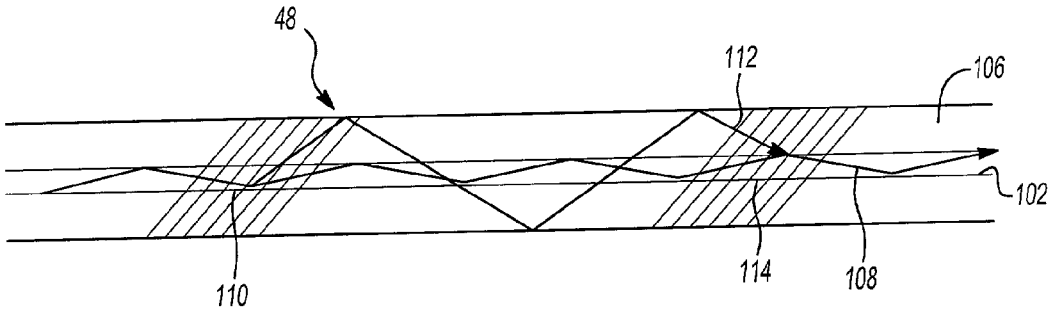


Fig-15

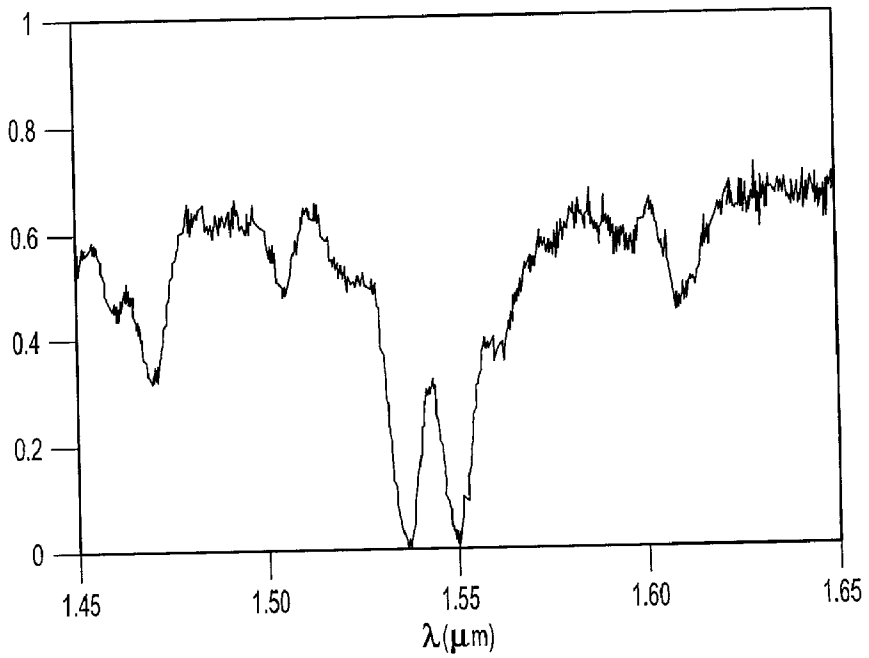

1
0.8
0.6
0.4
0.2
0
1.45
1.50
1.55
1.60
1.65
λ(μm)

