US 20080193085A1

(19) **United States**

(12) **Patent Application Publication**

**Singh et al.**

(10) **Pub. No.: US 2008/0193085 A1**

(43) **Pub. Date: Aug. 14, 2008**

# (54) MULTIMODE LONG PERIOD FIBER BRAGG GRATING MACHINED BY ULTRAFAST DIRECT WRITING

(75) Inventors: **Rajminder Singh**, Cambridge, MA (US); **Ming Li**, Cambridge, MA (US); **Jimmy Yi-Jie-Jia**, Cambridge, MA (US); **Xinbing Liu**, Cambridge, MA (US); **Tetsuo Ohara**, Cambridge, MA (US)

Correspondence Address:
**RATNERPRESTIA**
**P.O. BOX 980**
**VALLEY FORGE, PA 19482**

(73) Assignee: **Matsushita Electric Industrial Co., Ltd**, Osaka (JP)

(21) Appl. No.: **12/104,082**

(22) Filed: **Apr. 16, 2008**

**Related U.S. Application Data**

(62) Division of application No. 10/976,524, filed on Oct. 29, 2004, now Pat. No. 7,376,307.

**Publication Classification**

(51) **Int. Cl.**
***G02B 6/26*** (2006.01)

(52) **U.S. Cl.** .......................................................... **385/37**

## (57) ABSTRACT

An optical fiber with an integral photonic crystal structure. The optical fiber core is formed of a non-photosensitive material having an initial index of refraction. The optical fiber core includes a substantially cylindrical surface, a longitudinal core axis, a core radius, and a number of index-altered portions having an altered index of refraction different from the initial cladding index of refraction. The index-altered portions are arranged within the non-photosensitive material of the optical fiber core to form a photonic crystal structure. The photonic crystal structure may be a one dimensional, a two dimensional, or a three dimensional photonic crystal structure.

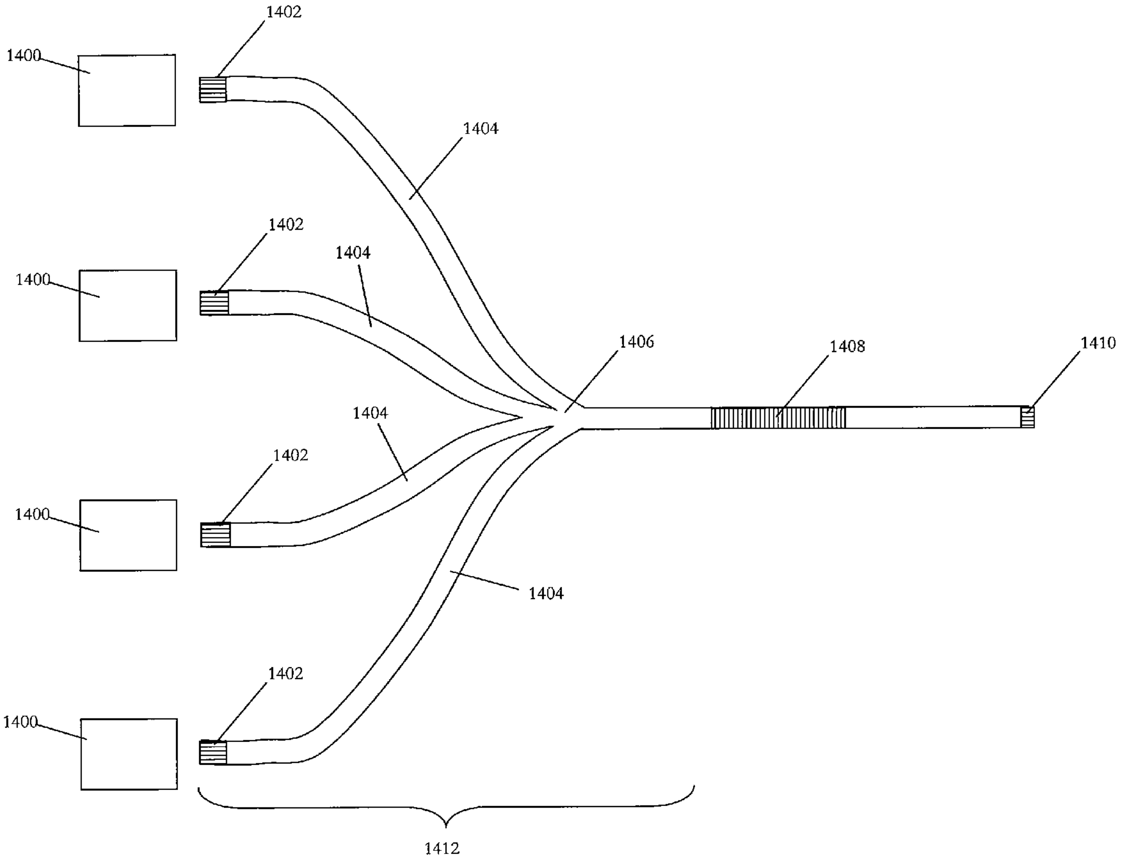


Figure 1A

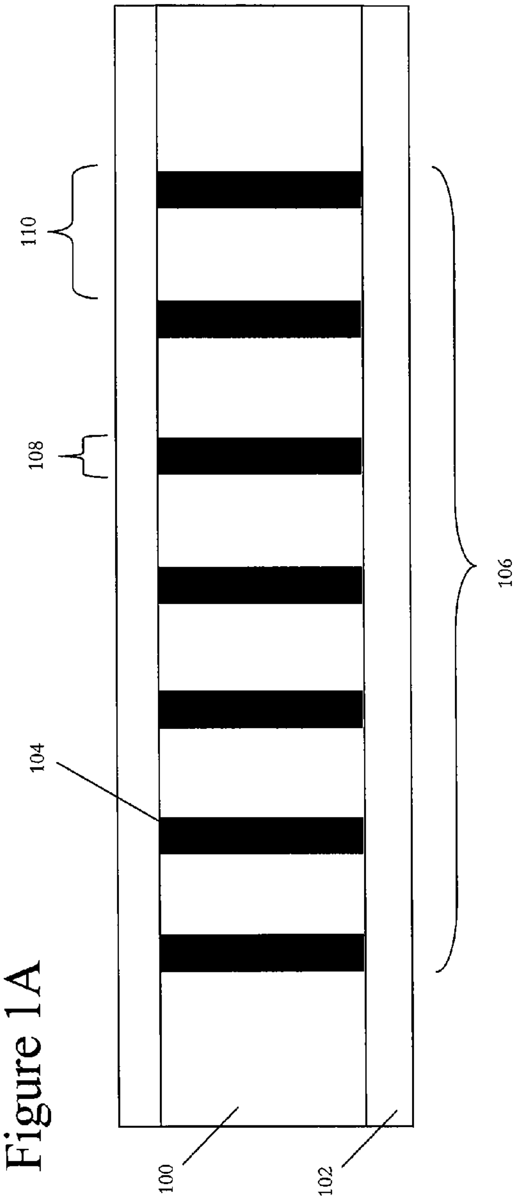
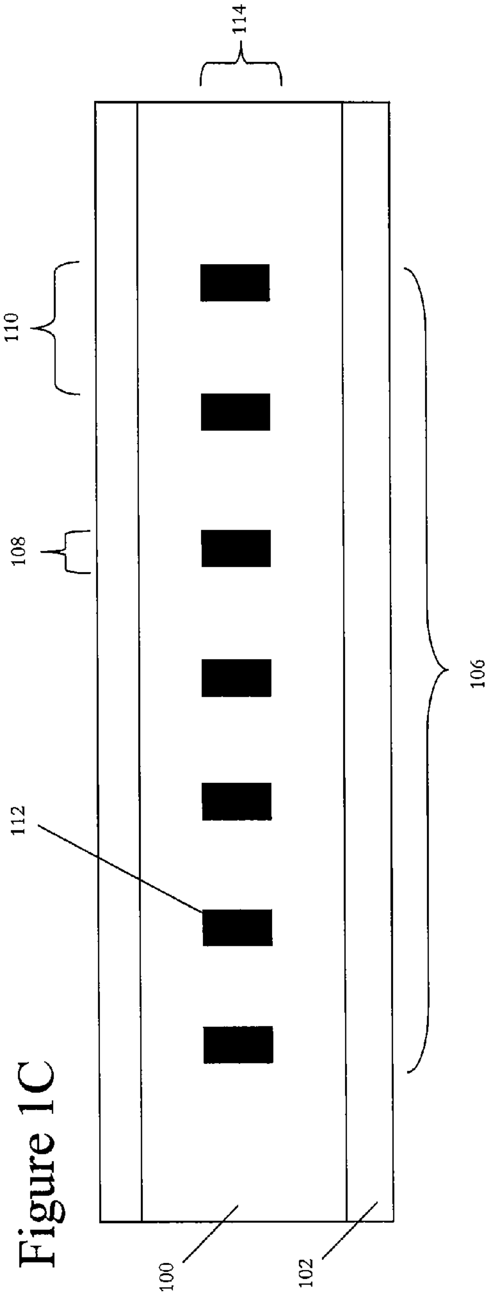