Fig-16

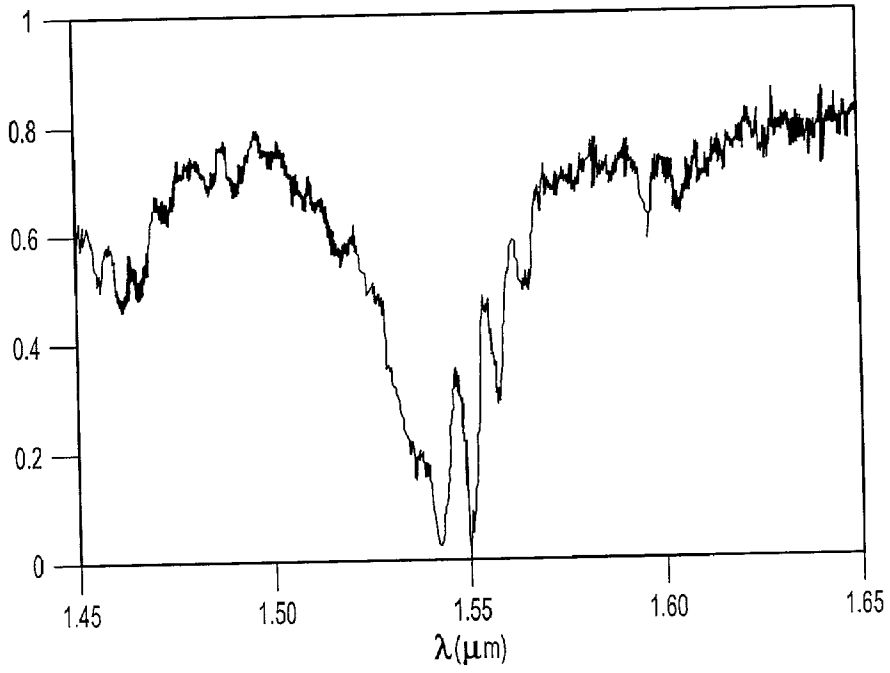

1
0.8
0.6
0.4
0.2
0
1.45
1.50
1.55
1.60
1.65
λ(μm)

Fig-17

LONG PERIOD FIBER BRAGG GRATINGS WRITTEN WITH ALTERNATE SIDE IR LASER ILLUMINATION

BACKGROUND OF THE INVENTION

[0001] The invention relates to a new method of producing an optical diffraction grating for an optical fiber using a CO_2 laser.

[0002] Optical fibers are used to transmit light for industrial purposes, such as for telecommunications and sensor applications. An optical fiber may comprise a core, a cladding, and a buffer. The core serves as the main transmission media or conduit for the light propagating through the fiber. A cladding layer surrounds the core and, typically, has a different index of refraction than the media of the conduit. The cladding may serve as another conduit for transmitting light. The buffer layer, which surrounds the core layer and the cladding layer, may be used to extinguish light in the cladding layer.

[0003] A single mode telecommunication fiber may comprise a core of fused silica, roughly 8 μm in diameter, doped to increase its index of refraction, surrounded by a cladding layer, 125 μm in diameter, of fused silica and a polymer buffer, 240 μm in diameter. Cladding modes are normally extinguished by the buffer but will propagate when the buffer is removed. While a single mode fiber has only a single core mode propagating in the forward direction, the fiber has numerous discrete cladding modes of light propagating in the cladding layer.

[0004] For certain applications, an optical fiber may have a light grating, such as a Bragg grating. In particular, such a grating is useful for various telecommunications applications. Moreover, such a fiber may be used as a sensor due to its sensitivity to temperature, pressure, and the index of refraction of the fiber's environment.

[0005] Generally, a Bragg grating in an optical fiber comprises a periodic variation in the fiber's physical state, such as an alteration in the index of refraction or ablation or removal of portions of the fiber, that may convert guided radiation in the fiber's core into another guided mode in the fiber or, in some cases, unguided radiation, which escapes from the fiber. Bragg gratings may have two forms: short period Bragg gratings and long period Bragg gratings. Short period Bragg gratings are normally used to retro-reflect the guided core mode in a single mode fiber into the core mode propagating in the reverse direction. Long period Bragg gratings convert the core mode into cladding modes.

[0006] A Bragg grating converts light from one mode to another guided mode or an unguided mode within a narrow range of wavelengths, so-called resonant wavelengths. As known, the resonant wavelengths are determined by the grating equation:

$$2\pi/\Lambda=|\beta_2(\lambda)-\beta_1(\lambda)|,$$

[0007] where Λ is the grating period, β_1 is the propagation constant of the initial core mode, and β_2 is the propagation constant of the outgoing mode. Propagation constants define the axial variation in phase of the guided mode and are functions of wavelength.

[0008] A Bragg grating for an optical fiber is most commonly made by directing a laser on one side of a fiber with a periodic distribution of ultraviolet light from an excimer laser. The process only works with silica fibers whose core index has been raised by doping with germania. Illuminating germania doped silica with ultraviolet radiation of a certain wavelength alters its index of refraction. The alteration of the index of refraction is then the mechanism responsible for grating formation.

[0009] The grating is normally produced using a mask as a stencil. The process is enhanced by hydrogenating the fiber prior to the fabrication of the grating. The hydrogenation consists of exposing the fiber to high-pressure hydrogen at an elevated temperature, a potentially hazardous procedure. After illumination with the ultraviolet radiation, the fiber must then be "baked" to expel the hydrogen and stabilize the grating. The resonance wavelength of the grating changes somewhat as a result of this baking. Gratings have also been formed with a CO_2 laser and a fusion splicer but published results appear to be inferior to that obtained with a photorefractive grating generated by ultraviolet radiation.