Figure 1C



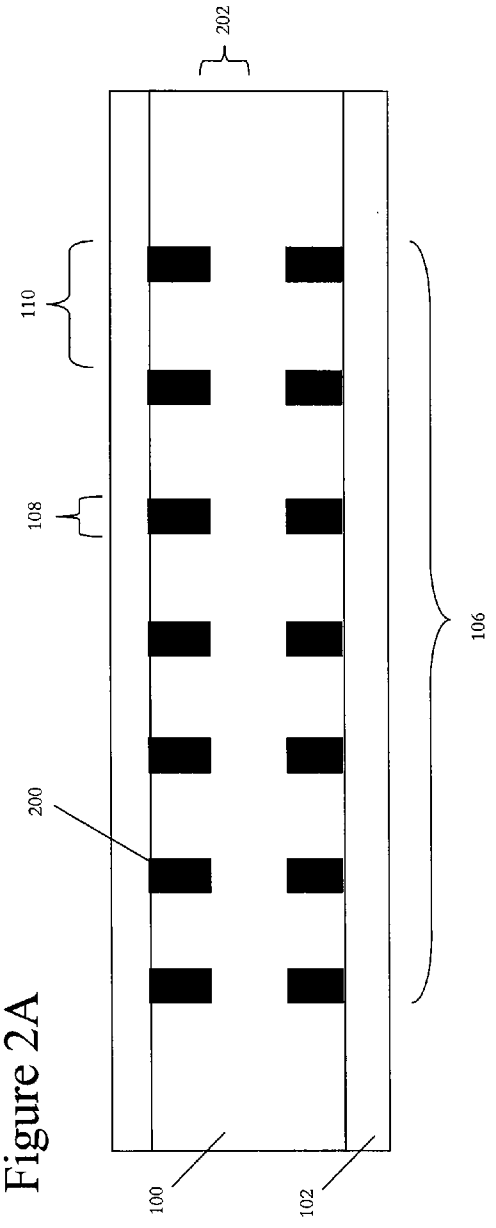


Figure 2A

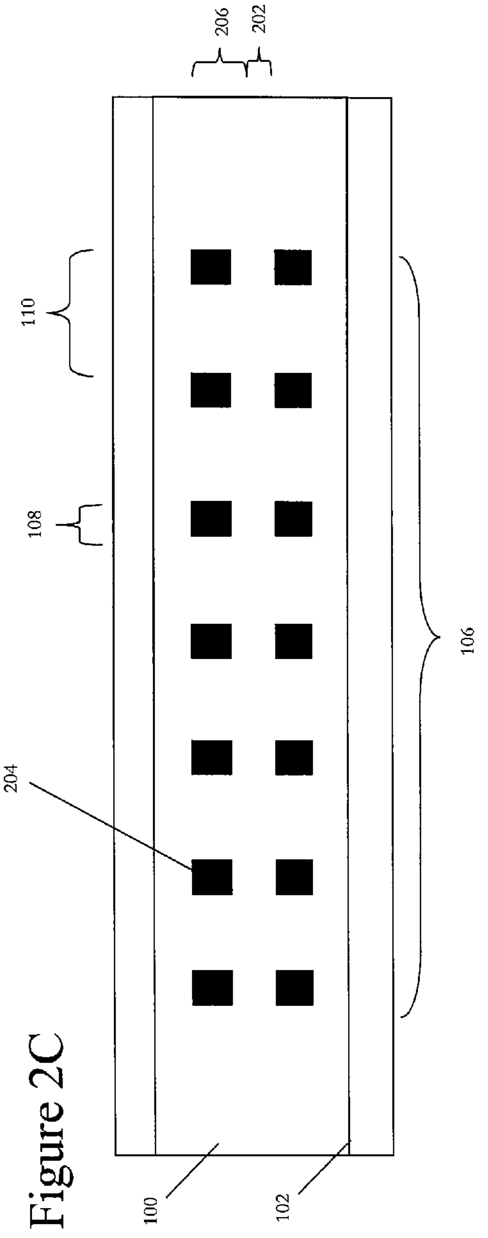


Figure 2C

Figure 1B

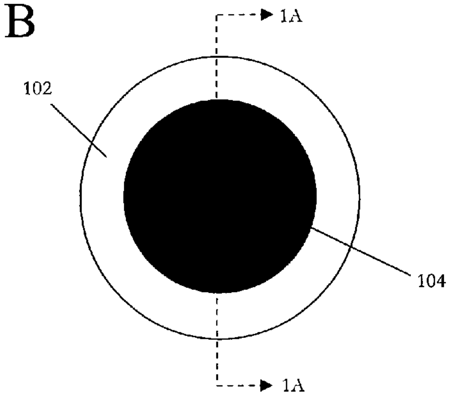


Figure 1D

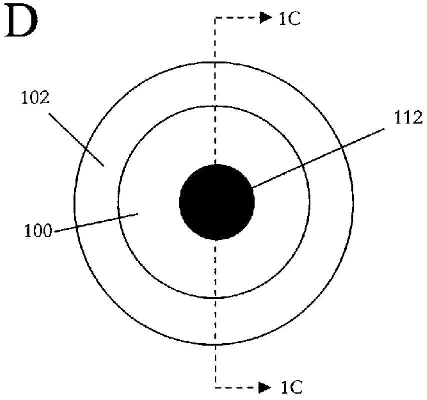


Figure 2B

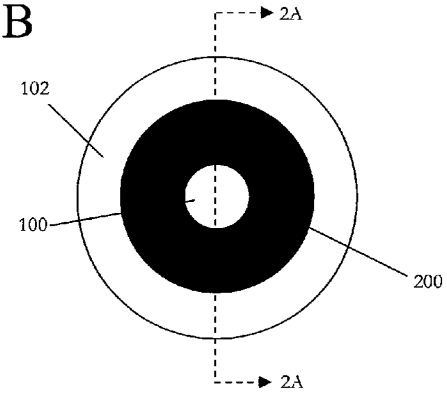
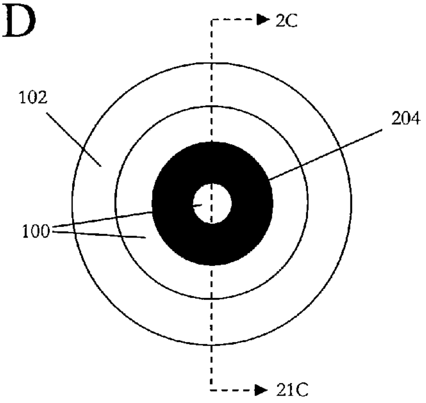


Figure 2D



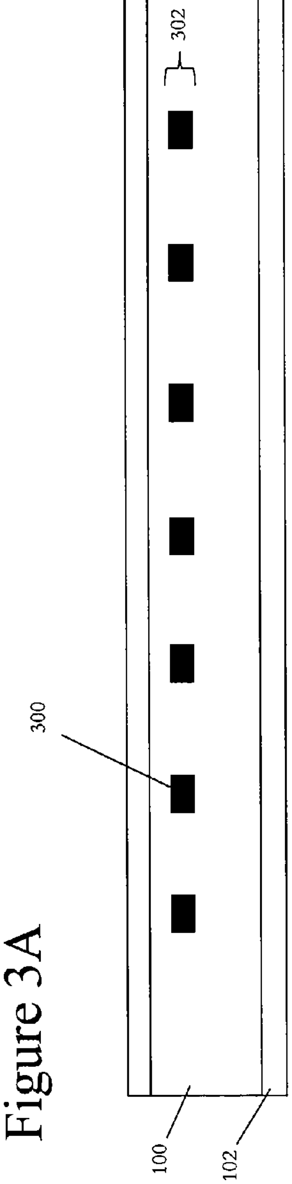


Figure 3A

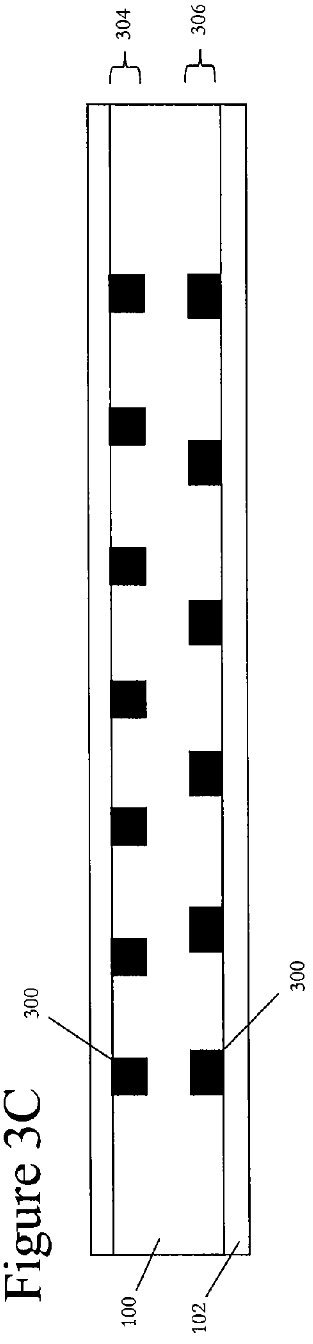


Figure 3C

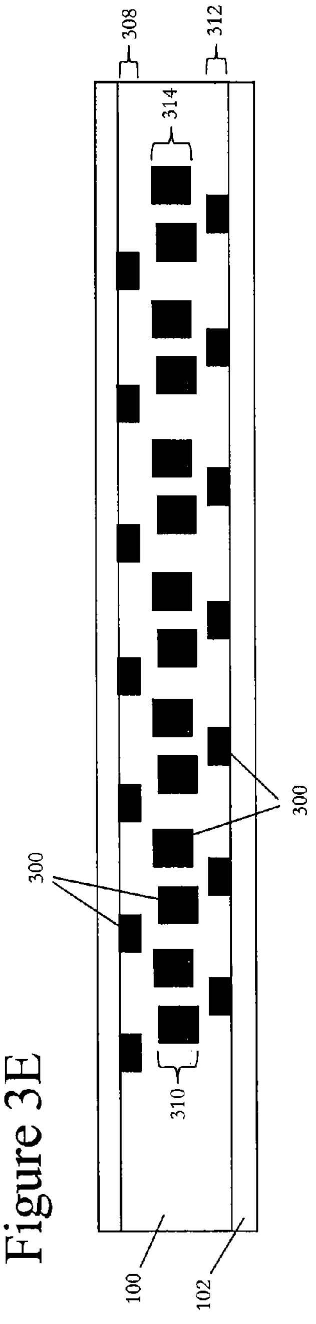


Figure 3E

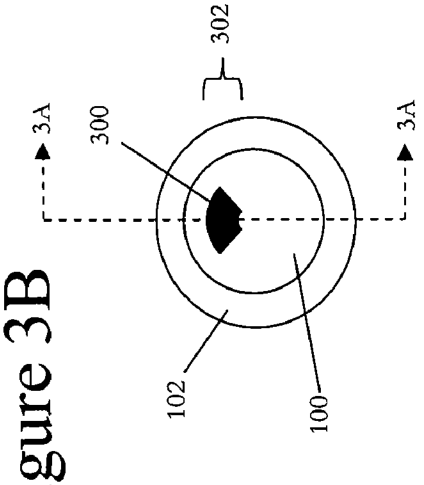


Figure 3B

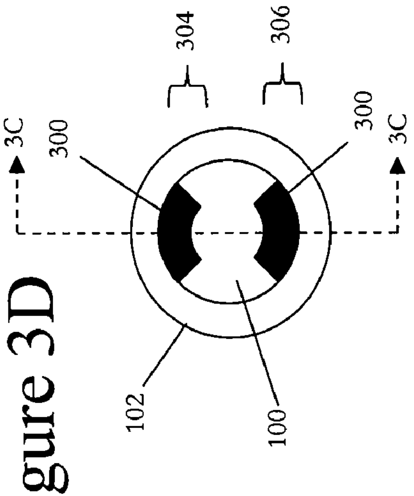


Figure 3D

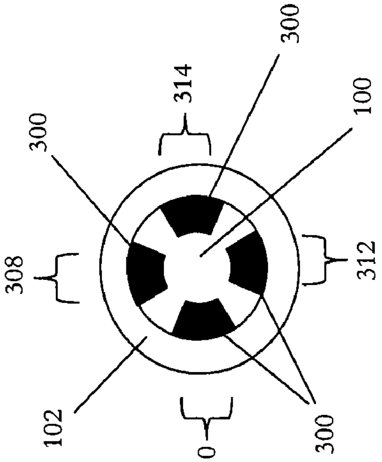


Figure 3F

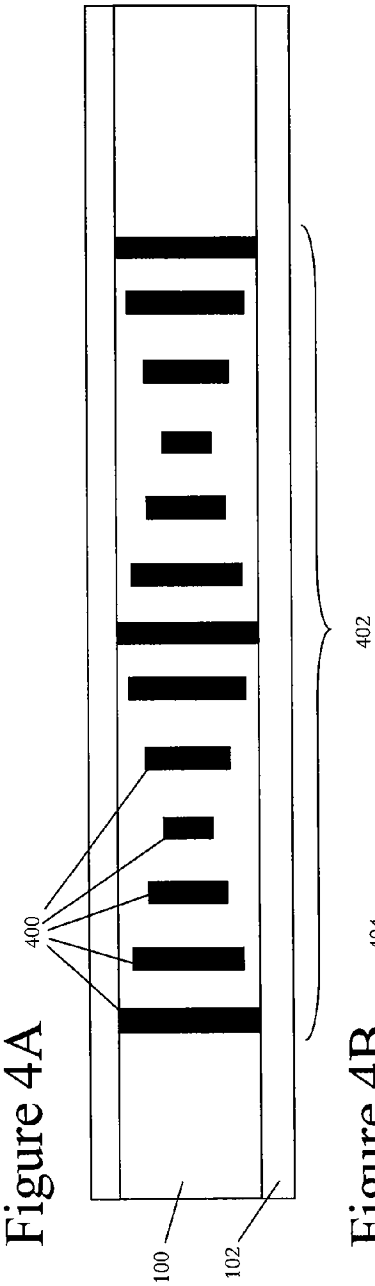


Figure 4A

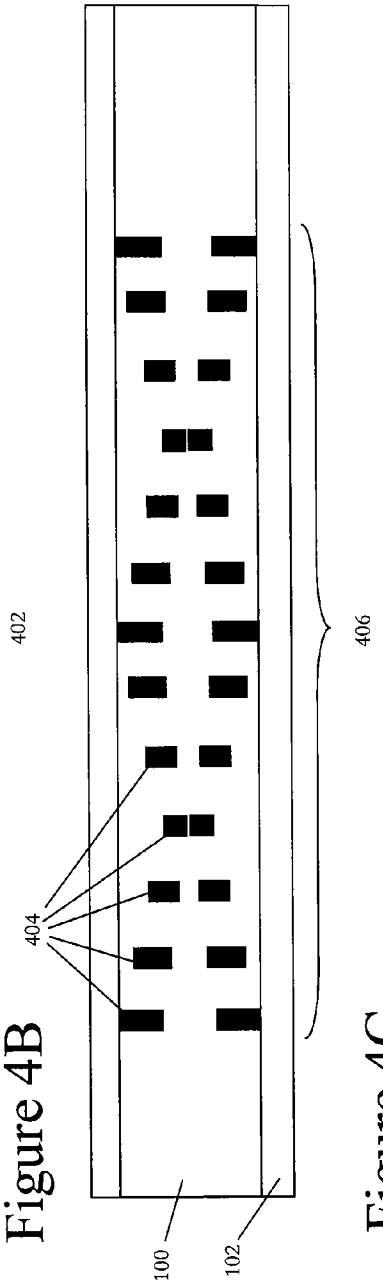


Figure 4B

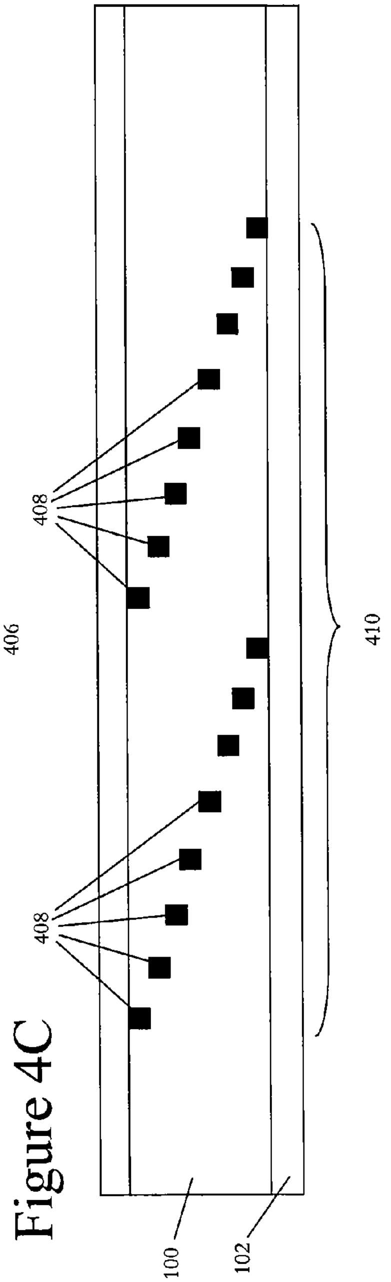


Figure 4C

Figure 5A

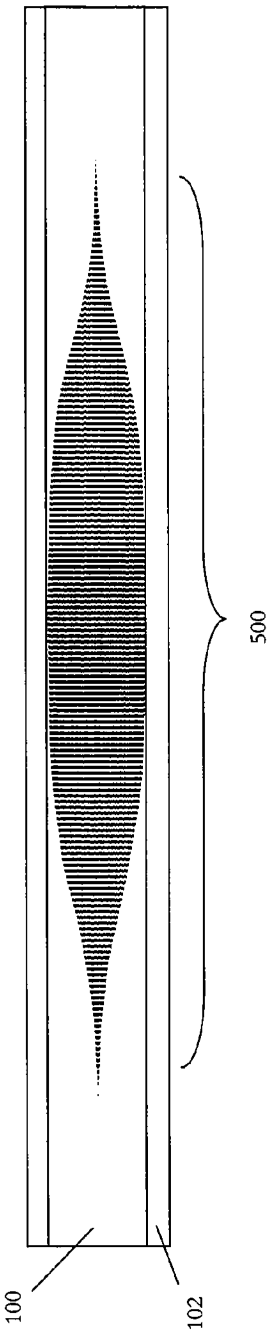
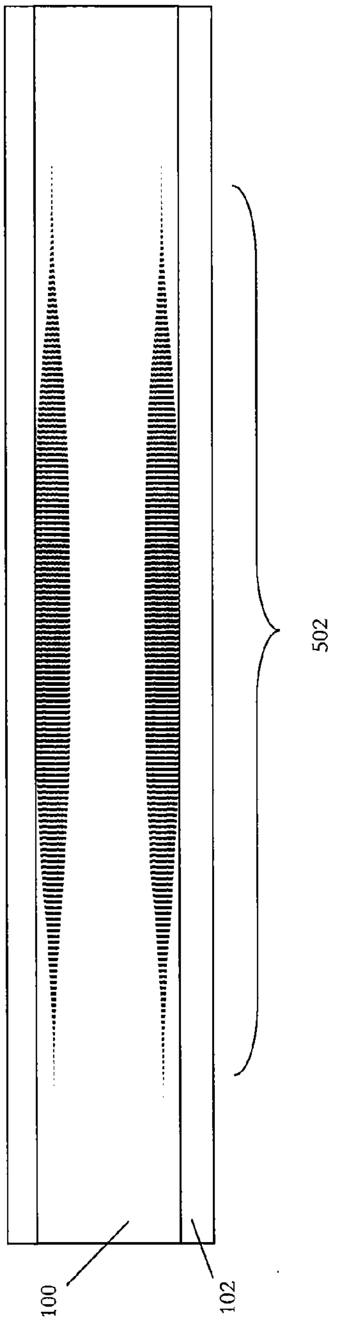