[0010] A need therefore exists for a technique of creating a grating in an optical fiber in a safe and effective manner.

SUMMARY OF THE INVENTION

[0011] The invention comprises a technique to manufacture optical fibers using a laser to create an optical grating on the fiber. In contrast to the prior art, the laser is first directed on a first spot on the fiber and then directed on a second spot radially displaced relative to the fiber from the first spot. In other words, the laser is shined on one side and then the other side of the fiber. The fiber alters locally at each spot to create a uniform grating.

[0012] The laser may heat and deform the spot on the optical fiber to form the grating. An infrared laser, such as the radiation from a CO_2 laser, may serve to deform the fiber. The laser may be scanned across the fiber and activated at predetermined points of the scanning pattern. In this way, the alteration of the fiber is consistent, producing a more efficient grating.

[0013] Moreover, the grating may be formed on an optical fiber having a transmission layer and a cladding layer. Two gratings spaced apart may be formed so as to form an optical fiber for sensor application purposes. One grating serves to eject light from the core into the cladding layer. The second grating returns light from the cladding layer to the core. Light from the cladding layer now in the core interferes with the light propagating through the core. The combined light reveals details about the environment surrounding the fiber.

[0014] An optical fiber made from the foregoing process is more accurate than an optical fiber made from many existing techniques. Modes of light traveling through the cladding layer are better defined. The method is also relatively safe.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiment. The drawings that accompany the detailed description can be briefly described as follows:

[0016] **FIG. 1** illustrates an embodiment of the invention, including optical fiber and laser.

[0017] **FIG. 1A** illustrates the optical fiber of **FIG. 1**, detailing a core, a cladding layer, and a buffer layer.

[0018] **FIG. 1B** illustrates an alternative view of the optical fiber of **FIG. 1**.

[0019] **FIG. 1C** illustrates a side view of the optical fiber of **FIG. 1**, showing a schematic representation of the grating.

[0020] **FIG. 2** illustrates an alternative view of the embodiment of **FIG. 1**, showing optical fiber, laser, scanning mirrors, and turning mirrors.

[0021] **FIG. 3** illustrates an overhead view of the optical fiber, including the direction of the laser of **FIGS. 1 and 2**.

[0022] **FIG. 4A** illustrates a model transmission of light through an optical fiber, showing the transmission of light through the core and cladding layers.

[0023] **FIG. 4B** illustrates a model transmission of light through an optical fiber, showing the transmission of light through the core and cladding layers.

[0024] **FIG. 5** illustrates the transmission of light through an optical fiber having a grating made from the inventive technique.

[0025] **FIG. 6** illustrates a spectral analysis of light through the optical fiber of **FIG. 5**.

[0026] **FIG. 7** illustrates a spectral analysis of light through an optical fiber similar to the fiber of **FIG. 6** without a grating.

[0027] **FIG. 8** illustrates the transmission of light through an optical fiber having a grating made from the inventive technique.

[0028] **FIG. 9** illustrates a spectral analysis of light through the optical fiber of **FIG. 8**.

[0029] **FIG. 10** illustrates a spectral analysis of light through an optical fiber similar to the fiber of **FIG. 8** without a grating.

[0030] **FIG. 11** illustrates the transmission of light through an optical fiber having a grating made from the inventive technique.

[0031] **FIG. 12** illustrates a spectral analysis of light through an optical fiber of **FIG. 11**.

[0032] **FIG. 13** illustrates a spectral analysis of light through an optical fiber similar to the fiber of **FIG. 11** without a grating.

[0033] **FIG. 14** illustrates a spectral analysis of light through an optical fiber having a grating made from the inventive technique.

[0034] **FIG. 15** illustrates a sensor, a Mach-Zehnder interferometer, showing a schematic representation of the grating made from the inventive technique.

[0035] **FIG. 16** illustrates a spectral analysis of light through a Mach-Zehnder interferometer employing a grating made from the inventive technique.

[0036] **FIG. 17** illustrates a spectral analysis of light through a Mach-Zehnder interferometer employing a grating made from the inventive technique.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0037] **FIG. 1** illustrates grating formation technique **20**, involving optical fiber **24** spaced between two turning mirrors, **28** and **32**. As illustrated in **FIG. 1A**, optical fiber **24** comprises core **36**, cladding **40**, and buffer **44**, which are all manufactured by known processes. Generally, light is principally transmitted through core **36** and alternatively through cladding **40**. Buffer **44** extinguishes light modes. As shown in **FIG. 1B**, in contrast to existing techniques, grating formation technique **20** involves directing laser beam **48** on first locality **56** and then directing laser beam **52** on second locality **58** that is circumferentially displaced from first locality **58**. Laser beam **48** and laser beam **52** may comprise a laser from the same source. Here, first locality **56** is displaced angularly from second locality **58** by an angle θ, preferably 180 degrees. In this way, grating **62** maybe formed on core **36**, cladding **40**, and buffer **44**, as illustrated schematically in **FIG. 1C**.

[0038] As illustrated in **FIG. 3**, first locality **56** is also displaced axially at regular intervals, along the Y-axis, from second locality **58**. The process is repeated down the length of optical fiber **24** to form a grating. Laser beam **48**, **52** may comprise an infrared beam from a focused infrared source, a beam whose wavelength is outside the range transmitted by fused silica, such as a CO_2 laser. Laser beam **48**, **52** heats optical fiber **24**, tending to deform the fiber locally into microbends **62**, as shown in **FIG. 3**. Laser beam **48**, **52** may leave residual strains in the fiber with a local refractive index change.

[0039] Grating formation technique **20** may produce a grating composed of microscopic bends **62** as shown schematically in **FIG. 3**. Microbends **62** may be formed on optical fiber **24**, including core **36**, cladding **40**, and buffer **44** and may comprise a generally symmetric sinusoidal shape in optical fiber **24**. This technique has the potential to form gratings in fibers without germania-doped cores and without hydrogenation.

[0040] In previous work using a CO_2 laser, the fiber was illuminated on only one side, i.e. spots axially displaced but not radially displaced from each other. Substantial one-sided curling of the fiber occurred, resulting in less than an efficient grating. The resulting radiation pattern produced in the cladding by the grating is not identifiable as any well-defined cladding mode. Indeed, no images of cladding modes have been published in previous work. Grating formation technique **20** may take advantage of curling to form a symmetric grating as shown in **FIG. 3**.

[0041] **FIG. 2** illustrates computer-controlled scanning system **66** to direct laser beam **48** generally along an axis, say Z-axis, on optical fiber **24** on one side and then the other at regular spaced intervals along the fiber's length. Localities, for example first locality **56** and second locality **58**, on opposite sides of fiber **24**, are separated by one-half the bending pattern period as shown in **FIG. 3**.

[0042] Two scanning mirrors, first scanning mirror **70** and second scanning mirror **74**, are used to raster laser beam **48** across optical fiber **24** in conjunction with first turning mirror **28** having reflective face **29** and second turning mirror **32** having reflective face **33**. Reflective face **29** partially faces reflective face **33**. Both first turning mirror **28**

and second turning mirror **32** are positioned at roughly 45 degrees in relation to the Z-axis shown on either side of optical fiber **24**. Computer control **78** operatively controls scanning mirrors **70**, **74** through known mechanisms and controls to direct laser beam from laser **82** to trace scanning pattern **84**, a square pattern with rounded corners to facilitate a smooth change in direction of the scanning mirror, across reflective face **29** and reflective face **33** as seen in **FIG. 1**. Other scanning patterns may be employed as known.

[**0043**] First scanning mirror **70** has reflective face **71** while second scanning mirror **74** has reflective face **75**. Reflective face **71** partially faces reflective face **75**. As further shown in figure, laser beam **48** is activated at the appropriate time, in darkened portions **88** of sinusoidal pattern, to illuminate optical fiber **24** alternately on either side and preferably not on the top of the fiber.

[**0044**] **FIG. 2** shows also the placement of optical fiber **24** between turning mirrors, **28** and **32**, and below scanning mirrors, **70** and **74**. **FIG. 1** shows the actual path of laser beam **48** as viewed from above and the portions of the path in which laser **82** is activated. In darkened portions **88**, laser beam **48** is always turned on with the rapidly moving scanning mirror moving in the same direction, so that on one side of optical fiber **24** is scanned from top to bottom (along direction of arrow A), while on the other side optical fiber **24** is scanned from bottom to top (along direction of arrow B). This is important to produce a more symmetric pattern, since the fiber gets hotter as the beam moves across it.