Figure 5B



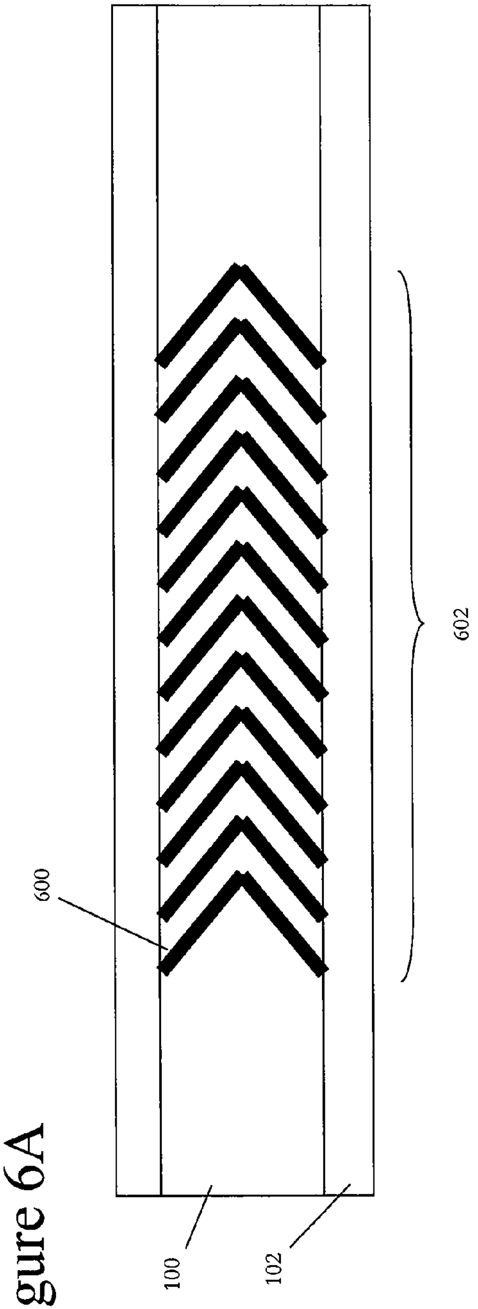


Figure 6A

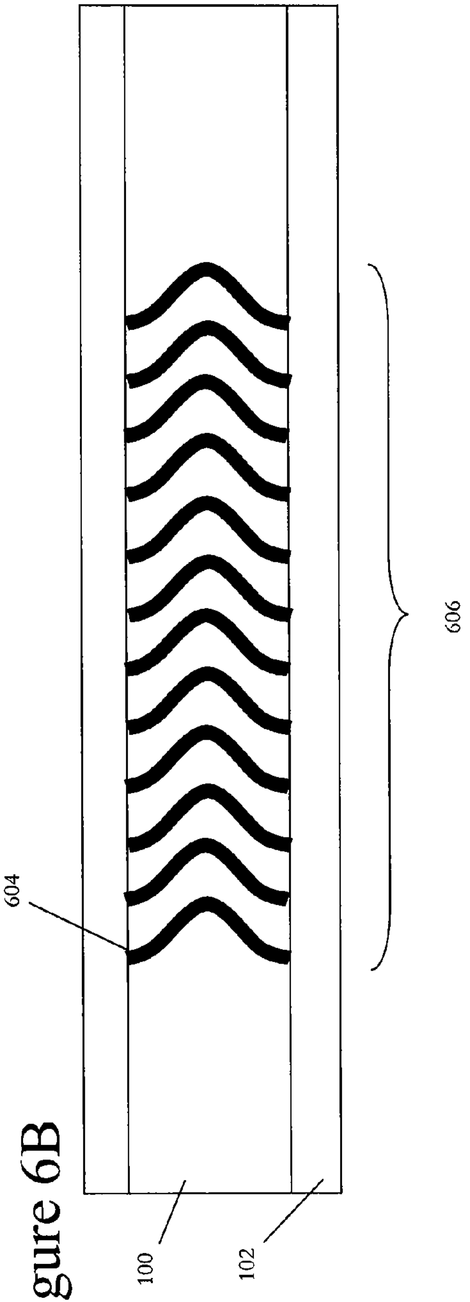


Figure 6B

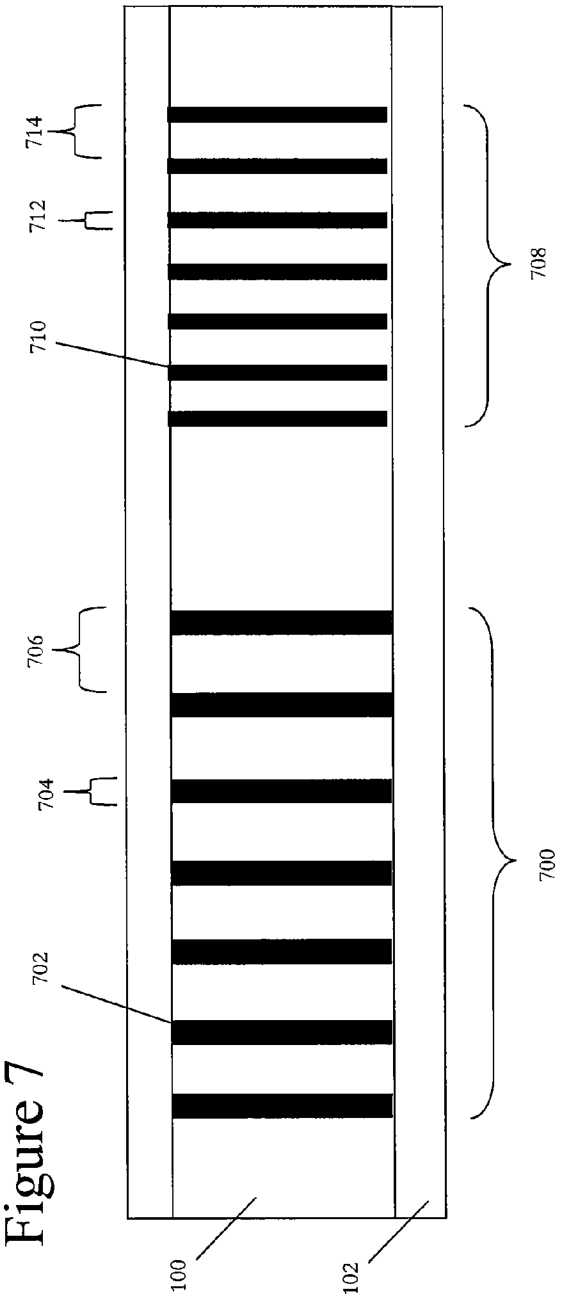


Figure 7

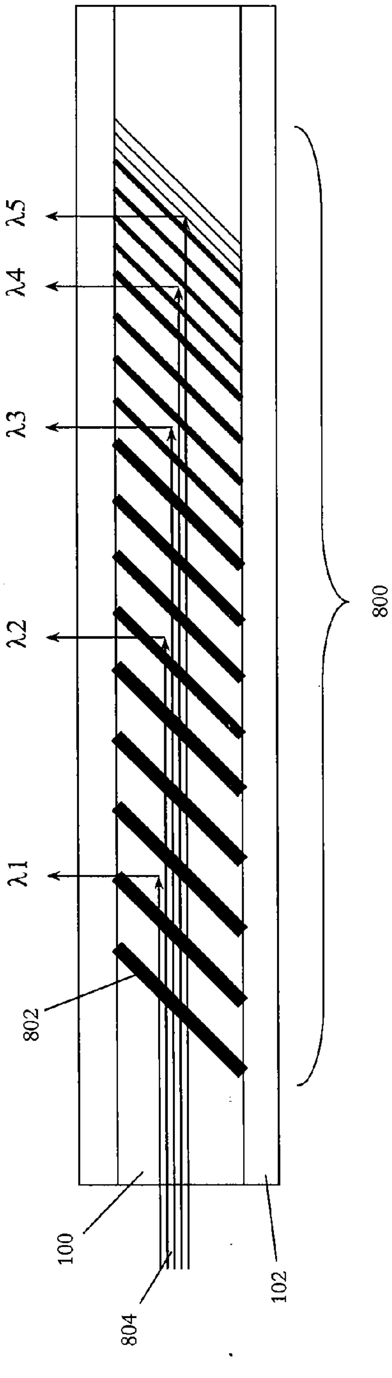


Figure 8

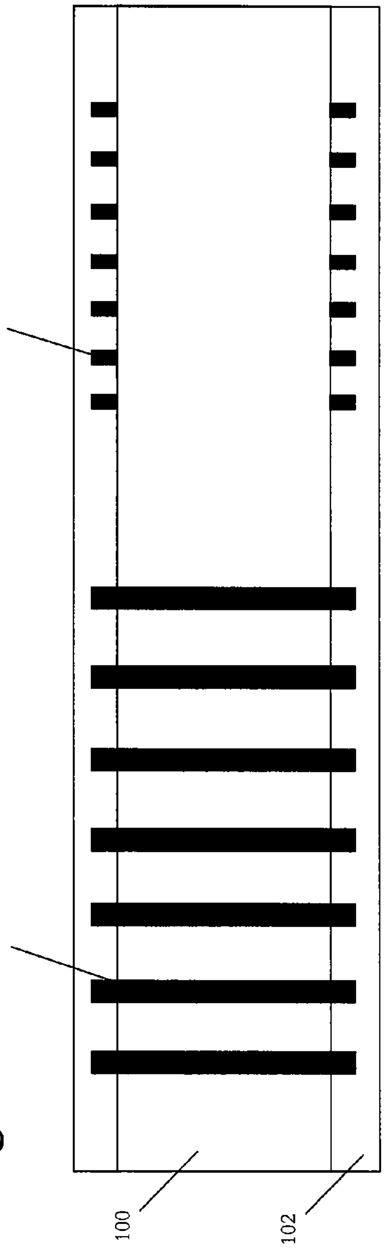


Figure 9

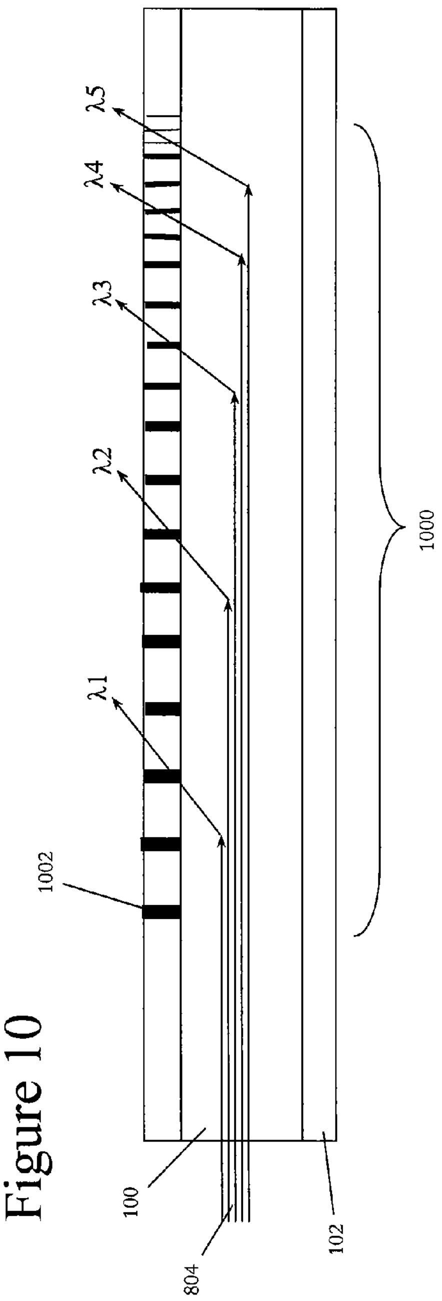


Figure 10

Figure 11A

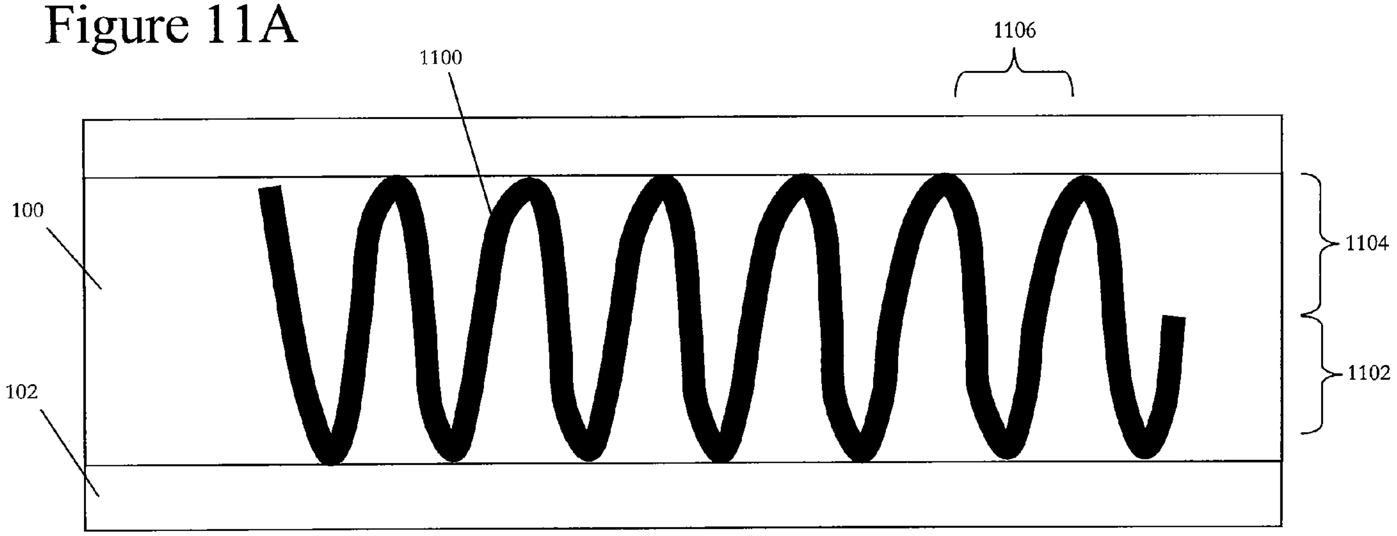


Figure 11B

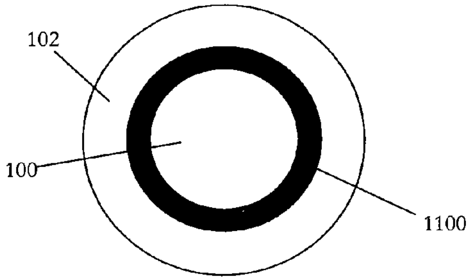


Figure 12A

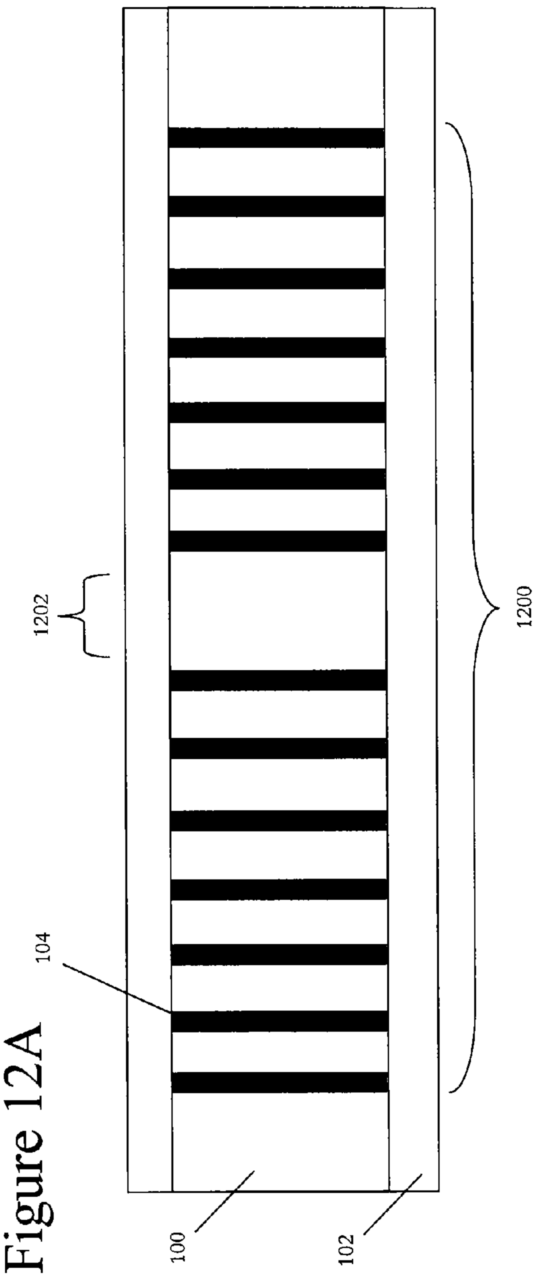


Figure 12B

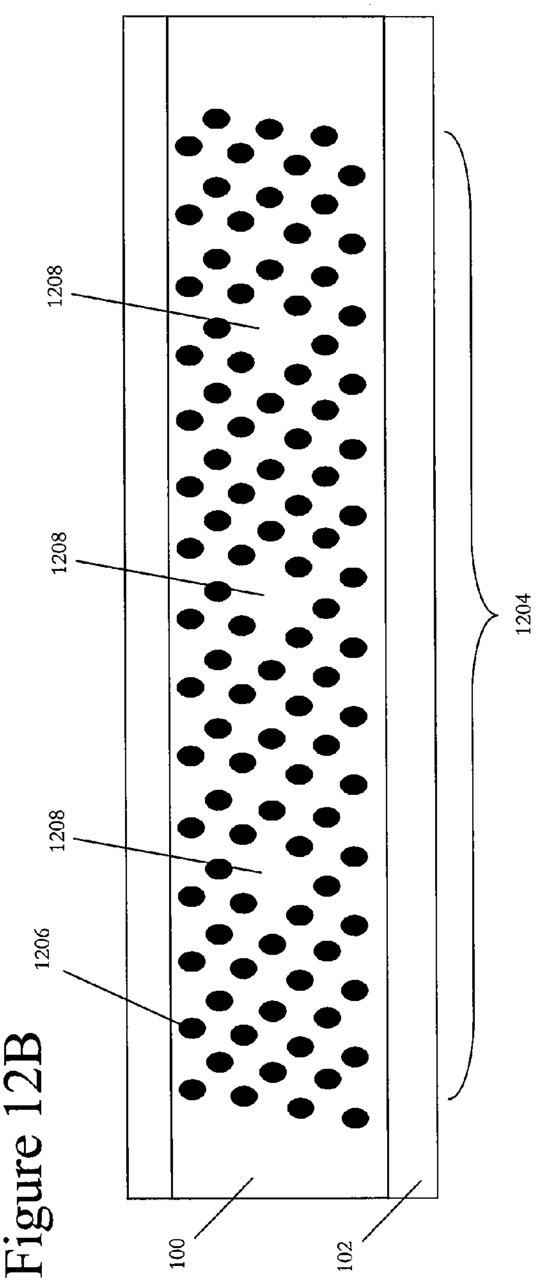


Figure 13A

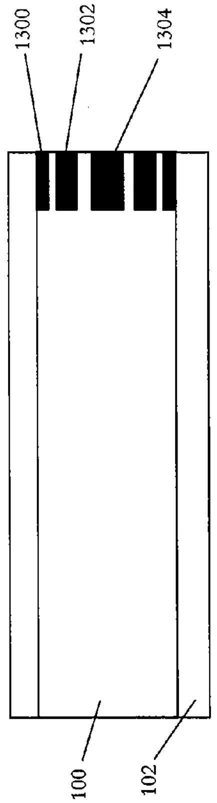


Figure 13B

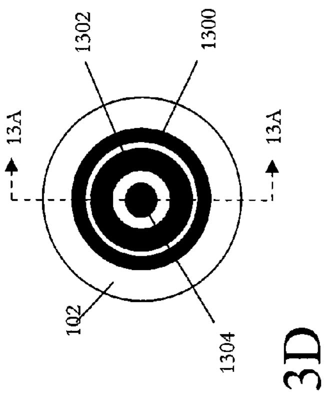


Figure 13C

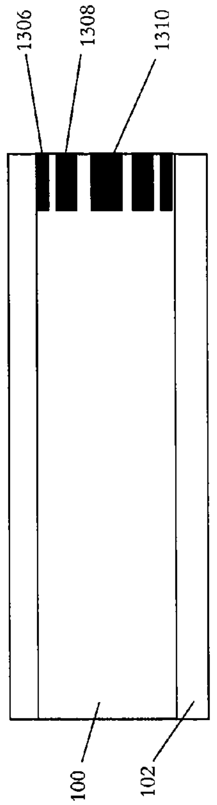


Figure 13D

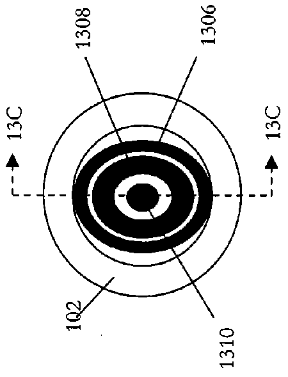


Figure 13E

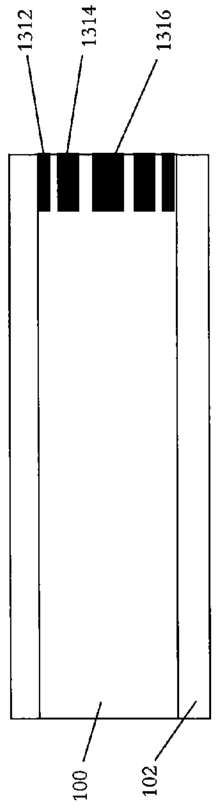


Figure 13F

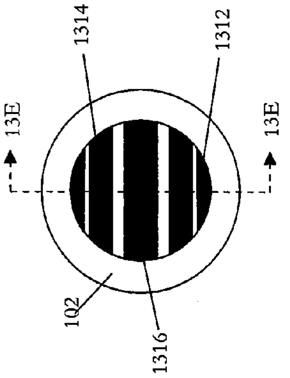
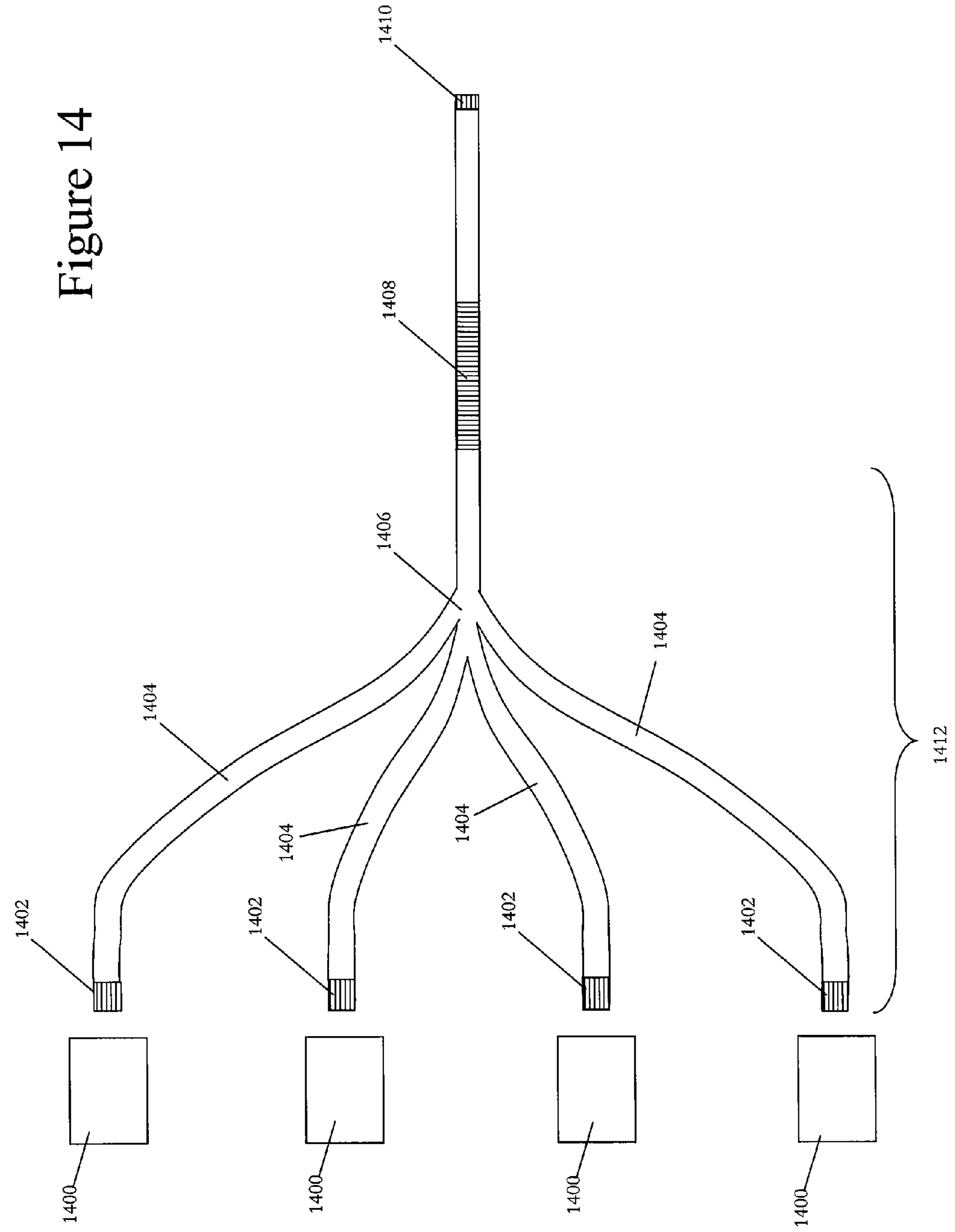


Figure 14


1410
1408
1406
1404
1404
1404
1404
1412
1402
1402
1402
1402
1400
1400
1400
1400

# MULTIMODE LONG PERIOD FIBER BRAGG GRATING MACHINED BY ULTRAFAST DIRECT WRITING

**[0001]** This application claims the benefit of U.S. patent application Ser. No. 10/976,524, filed Oct. 29, 2004 the contents of which are incorporated herein by reference.

## FIELD OF THE INVENTION

**[0002]** The present invention relates generally to structures formed in optical fibers by ultrafast laser direct writing. More particularly these structures may be long period Bragg gratings, photonic crystal structures, and/or diffractive optical elements formed within the cores of multimode optical fibers.

## BACKGROUND OF THE INVENTION

**[0003]** A Bragg grating is a periodic or aperiodic perturbation of the effective absorption coefficient and/or the effective refractive index of an optical waveguide. More simply put, a Bragg grating can reflect a predetermined narrow or broad range of wavelengths of light incident on the grating, while passing all other wavelengths of the light. Such structures provide a desirable means to manipulate light traveling in the optical waveguide.

**[0004]** A fiber Bragg grating (FBG) is a Bragg grating formed in an optical fiber. FBG's may be formed from photo-imprinted gratings in optical fibers. Photo-imprinting involves the irradiation of an optical waveguide with a laser beam of ultraviolet light to change the refractive index of the core of the waveguide. By irradiating the fiber with an intensive pattern that has a periodic (or aperiodic) distribution, a corresponding index perturbation is permanently induced in the core of the waveguide. The result is an index grating that is photo-imprinted in the optical waveguide. This method requires that the glass be photosensitive, an effect discovered in 1978 by Dr. Kenneth Hill of the Communications Research Centre Canada.

**[0005]** The FBG may become a very selective spatial reflector in the core of the fiber. Any change to the spatial period of the grating, or index of refraction, causes a proportional shift in the reflected and transmitted spectrum. FBG's have proven attractive in a wide variety of optical fiber applications, such as: narrowband and broadband tunable filters; optical fiber mode converters; wavelength selective filters, multiplexers, and add/drop Mach-Zehnder interferometers; dispersion compensation in long-distance telecommunication networks; gain equalization and improved pump efficiency in erbium-doped fiber amplifiers; spectrum analyzers; specialized narrowband lasers; and optical strain gauges in bridges, building structures, elevators, reactors, composites, mines and smart structures.

**[0006]** Since their market introduction in 1995, the use of optical FBG's in commercial products has grown exponentially, largely in the fields of telecommunications and stress sensors. The demand for more bandwidth in telecommunication networks has rapidly expanded the development of new optical components and devices (especially Wavelength Division Multiplexers). FBG's have contributed to the phenomenal growth of some of these products, and are recognized as a significant enabling technology for improving fiber optic communications.

**[0007]** Photo-imprinted FBG's may have low insertion losses and are compatible with existing optical fibers used in telecommunication networks, but as the optical power being transmitted in a photo-imprinted FBG increases, some undesirable effects may arise. One drawback of photo-imprinted FBG's is the requirement that the optical fiber have a photosensitive core. Photosensitive materials typically have absorption coefficients higher than are desirable for high power applications, as well as potentially undesirable nonlinearities that may become large at high optical powers. Photo-imprinted FBG's are also susceptible to degradation over time, particularly is the photosensitive material of the fiber core is heated or exposed to UV radiation.

**[0008]** In their article, FIBER BRAGG GRATINGS MADE WITH A PHASE MASK AND 800-NM FEMTOSECOND RADIATION (Optics Letters, Vol. 28, No. 12, pgs. 995-97 (2003)), Stephen J. Mihailov, et al. disclose a first order FBG formed in a single mode fiber using a femtosecond laser. The single mode fiber used was a standard SMG-28 telecommunications fiber with a non-photosensitive Ge doped core. The authors were able to form a first order Bragg grating structure in this core. This direct laser written single mode FBG was found to have superior thermal stability as compared to a photo-imprinted FBG.

**[0009]** Although the direct laser written single mode FBG of Stephen J. Mihailov, et al. may overcome many of the disadvantages of the photo-imprinted FBG's, the present invention includes a number of additional improvements that may provide superior performance, particularly at higher power levels, and increased versatility of the Bragg grating structures that may be formed. Additionally, the present invention includes additional diffractive structures that may be formed in optical fibers to control and monitor light propagating in the fiber.

## SUMMARY OF THE INVENTION

**[0010]** An exemplary embodiment of the present invention is a multimode long period fiber Bragg grating (LPFBG) for a predetermined wavelength band. The LPFBG formed of a non-photosensitive material having an initial index of refraction. The multimode optical fiber core includes a substantially cylindrical surface, a longitudinal core axis, a core radius, and a number of index-altered portions having an altered index of refraction different from the initial cladding index of refraction. Each of the index-altered multimode optical fiber core has a first transmission surface and second transmission surface that is substantially parallel to the first transmission surface. Also, these index-altered portions are arranged within the non-photosensitive material of the multimode optical fiber core such that the first transmission surface of one portion of the plurality of index-altered portions is substantially parallel to the second transmission surface of a neighboring portion to form a long period Bragg grating structure.

**[0011]** Another exemplary embodiment of the present invention is a fiber Bragg grating (FBG) for a predetermined wavelength band. The FBG includes: an optical fiber core having a substantially cylindrical surface, a longitudinal core axis, and a core radius; and a cladding layer formed of a non-photosensitive material on the substantially cylindrical surface of the optical fiber core. The optical fiber core has a core index of refraction and the non-photosensitive material of the cladding layer has an initial cladding index of refraction that is lower than the core index of refraction. The cladding layer includes an outer cladding radius and a number of index-altered portions having an altered index of refraction different from the initial cladding index of refraction. Each of the index-altered portions of the cladding layer extends into the cladding layer from the substantially cylindrical surface of the optical fiber core. Also, these index-altered portions are arranged within the non-photosensitive material of the cladding layer to form a Bragg grating structure.

**[0012]** A further exemplary embodiment of the present invention is an optical fiber with integral photonic crystal section. The optical fiber includes an optical fiber core formed of a non-photosensitive material having an initial index of refraction. The optical fiber core includes a substantially planar end surface, a substantially cylindrical surface, a longitudinal core axis, a core radius, and a coupling section adjacent to the substantially planar end surface with a number of index-altered portions. The index-altered portions have an altered index of refraction that is different from the initial index of refraction and are arranged within the coupling section of the optical fiber core to form a photonic crystal structure.

**[0013]** An additional exemplary embodiment of the present invention is an optical fiber with integral diffractive coupling optics. The optical fiber includes an optical fiber core formed of a non-photosensitive material having an initial index of refraction. The optical fiber core includes a substantially planar end surface, a substantially cylindrical surface, a longitudinal core axis, a core radius, and a coupling section adjacent to the substantially planar end surface with a number of index-altered portions. The index-altered portions have an altered index of refraction that is different from the initial index of refraction and are arranged within the coupling section of the optical fiber core to form the integral diffractive coupling optics.

**[0014]** Yet another exemplary embodiment of the present invention is a wavelength stabilized, high power, uncooled laser source. The wavelength stabilized, high power, uncooled laser source includes one or more high power laser (s) and a multimode optical fiber with a LPFBG that is optically coupled to the high power laser(s). The multimode optical fiber includes a multimode core formed of a non-photosensitive material having an initial index of refraction. This multimode core includes a substantially cylindrical surface, a longitudinal core axis, a core radius, and a number of index-altered portions. The index-altered portions have an altered index of refraction that is different from the initial index of refraction and are arranged within the non-photosensitive material of the multimode core to form a long period Bragg grating structure. This long period Bragg grating structure reflects a predetermined fraction of light in a predetermined wavelength band that is propagating in the multimode core back into the high power laser(s). This desirably locks the output wavelength band of the wavelength stabilized, high power, uncooled laser source to the predetermined wavelength band.

**[0015]** Yet a further exemplary embodiment of the present invention is a multimode optical fiber with a helical fiber Bragg grating. The optical fiber includes a multimode optical fiber core formed of a non-photosensitive material having an initial index of refraction. The optical fiber core has a substantially cylindrical surface, a longitudinal core axis, a core radius, and a helical index-altered portion having an altered index of refraction different from the initial index of refraction. This helical index-altered portion includes a longitudinal index-altered portion axis that is coaxial to the core axis of the core, an index-altered portion outer radius, an index-altered portion inner radius which is less than the index-altered portion outer radius, and a longitudinal pitch. Also, the helical index-altered portion is arranged within the non-photosensitive material of the multimode optical fiber core to form a long period Bragg grating structure.

**[0016]** Yet an additional exemplary embodiment of the present invention is an optical fiber with an alternative helical fiber Bragg grating. The optical fiber includes: an optical fiber core having a substantially cylindrical surface, a longitudinal core axis, and a core radius; and a cladding layer formed of a non-photosensitive material on the substantially cylindrical surface of the optical fiber core. The optical fiber core has a core index of refraction and the non-photosensitive material of the cladding layer has an initial cladding index of refraction that is lower than the core index of refraction. The cladding layer includes an outer cladding radius and a helical index-altered portion having an altered index of refraction different from the initial cladding index of refraction. This helical index-altered portion includes a longitudinal index-altered portion axis that is coaxial to the core axis of the core, an index-altered portion outer radius, an index-altered portion inner radius which equal to the core radius of the optical fiber core, and a longitudinal pitch. Also, the helical index-altered portion is arranged within the non-photosensitive material of the cladding layer to form a Bragg grating structure.