[**0045**] It is also preferable that the laser beam not be tightly focused on the fiber because a tightly focused laser spot tends to ablate the fiber. The spot size on the locality of the fiber may be chosen to be roughly half the period of the desired bending pattern to give a more sinusoidal undulation of the fiber. The grating period A, as well as the resulting spectral resonance, is varied by simply altering the spacing between the scanning lines.

[**0046**] A grating composed of microscopic bends in a fiber, as seen in **FIG. 3**, can be expected to produce asymmetric cladding modes, that is, with an azimuthal number of 1. In a circular coordinate system, the amplitude of the cladding mode varies as cos θ or sin θ and the intensity pattern as $\cos^2$ θ or $\sin^2$ θ. (Other azimuthal numbers would result in an intensity pattern varying as $\cos^{2v}\theta$ or $\sin^{2v}\theta$.) The low order cladding modes can be approximated by what are known in the art as LP modes. The modes are characterized by increasing number of rings as the mode number increases.

[**0047**] **FIG. 4A and 4B** show a model intensity profile in the cross-section of an optical fiber for the LP14 and LP15 modes, respectively. Asymmetric mode gratings are difficult to produce with excimer-laser produced photorefractive gratings because the grating must be steeply blazed. That is, the grating lines are closely spaced and nearly parallel to the fiber core.

[**0048**] **FIGS. 5, 8** and **11** show experimentally produced images of cladding modes generated with gratings produced from grating formation technique **20**. **FIGS. 5 and 8** show images that appear to be good approximations for LP14 modes. **FIG. 11** shows an early attempt to generate an LP15 mode. In the latter case, a poor cleave of the fiber end resulted in a distorted image, but five rings are clearly recognizable.

[**0049**] Also shown with these figures are spectral analyses of white light transmitted through the gratings of the foregoing optical fibers (see **FIGS. 6, 9, 12**). Transmitted power is plotted versus wavelength. In each of these figures, resonances associated with the grating are clearly visible including one near a wavelength of 1.55 μm. The spectrum of the white light source, transmitted through each fiber before the grating was written, is shown for comparison. The cladding mode images were generated with a laser at a wavelength of 1.55 μm, which is near the resonance of interest. The LP14 gratings were 3 cm long. The LP15 grating was 2 cm long.

[**0050**] **FIG. 6** shows a spectral analysis of white light transmitted through the optical fiber of **FIG. 5**, which shows white light transmitted through core **90** and cladding **94**. **FIG. 7** is a spectral analysis of the white light through a similar fiber without a grating. As seen in **FIGS. 6 and 7**, the cladding mode appears to be an LP14 with lobes oriented horizontally.

[**0051**] **FIG. 9** shows a spectral analysis of white light transmitted through the optical fiber of **FIG. 8** with a grating. **FIG. 10** shows the spectral analysis of the white light through a similar fiber without a grating. The cladding mode appears to be close to an LP14 with the lobes oriented about 60 degrees to the horizontal.

[**0052**] **FIG. 12** shows a spectral analysis of white light transmitted through the optical fiber of **FIG. 11** with a grating. **FIG. 13** shows the spectral analysis of the white light through a similar fiber without a grating. Although **FIG. 11** shows a distorted image due to a bad fiber cleave, the cladding mode has five identifiable rings and is likely an LP15 mode.

[**0053**] The LP14 grating resonances near 1.55 μm in **FIGS. 5 and 8** are more than 90% deep. **FIG. 14** shows the transmission of a similarly written grating on a logarithmic scale. It shows that it is possible to get resonances more than 20 dB deep (99%). The gratings with the deepest resonances tend to generate cladding modes that are not as well formed as those shown above, but optimizing the process may improve this result. Variations in parameters such as spot size on the fiber, scan speed, and laser power may alter results.

[**0054**] Previous work with CO_2 laser produced gratings, in which the fiber was illuminated on only one side, resulted in gratings that produced by an index increase in the core, as with excimer-laser produced gratings. That process is enhanced by hydrogenation. This index increase results in a shift in the resonant wavelength towards longer wavelengths as the grating is formed, that is, as the average index of the core and the grating strength are increasing. This results primarily from a shift in the propagation constant of the core mode with increasing code index.

[**0055**] With gratings written with a CO_2 laser, using alternate side illumination as described above, the shift with increasing grating strength is towards shorter wavelengths. The mechanism of grating formation may be different than that of excimer-laser produced gratings. It may be the result of the formation of microscopic bends or microbends as seen in **FIG. 3**.