**[0017]** It is to be understood that both the foregoing general description and the following detailed description are exemplary, but are not restrictive, of the invention.

## BRIEF DESCRIPTION OF THE DRAWING

**[0018]** The invention is best understood from the following detailed description when read in connection with the accompanying drawing. It is emphasized that, according to common practice, the various features of the drawing are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawing are the following figures.

**[0019]** FIG. **1**A is a cut-away side plan drawing illustrating an exemplary multimode long period fiber Bragg grating (LPFBG) according to the present invention cut along line **1**A of FIG. **1**B.

**[0020]** FIG. **1**B is an end plan drawing illustrating the exemplary multimode LPFBG of FIG. **1**A.

**[0021]** FIG. **1**C is a cut-away side plan drawing illustrating an alternative exemplary multimode LPFBG according to the present invention cut along line **1**C of FIG. **1**D.

**[0022]** FIG. **1**D is an end plan drawing illustrating the alternative exemplary multimode LPFBG of FIG. **1**C.

**[0023]** FIG. **2**A is a cut-away side plan drawing illustrating another exemplary multimode LPFBG according to the present invention cut along line **2**A of FIG. **2**B.

**[0024]** FIG. **2**B is an end plan drawing illustrating the exemplary multimode LPFBG of FIG. **2**A.

**[0025]** FIG. **2**C is a cut-away side plan drawing illustrating a further exemplary multimode LPFBG according to the present invention cut along line **2**C of FIG. **2**D.

**[0026]** FIG. **2**D is an end plan drawing illustrating the exemplary multimode LPFBG of FIG. **2**C.

**[0027]** FIG. **3**A is a cut-away side plan drawing illustrating an additional exemplary multimode LPFBG according to the present invention cut along line **3**A of FIG. **3**B.

**[0028]** FIG. **3**B is an end plan drawing illustrating the exemplary multimode LPFBG of FIG. **3**A.

**[0029]** FIG. **3**C is a cut-away side plan drawing illustrating an exemplary multi-wavelength multimode LPFBG according to the present invention cut along line **3**C of FIG. **3**D.

**[0030]** FIG. **3**D is an end plan drawing illustrating the exemplary multi-wavelength multimode LPFBG of FIG. **3**C.

**[0031]** FIG. **3**E is a side plan drawing illustrating yet another exemplary multimode LPFBG according to the present invention.

**[0032]** FIG. **3**F is an end plan drawing illustrating the exemplary multimode LPFBG of FIG. **3**E.

**[0033]** FIGS. **4**A, **4**B, and **4**C are cut-away side plan drawings illustrating yet further exemplary multimode LPFBG's according to the present invention.

**[0034]** FIGS. **5**A and **5**B are cut-away side plan drawings illustrating exemplary apodized multimode LPFBG's according to the present invention.

**[0035]** FIGS. **6**A and **6**B are cut-away side plan drawings illustrating other exemplary multimode LPFBG's according to the present invention.

**[0036]** FIG. **7** is a cut-away side plan drawing illustrating an exemplary multi-wavelength multimode LPFBG according to the present invention.

**[0037]** FIG. **8** is a cut-away side plan drawing illustrating an exemplary multi-wavelength multimode LPFBG optical tap according to the present invention.

**[0038]** FIG. **9** is a cut-away side plan drawing of an exemplary multi-wavelength multimode fiber Bragg grating (FBG) according to the present invention illustrating two alternative Bragg grating structures.

**[0039]** FIG. **10** is a cut-away side plan drawing illustrating an exemplary multi-wavelength multimode FBG optical tap according to the present invention

**[0040]** FIG. **11**A is a side plan drawing illustrating an exemplary multimode helical FBG according to the present invention.

**[0041]** FIG. **11**B is an end plan drawing illustrating the exemplary multimode helical FBG of FIG. **11**A.

**[0042]** FIG. **12**A is a cut-away side plan drawing illustrating an exemplary multimode fiber with an integral one-dimensional photonic crystal according to the present invention.

**[0043]** FIG. **12**B is a cut-away side plan drawing illustrating an exemplary multimode fiber with an integral three-dimensional photonic crystal according to the present invention.

**[0044]** FIG. **13**A is a cut-away side plan drawing illustrating an exemplary multimode fiber with integral diffractive coupling optics according to the present invention cut along line **13**A of FIG. **13**B.

**[0045]** FIG. **13**B is an end plan drawing illustrating the exemplary multimode fiber with integral diffractive coupling optics of FIG. **13**A.

**[0046]** FIG. **13**C is a cut-away side plan drawing illustrating an alternative exemplary multimode fiber with integral diffractive coupling optics according to the present invention cut along line **13**C of FIG. **13**D.

**[0047]** FIG. **13**D is an end plan drawing illustrating the exemplary multimode fiber with integral diffractive coupling optics of FIG. **13**C.

**[0048]** FIG. **13**E is a cut-away side plan drawing illustrating another exemplary multimode fiber with integral diffractive coupling optics according to the present invention cut along line **13**E of FIG. **13**F.

**[0049]** FIG. **13**F is an end plan drawing illustrating the exemplary multimode fiber with integral diffractive coupling optics of FIG. **13**E.

**[0050]** FIG. **14** is a block schematic diagram illustrating an exemplary wavelength stabilized, high power, uncooled laser source according to the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

**[0051]** The extremely high intensities achievable in ultrafast laser machining of materials allow the material to be changed in a number of ways. The most common way that a material may be changed during ultrafast laser machining is for the material to be removed from the surface via ablation. Alternatively, various properties of the material may be changed such as the crystallinity and/or the refractive index. These material changes may occur on the surface of the material or, for substantially transparent materials, the ultrafast pulses may be focused within the material to cause these changes to take place inside of the bulk of the material. These internal changes may occur only above a specific fluence, so that the intervening material may be unaffected by the ultrafast laser pulses. Careful control of the pulse energy, pulse duration, and focus of the pulses may allow for the creation of precise regions with changed properties that have sharp boundaries.

**[0052]** Thus, the use of ultrafast lasers for direct writing of Bragg grating structures in optical fibers may have the advantage of providing sharp contrasts between index-altered portions of the fiber and surrounding unaltered portions of the fiber. Additionally, the use of an ultrafast laser machining system designed for direct writing of structures in optical fibers, such as the exemplary systems disclosed in US patent application ULTRAFAST LASER MACHINING SYSTEM FOR FORMING MULTIMODE LONG PERIOD FIBER BRAGG GRATING, filed concurrently with the present application, allows for the creation complex structures within optical fibers, particularly in multimode optical fibers.

**[0053]** Such an ultrafast laser machining system may be focused to a small region within an optical fiber. The fluence of each pulse of laser light of this exemplary ultrafast laser machining system may be controlled such that only this small region near the beam spot is machined by the pulse. The optical fiber may be moved in three dimensions so that the beam spot of the laser pulses is scanned within in the optical fiber, tracking through the portions of the non-photosensitive material of the optical fiber to be machined. The location of the machined region may be viewed through a stereo imaging system throughout the machining process to allow for more accurate machining of the diffractive structure. In this manner, a complex diffractive structure may be written three dimensionally within an optical fiber with a high level of precision.

**[0054]** Single mode optical fibers have relatively small fiber cores, typically less that 9 μm for telecommunication wavelengths. The creation of diffractive structures within the cores of single mode fiber may require highly accurate and precise control of the beam spot of an exemplary ultrafast laser machining system. Multimode fibers, however, may have significantly more space for forming structures within the core. This additional space may be desirable to lower the machining accuracy requirements of the laser machining system used to form these exemplary structures. Typical multimode fiber core radii range from about 10 μm to about 200 μm, with 25 μm and 31.25 μm being the most common multimode fiber core radii for telecommunication wavelengths. Also, the multiple transverse modes utilized by light propagating in multimode fibers may lead to a large number of potential structural forms for controlling and monitoring light in these fibers.

**[0055]** Thus, applying ultrafast laser machining techniques to multimode optical fibers may create a significant expansion of the potential uses of direct laser written structures in optical fibers over the first order, single mode FBG's disclosed in Stephen J. Mihailov, et al.'s article. Also, the use of highly accurate and precise ultrafast laser machining systems may allow for addition diffractive structures to be formed within single mode fibers.

**[0056]** Exemplary embodiments of the present invention include a number of diffractive structures formed within optical fibers such as: multimode long period FBG's (LPFBG's); multimode optical fibers with helical FBG structures; optical fibers with integral photonic crystal sections and/or diffractive coupling optics; and optical fibers with FBG's formed in the cladding layer. These modified optical fibers may be useful in a variety of situations, including: wavelength stabilized, high power, uncooled laser sources; dispersion compensation applications; optical filters; and in many optical telecommunications applications to name a few.

**[0057]** FIGS. **1**A and **1**B illustrate exemplary multimode LPFBG **106** designed for a predetermined wavelength band. This exemplary multimode LPFBG is formed by a number of cylindrical index-altered portions **104** with substantially planar transmission surfaces located in multimode optical fiber core **100**. The transmission surfaces of each index-altered portion are substantially parallel, as are the facing transmission surfaces of neighboring index-altered portions. These index-altered portions have an index of refraction which has been altered, from the initial index of refraction of the non-photosensitive material of multimode optical fiber core **100**, desirably by selective irradiation of portions of the non-photosensitive material by pulses of ultrafast laser light.

**[0058]** Multimode optical fiber core **100** includes a substantially cylindrical surface, a longitudinal core axis, and a core radius. Cladding layer **102** may be desirably formed on the substantially cylindrical surface of multimode optical fiber core **100**. Multimode optical fiber core **100** is desirably formed of a non-photosensitive material that has an index of refraction, which may be altered by high intensity, ultrafast laser irradiation. The fractional index change between multimode optical fiber core **100** and index-altered portions **104** is dependent on the selection of the non-photosensitive material. Many materials exhibit a fractional index change between $10^{-5}$ and $10^{-3}$, with approximately $10^{-4}$ being typical, although it is noted that arsenic trioxide may exhibit a fractional index change as high as $10^{-2}$. Crystalline or semi-crystalline materials may also exhibit higher fractional index changes. In these materials the crystallinity of the index-altered portions **104** may be altered by the ultrafast laser machining, leading to a relatively higher fractional index change compared to non-crystalline materials. The non-photosensitive material of multimode optical fiber core **100** may desirably include one or more of: fused silica; borosilicate; quartz; zirconium fluoride; silver halide; chalcogenide glass; optical plastic; clear fused quartz; aluminosilicate; polymethylmeth-acrylate; polystyrene; acrylic; and/or arsenic trioxide.

**[0059]** Cladding layer **102** has a cladding index of refraction that is desirably lower than the initial index of refraction of the non-photosensitive material of the multimode optical fiber core. The cladding layer may be formed of any material typically used for optical fiber cladding, although it may be desirable to use a non-photosensitive material similar to the non-photosensitive material of multimode optical fiber core **100**, particularly if it is desired to form diffractive structures in cladding layer **102**, as shown in FIG. **9**.

**[0060]** Index-altered portions **104** of the exemplary long period Bragg grating structure shown in FIGS. **1**A and **1**B have constant longitudinal thickness **108** and constant longitudinal pitch **110**. Longitudinal thickness **108** and longitudinal pitch **110** are selected such that the resulting long period Bragg grating structure is preferentially coupled to the predetermined wavelength band. The longitudinal pitch of a long period Bragg grating structure determines the peak wavelength reflected by the structure, and the longitudinal pitch of the index-altered portions affects the Q of the grating structure and, thus, the full width half maximum of the reflected wavelength band. Desirably, longitudinal pitch **110** is greater than the longest wavelength of the predetermined wavelength band in the material. Longitudinal thickness **108** is desirably less than half of longitudinal pitch **110**. The minimum longitudinal thickness is determined by the minimum feature size that may be formed by the ultrafast laser machining system used to form the LPFBG, typically greater than 10 nm.

**[0061]** In telecommunication wavelength bands, the index-altered portions **104** of an exemplary long period Bragg grating structure may desirably have a longitudinal thickness in the range of 1 μm to 20 μm, preferably in the range of 5 μm to 10 μm. Their longitudinal pitch may desirably be in the range of 1 μm to 500 μm, preferably in the range of 15 μm to 20 μm.

**[0062]** It is noted that the number of periods of the long period Bragg grating structure, the filling factor, and the fractional index change between multimode optical fiber core **100** and index-altered portions **104** determine the fraction of light reflected (or transmitted) in the predetermined wavelength band. The filling factor is a measure of the cross-sectional area of multimode fiber core **100** filled by index-altered portions **104**. For example, the exemplary LPFBG of FIGS. **1**A and **1**B has a higher filling factor than the exemplary LPFBG of FIGS. **1**C and **1**D. Therefore, if the number of periods and the fractional index change of these two exemplary LPFBG's are the same, the fraction of light reflected (or transmitted) in the predetermined wavelength band by the exemplary LPFBG of FIGS. **1**A and **1**B is greater (less) than that of the exemplary LPFBG of FIGS. **1**C and **1**D.

**[0063]** The desired fraction of light reflected back along multimode optical fiber core **100** by long period Bragg grating structure **106** may be up to 99.9%, though for a number of applications, such as laser wavelength locking, the reflected light fraction may be preferably in the range of 3% to 20%. Although the exemplary multimode LPFBG of FIG. **1**A has only seven index-altered portions **104**, forming six periods of the long period Bragg grating structure, it is noted that long period Bragg grating structures of 100 or more periods may be more typical. The number of periods in an LPFBG is only limited by the length of the optical fiber. For some applications, long period Bragg grating structures with thousands, or even tens of thousands, of periods may be desirable.

**[0064]** FIGS. **1**C and **1**D illustrate another exemplary multimode LPFBG **106** formed by a number of cylindrical index-altered portions **112** with substantially planar transmission surfaces located in multimode optical fiber core **100**. The difference between the exemplary multimode LPFBG of FIGS. **1**C and **1**D and that of FIGS. **1**A and **1**B is index-altered portion radius **114** of cylindrical index-altered portions **112** which is less than core radius of multimode optical fiber core **100**. In the exemplary embodiment of FIGS. **1**C and **1**D, index-altered portion radius **114** provides a parameter that may selected to preferentially couple the exemplary long period Bragg grating structure to a desired subset of transverse modes of multimode optical fiber core **100**.

**[0065]** As shown in FIG. **4**A, the index-altered portion radius of cylindrical index-altered portions **400** may be varied between different index-altered portions in the longitudinal direction of multimode optical fiber core **100** to preferentially couple exemplary long period Bragg grating structure **402** to a more specific subset of transverse modes of multimode optical fiber core **100**.

**[0066]** FIGS. **2**A and **2**B illustrate alternative exemplary multimode LPFBG **106** designed for a predetermined wavelength band. This exemplary multimode LPFBG is formed by a number of annular index-altered portions **200** with substantially planar transmission surfaces located in multimode optical fiber core **100**. Each of these annular index-altered portions includes: a longitudinal index-altered portion axis coaxial to the longitudinal core axis of multimode optical fiber core **100**; an index-altered portion outer radius, which, in the exemplary embodiment of FIGS. **2**A and **2**B, is equal to the core radius; and index-altered portion inner radius **202**. Index-altered portion inner radius **202** may be selected to preferentially couple long period Bragg grating structure **106** to a desired subset of transverse modes of multimode optical fiber core **100**.

**[0067]** FIGS. **2**C and **2**D illustrate another exemplary multimode LPFBG **106** formed by a number of annular index-altered portions **204** located in multimode optical fiber core **100**. The exemplary multimode LPFBG of FIGS. **2**C and **2**D differs from the exemplary multimode LPFBG of FIGS. **2**A and **2**B in that index-altered portion outer radius **206** of annular index-altered portions **204**, as well as index-altered portion inner radius **202**, may be varied to preferentially couple long period Bragg grating structure **106** to a desired subset of transverse modes of multimode optical fiber core **100**. Also, as shown in FIG. **4**B, one or both of the index-altered portion outer radius and the index-altered portion inner radius **202** of annular index-altered portions **404** may be varied between different index-altered portions in the longitudinal direction of multimode optical fiber core **100** to preferentially couple exemplary long period Bragg grating structure **406** to a more specific subset of transverse modes of multimode optical fiber core **100**.

**[0068]** FIGS. **3**A and **3**B illustrate further exemplary multimode LPFBG **302** designed for a predetermined wavelength band. This exemplary multimode LPFBG is formed by a number of index-altered portions **300** located in multimode optical fiber core **100**. Each of these index-altered portions is in the shape of an annular arcuate segment that includes: an index-altered portion outer radius, which is less than the core radius of multimode optical fiber core **100** in the exemplary embodiment of FIGS. **3**A and **3**B; an index-altered portion inner radius; and an angular extent around the longitudinal core axis of multimode optical fiber core **100**.

**[0069]** Although not necessary, it may be desirable for the angular extent of annular arcuate segments to be equal to approximately 360°/n, where n is an integer greater than 1. Such annular arcuate segments may be desirable to preferentially couple to subsets of transverse modes of multimode optical fiber core **100** described by Laguerre polynomials.

**[0070]** In the exemplary embodiment of FIGS. **3**A and **3**B, annular arcuate segments **300** are longitudinally arranged in a single line parallel to the longitudinal core axis of multimode optical fiber core **100**.

**[0071]** It is noted that annular arcuate segments **300** may alternatively be aligned in a helix about the longitudinal core axis, as shown in FIGS. **3**E and **3**F. In this alternative exemplary embodiment, the annular arcuate segments are desirably longitudinally arranged in the helix with neighboring annular arcuate segments having an angular separation of approximately 360°/n, where n is an integer greater than 1 representing the number of annular arcuate segments in one period of the helix. FIGS. **3**E and **3**F have four annular arcuate segments per period of the helix and, thus, annular arcuate segments **300** of this exemplary multimode LPFBG may be aligned into four subsets of annular arcuate segments **308**, **310**, **312**, and **314**.

**[0072]** FIGS. **3**C and **3**D illustrate an exemplary multi-wavelength multimode LPFBG formed by two subsets of annular arcuate segments **300** located in multimode optical fiber core **100**. The annular arcuate segments of subset **304** have a first longitudinal thickness and a first longitudinal pitch within multimode optical fiber core **100**. The first longitudinal thickness and pitch of these annular arcuate segments are selected such that the portion of the long period Bragg grating structure formed by subset **304** is preferentially coupled to a first subband of wavelengths of the predetermined wavelength band. The annular arcuate segments of subset **306** have a second longitudinal thickness and a second longitudinal pitch within multimode optical fiber core **100**, which are selected such that the portion of the long period Bragg grating structure formed by subset **306** is preferentially coupled to a second subband of wavelengths of the predetermined wavelength band. This second subband of the predetermined wavelength band is desirably different than the first subband, allowing the exemplary multimode LPFBG of FIGS. **3**C and **3**D to couple two subbands of the predetermined wavelength band. The selection of two subsets of annular arcuate segments in FIGS. **3**C and **3**D is merely illustrative and is not meant to be limiting.

**[0073]** It is noted that any or all of the index-altered portion outer radius, the index-altered portion inner radius, or the angular extent of the annular arcuate segments may be selected to preferentially couple long period Bragg grating structure **302** to a desired subset of transverse modes of multimode optical fiber core **100**. Also, as shown in FIG. **4**C, the index-altered portion outer radius, index-altered portion inner radius, and/or angular extent of annular arcuate segments **408** may be varied between different index-altered portions in the longitudinal direction of multimode optical fiber core **100** to preferentially couple exemplary long period Bragg grating structure **410** to a more specific subset of transverse modes of multimode optical fiber core **100**.

**[0074]** FIGS. **5**A and **5**B illustrate exemplary apodized multimode LPFBG's. FIG. **5**A illustrates exemplary apodized multimode LPFBG which includes a plurality of index-altered portions having cylindrical shape. The index-altered portion radii of these cylindrical index-altered portions are varied between different index-altered portions in the longitudinal direction of multimode optical fiber core **100** such that long period Bragg grating structure **500** is an apodized long period Bragg grating structure. FIG. **5**B illustrates similar apodized multimode LPFBG structure **502** formed of either annular or annular arcuate index-altered portions. In this exemplary structure at least one of the index-altered portion outer radii or the index-altered portion inner radii (or the angular extent for angular arcuate segments) of the plurality of index-altered portions are varied between different index-altered portions in the longitudinal direction of multimode optical fiber core **100**, desirably forming exemplary apodized long period Bragg grating structure **502**.

**[0075]** FIGS. **6**A and **6**B illustrate two additional exemplary multimode LPFBG's. In FIG. **6**A, exemplary long period Bragg grating structure **602** is formed by index-altered portions **600** which have transmission surfaces that are conic surfaces, and in FIG. **6**B, exemplary long period Bragg grating structure **606** is formed by index-altered portions **604** which have curved transmission surfaces. The curved transmission surfaces of index-altered portions **604** may be aspherical curved, as shown in FIG. **6**B, or they may be spherical curved surfaces. Exemplary long period Bragg grating structures, such as those of FIGS. **6**A and **6**B, in which the index-altered portions have non-planar transmission surfaces may be desirable for converting transverse modes of light propagating in multimode fiber core **100**. Such control of the relative power in various transverse modes of the propagating field may desirably improve coupling efficiencies in spliced fiber couplers or other fiber coupling means. Although the exemplary index-altered portions with non-planar transmission surfaces are shown in FIGS. **6**A and **6**B extending across the width of multimode fiber core **100**, it is contemplated that non-planar transmission surface index-altered portions may also be formed with index-altered portion radii less than the fiber core radius and/or may be formed as annuli or annular arcuate segments.

**[0076]** FIGS. **7**, **8**, **9**, and **10** illustrate several exemplary multi-wavelength multimode LPFBG's. FIG. **7** illustrates an exemplary multi-wavelength multimode LPFBG in which the index-altered portions are separated longitudinally into two subsets, index-altered portions **702**, which form first portion **700** of the long period Bragg grating structure, and index-altered portions **710**, which form second portion **708**. Index-altered portions **702** in first portion **700** have a first longitudinal thickness **704** and a first longitudinal pitch **706** within multimode optical fiber core **100** which are selected such that first portion **700** of the long period Bragg grating structure is preferentially coupled to a first subband of wavelengths of the predetermined wavelength band. Index-altered portions **710** in second portion **708** have a second longitudinal thickness **712** and a second longitudinal pitch **714** within multimode optical fiber core **100** which are selected such that second portion **708** of the long period Bragg grating structure is preferentially coupled to a second subband of wavelengths of the predetermined wavelength band, which is different than the first subband of wavelengths. Thus, the resulting long period Bragg grating structure may desirably act as two separate multimode LPFBG's.

**[0077]** It is noted that although FIG. **7** includes only two portions the long period Bragg grating structure coupled to different subband of wavelengths of the predetermined wavelength band, this choice is merely for simplified illustration and is not limiting. Also, although exemplary subsets of index-altered portions **702** and **710** are shown in FIGS. **6**A and **6**B as cylindrical portions extending across the width of multimode fiber core **100**, it is contemplated that cylindrical index-altered portions with index-altered portion radii less than the fiber core radius and/or annular or annular arcuate index-altered portions may be used to form exemplary multi-wavelength multimode LPFBG's. The use of these alternative index-altered portions may allow for the various portions of the resulting long period Bragg grating structure to be preferentially coupled to different subsets of transverse modes of the multimode fiber core as well as different subbands of wavelengths. Further the use of annular arcuate index-altered portions in multi-wavelength multimode LPFBG's may allow for a reduction of the longitudinal length of the long period Bragg grating structure, as shown in FIG. **3**C.

**[0078]** FIG. **8** illustrates another exemplary multi-wavelength multimode LPFBG **800** which may function as a wavelength dispersive optical tap. In this exemplary embodiment, oblique cylindrical of index-altered portions **802** have tilted planar transmission surfaces. These are planar transmission surfaces are tilted within multimode optical fiber core **100** such that the longitudinal core axis of the optical fiber core has a predetermined angle of incidence with the surfaces. These tilted planar transmission surfaces allow multi-wavelength multimode LPFBG **800** to reflect a predetermined fraction of propagating light **804** through cladding **102** so that the intensity of propagating light **804** may be monitored. It is noted that other long period Bragg grating structures, particularly those with asymmetric index-altered portions and/or index-altered cladding portions (such as those shown in FIGS. **9** and **10**), may predictably scatter light through cladding layer **102** and, thus, may also be used to form optical taps in multimode optical fibers.

**[0079]** Additionally, the longitudinal thickness and the longitudinal pitch of oblique cylindrical of index-altered portions **802** is continuously varied along the longitudinal direction of the multimode optical fiber core to form a chirped long period Bragg grating structure. This allows the various wavelengths of propagating light **804** ($\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, and $\lambda_5$) to be reflected through cladding **102** at different points by multi-wavelength multimode LPFBG **800**. In this way the spectral composition of propagating light **804** may be monitored.