[**0056**] A Mach-Zehnder interferometer maybe formed using gratings written from the technique described above as

shown in **FIG. 15**. Such a device is useful as a sensor or a switch. Interferometer **98** comprises core **102** and cladding **106**. Light **108** propagates through core **102**. First grating **110** ejects light **108** into cladding **106**. Ejected light **112** returns to core **102** through second grating **114**, where ejected light **112** interferes with light **108** that remains behind in core **102**. This interference produces interference fringes.

[**0057**] To get high fringe visibility requires cladding modes to propagate without significant distortion. **FIGS. 16 and 17** shows the results of light transmitted through interferometer **98**. As seen in these figures, fringes are clearly evident, but, significantly, less than 100% of the light is returned to the core, at the center of the resonance. However, this grating is superior to other gratings produced using different techniques. Indeed, grating formation technique **20** permits the quick writing of long period Bragg gratings using a CO_2 laser. The grating period can be easily changed, since the process does not involve using masks. Hydrogenation of the fiber is not required. Consequently, no after baking is required. A lower cost, more efficient laser, is used. Asymmetric cladding modes are produced, which are difficult to achieve with excimer laser produced photorefractive gratings.

[**0058**] The aforementioned description is exemplary rather that limiting. Many modifications and variations of the present invention are possible in light of the above teachings. The preferred embodiments of this invention have been disclosed. However, one of ordinary skill in the art would recognize that certain modifications would come within the scope of this invention. Hence, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described. For this reason the following claims should be studied to determine the true scope and content of this invention.

What is claimed is:

1. A method of optical fiber manufacture comprising the steps of:

directing a first laser beam on a first locality of an optical fiber having a circumference;

directing a second laser beam on a second locality of the optical fiber circumferentially displaced from the first locality; and

forming a grating on the optical fiber.

2. The method of optical fiber manufacture of claim 1 wherein the first laser beam comprises the second laser beam.

3. The method of optical fiber manufacture of claim 1 wherein at least one of the laser beams heats the optical fiber to form the grating.

4. The method of optical fiber manufacture of claim 3 wherein the optical fiber is deformed about one of the localities.

5. The method of optical fiber manufacture of claim 1 wherein at least one of the laser beams arises from a carbon dioxide laser source.

6. The method of optical fiber manufacture of claim 1 wherein at least one of the laser beams arises from an infrared laser source.

7. The method of optical fiber manufacture of claim 1 wherein at least one of the laser beams traces at least in part a scanning pattern.

8. The method of optical fiber manufacture of claim 7 wherein at least one of the laser beams arises from a laser source activated at predetermined points of the scanning pattern.

9. The method of optical fiber manufacture of claim 1 wherein the optical fiber comprises a transmission layer and a cladding layer.

10. The method of optical fiber manufacture of claim 9 wherein at least two gratings are formed.

11. A system for optical fiber manufacture comprising:

a laser source;

a first turning mirror having a first reflective face for receiving a first laser beam from said laser source and for reflecting said first laser beam on an optical fiber having a circumference; and

a second turning mirror having a second reflective face for receiving a second laser beam from said laser source and for reflecting said second laser beam on said optical fiber.

12. The system for optical fiber manufacture of claim 11 wherein said first laser beam comprises said second laser beam.

13. The system of claim 11 wherein said first reflective face at least partially faces said second reflective face.

14. The system of claim 11 wherein each of said turning mirrors generally directs a laser along the same axis.

15. The system of claim 14 wherein at least one of said turning mirrors is angled about 45 degrees relative to said axis.

16. The system of claim 11 wherein said first turning mirror directs said first laser beam on a first locality of said optical fiber and said second turning mirror directs a second laser beam on a second locality circumferentially displaced from said first locality.

17. The system of claim 11 including at least one scanning mirror directing at least one of said laser beams on at least one of said turning mirrors.

18. The system of claim 17 wherein said at least one scanning mirror comprises a first scanning mirror having a first reflective face and a second scanning mirror having a second reflective face.

19. The system of claim 17 wherein a computer controls said at least one scanning mirror.

20. An optical fiber made by a process comprising the steps of:

directing a first laser beam on a first locality of an optical fiber having a circumference;

directing a second laser beam on a second locality of the optical fiber circumferentially displaced from the first locality; and

forming a grating on the optical fiber.

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