**[0080]** FIG. **9** illustrates an additional exemplary multi-wavelength multimode LPFBG with the two portions of the long period Bragg grating structure formed by different types of index-altered portions. Cylindrical index-altered portions **900** extend from multimode fiber core **100** into cladding layer **102**, while annular index-altered cladding portions **902** are formed entirely within cladding layer **102**. Index-altered portions **900** and index-altered cladding portions **902** may extend part way through cladding layer **102**, as shown in FIG. **9**, or all of the way to the outer cladding surface. The extension of index-altered portions into the cladding layer may increase the coupling of some higher order transverse modes to the long period Bragg grating structure, while the formation of index-altered cladding portions entirely within cladding layer **102** may reduce perturbations to lower order transverse modes caused by the long period Bragg grating structure. In single mode fibers, the formation of index-altered cladding portions within the cladding layer may allow coupling of evanescent portions of the propagating light either to reflect a fraction of the light in the predetermined wavelength band back along the optical fiber core or to scatter a fraction of the light in the predetermined wavelength band out of the fiber to form an optical tap. As with index-altered portions formed entirely within a multimode fiber core, various parameters of index-altered portions formed partially or entirely within the cladding layer of an optical fiber may be varied between different index-altered portions in the longitudinal direction of the optical fiber such that the resulting Bragg grating structure is an apodized Bragg grating structure.

**[0081]** It is noted that, because index-altered cladding portions preferentially couple to higher order transverse modes and evanescent portions of the propagating light, the predetermined fraction of light reflected back along the optical fiber core by FBG's formed entirely in the cladding layer may be less than by FBG's formed in the fiber core, but fractions in the range of 0.01% to 10% may be reflected by such Bragg grating structures.

**[0082]** It is contemplated that both annular and annular arcuate index-altered portions may be extended into the cladding layer, as well. Also, index-altered portions formed entirely in multimode fiber core **100** may be combined with index-altered portions extended into cladding layer **102** and/or index-altered cladding portions are formed entirely within cladding layer **102**.

**[0083]** FIG. **10** illustrates another exemplary chirped multimode LPFBG **1000**, formed by index-altered annular arcuate segments **1002** formed entirely within cladding layer **102**. As illustrated by the exemplary scattering of propagating light **804** through cladding layer **102**, exemplary chirped multimode LPFBG **1000** may be used as a wavelength dispersive optical tap to monitor the spectral composition of propagating light **804**.

**[0084]** FIGS. **11**A and **11**B illustrate a multimode optical fiber with a helical FBG formed in multimode optical fiber core **100**. Helical index-altered portion **1100** includes: a longitudinal index-altered portion axis which is coaxial to the longitudinal core axis of multimode core **100**; index-altered portion outer radius **1104**; index-altered portion inner radius **1102**; and longitudinal pitch **1106**. The index-altered portion outer radius **1104** and index-altered portion inner radius **1102** may varied to preferentially couple the helical FBG to a subset of the transverse modes of multimode optical fiber core **100**. Longitudinal pitch **1106** may be altered to selectively couple the helical FBG to a predetermined wavelength band. The longitudinal thickness of helical index-altered portion **1100** may also be varied to further define the predetermined wavelength band coupled to the helical FBG. It is noted that helical index-altered portion **1100** may be formed entirely within multimode optical fiber core **100**, as shown in FIGS. **11**A and **11**B, or may be extended into cladding layer **102**. Additionally, a helical FBG may include a helical index-altered cladding portion formed entirely within the cladding layer of either a single mode or multimode optical fiber.

**[0085]** It is contemplated that an exemplary multimode long period fiber Bragg grating may also be formed in which the index-altered portions are arranged in a non-periodic pattern. The resulting long period Bragg grating structure may desirably be formed to have a predetermined transmission spectrum in the predetermined wavelength band for light propagating in the multimode optical fiber core, thus allowing the spectrum of light transmitted through the fiber to be altered to a desired spectral shape.

**[0086]** Another exemplary embodiment of the present invention is an optical fiber with an integral photonic crystal section. These integral photonic crystal structures may be formed using an ultrafast laser machining system alter portions of an optical fiber core in a manner similar to the methods used to form the Bragg grating structures described above. The inclusion of photonic crystal sections within the core of single mode and multimode optical fibers may allow even greater control of the light propagated along these fibers. Additionally, these integral photonic crystal structures may be useful for improving coupling efficiencies between optical fibers and other optical components, including other optical fibers. Further, highly selective wavelength specific couplers may be created using these integral photonic crystal structures. Such couplers may be particularly desirable for use in dense wavelength division multiplexing optical communication systems.

**[0087]** FIGS. **12**A and **12**B illustrate such exemplary structures formed in the cores of multimode optical fibers. Multimode optical fibers have been selected for the examples for illustrative purposes. In FIG. **12**A, multimode optical fiber core **100** includes cylindrical index-altered portions **104**, which have an altered index of refraction different from the initial index of refraction of the non-photosensitive material of multimode optical fiber core **100**. Cylindrical index-altered portions **104** are arranged within multimode optical fiber core **100** to form one dimensional photonic crystal structure **1200**. One dimensional photonic crystal structure **1200** appears similar to long period Bragg grating structure **106** of FIG. **1**A, except for the inclusion of defect **1202**. (It is also noted that the longitudinal thickness and longitudinal pitch of cylindrical index-altered portions **104** in one dimensional photonic crystal structure **1200** are desirably significantly less than those in long period Bragg grating structure **106**, although this is not clear in the scaled Figures.)

**[0088]** FIG. **12**B illustrates an exemplary multimode optical fiber with three dimensional photonic crystal structure **1204** formed within multimode fiber core **100**. Exemplary three dimensional photonic crystal structure **1204** is formed of large number of regularly spaced spherical index-altered portions **1206**. The lattice formed by spherical index-altered portions **1206** is interrupted by defects **1208**, which occur at regular intervals.

**[0089]** It is noted that, although both defect **1202** in one dimensional photonic crystal structure **1200** and defects **1208** in three dimensional photonic crystal structure **1204** result from a missing index-altered portion, other types of defects may be formed in these exemplary photonic crystal structures, such as an additional index-altered portion, an index-altered portion having a different shape, or change in the period structure of the photonic crystal. It is also noted that exemplary two dimensional photonic crystal structures may be formed in multimode optical fiber cores according to this exemplary embodiment of the present invention.

**[0090]** A further exemplary embodiment of the present invention is an optical fiber with integral diffractive coupling optics. These integral diffractive coupling optics structures may also be formed using an ultrafast laser machining system to alter portions of the optical fiber core near the input and output surfaces of the fiber. The inclusion of integral diffractive coupling optics within the core of optical fibers may greatly improve coupling efficiencies between optical fibers and other optical components. They may also allow for space saving solutions in fiber optics systems by reducing, or eliminating, the need for free space coupling optics within these systems. As in the exemplary embodiments of FIGS. **12**A and **12**B, multimode optical fibers have been selected in FIGS. **13**A-F for illustrative purposes.

**[0091]** FIGS. **13**A and **13**B illustrate one exemplary multimode optical fiber with integral diffractive coupling optics. In this example, multimode optical fiber core **100** includes a coupling section adjacent to the substantially planar end surface. This coupling section is formed by concentric annular index-altered portions **1300** and **1302** and cylindrical index-altered portion **1304** which have an altered index of refraction different from the initial index of refraction of the non-photosensitive material of multimode fiber core **100**. Concentric annular index-altered portions **1300** and **1302** and cylindrical index-altered portion **1304** are arranged to form a circular two dimensional diffractive optical lens. This lens may be spherical or aspherical depending on the radii of the index-altered portions. It is noted that the focal length of this exemplary circular two dimensional diffractive optical lens is wavelength dependent. Thus, such lenses may not be desirable for broad bandwidth applications.

**[0092]** FIGS. **13**C and **13**D illustrate another exemplary multimode optical fiber with an integral elliptical two dimensional diffractive optical lens. In this example, the coupling section is formed by concentric elliptical annular index-altered portions **1306** and **1308** and elliptical index-altered portion **1310** which have an altered index of refraction different from the initial index of refraction of the non-photosensitive material of multimode fiber core **100**. This lens may be designed to have a small ellipticity of a large ellipticity depending on the desired ratio of the cone angles in the X and Y directions.

**[0093]** FIGS. **13**E and **13**F illustrate a further exemplary multimode optical fiber with an integral one dimensional diffractive optical lens. This exemplary integral coupling optics section may function as a cylindrical lens. Such lens may be particularly desirable for coupling light from semiconductor lasers into the multimode optical fiber. The coupling section of FIGS. **13**E and **13**F is formed in multimode fiber core **100** by parallel linear index-altered portions **1312**, **1314**, and **1316**. Parallel linear index-altered portions **1312**, **1314**, and **1316** are sized and arranged such that the integral diffractive coupling optics formed in the coupling section of multimode optical fiber core **100** is a one dimensional diffractive optical lens. It is noted that parallel linear index-altered portions **1312**, **1314**, and **1316** may also form a transmission grating, if equally sized and spaced, allowing various wavelengths of light propagating in the multimode optical fiber to by diffracted in separate directions.

**[0094]** The various multimode optical fiber structures described above may be used to design a number of exemplary optical devices, one example of which is a wavelength stabilized, high power, uncooled laser source. Operating a laser in an uncooled mode may be desirable to reduce power consumption used to cool the laser, as well as to reduce the feedback circuitry used to control the laser's temperature. Unfortunately, such uncooled operation may cause difficulties with maintaining a constant output wavelength of the laser. This is due to the thermal dependence of the output wavelength of the laser. These difficulties may be magnified in high power applications where large quantities of heat are generated by the laser and the temperature may vary over a large range.

**[0095]** One method of overcoming these difficulties is the use of an external optical cavity to lock the output wavelength of the laser by coupling light resonant with the external cavity back into the laser. Optically coupling the laser and the external cavity may necessitate additional optics, leading to added complexity and increased power loss. Such external cavities also are desirably thermally isolated or are designed to have low temperature dependence.

**[0096]** FIG. **14** illustrates an exemplary wavelength stabilized, high power, uncooled laser source, which uses exemplary multimode LPFBG **1408** to lock the laser output wavelength. An exemplary type of high power laser for which the exemplary embodiment of FIG. **14** may be particularly desirable is a continuous wave semiconductor laser. This exemplary wavelength stabilized, high power, uncooled laser source includes four high power lasers **1400**. These four lasers are optically coupled into four coupling multimode optical fibers **1404**, which are optically coupled to a single multimode optical fiber at fiber coupler **1406**. Fiber coupler **1406** is desirably a low loss fiber coupler, such as a star coupler or a spliced fiber coupler, as shown in FIG. **14**. It is noted that multimode optical fibers are desirable in this application for their high power handling capabilities.

**[0097]** The single multimode optical fiber desirably includes a low loss multimode core formed of a non-photosensitive material in which a plurality of index-altered portions, having an altered index of refraction, have been formed using an ultrafast laser machining system. The index-altered portions are arranged within the non-photosensitive material of the multimode core to form long period Bragg grating structure **1408**. This long period Bragg grating structure is desirably adapted to reflect a predetermined fraction of light in the desired wavelength band back along the optical fibers and into high power lasers **1400**, thereby locking the output wavelength band of the wavelength stabilized, high power, uncooled laser source to the desired wavelength band. Long period Bragg grating structure **1408** may desirably reflect up to 99.9%, preferably 3% to 20%, of the light provided by the laser in the desired wavelength band back into the laser.

**[0098]** It is noted that it may be desirable for high power lasers **1400** and the multimode optical fibers of the exemplary system to be substantially thermally uncoupled, or, alternatively, for the non-photosensitive material of the multimode core of the single multimode optical fiber to have a coefficient of thermal expansion low enough to prevent an undesirable shift in the desired wavelength band reflected by long period Bragg grating structure **1408** during operation. Another approach to reduce heating of long period Bragg grating structure **1408** during operation of high power lasers **1400** is to provide thermal buffering section **1412** between the laser coupling surface and long period Bragg grating section **1408**.

**[0099]** This exemplary external cavity wavelength locker includes only a small number of relatively simple optical components. Also, by utilizing low loss multimode optical fibers with multimode cores formed of non-photosensitive materials, power loss in the system is kept low. Additionally, coupling losses may be reduced further by forming additional exemplary diffractive structures in the multimode optical fiber cores, such as coupling sections **1402**, similar to those shown in FIGS. **13**A-F, adjacent to the laser coupling surfaces of coupling multimode optical fibers **1404** and output section **1410** adjacent to the output surface of the single multimode optical fiber. Because these diffractive structures are formed within the multimode optical fibers, they may have lower losses than the free standing optical elements that they may replace.

**[0100]** It is noted that the exemplary wavelength stabilized, high power, uncooled laser source shown in FIG. **14** includes four high power lasers **1400**. The choice of four lasers is only exemplary and one skilled in the art may understand that other numbers of high power lasers may be used in an exemplary wavelength stabilized, high power, uncooled laser source according to the present invention. This may include a system with a single high power laser, in which case, coupling multimode optical fibers **1404** and fiber coupler **1406** may be omitted from the laser source without affecting its operation.

**[0101]** Further, long period Bragg grating structure **1408** may include any of the alternative embodiments described above with reference to FIGS. **1A-1B**. In particular, long period Bragg grating structure **1408** may include multiple subsets of index-altered portions preferentially coupled to different subband of wavelengths of the predetermined wavelength band and/or different transverse modes of the laser light propagating in the multimode fiber in which long period Bragg grating structure **1408** is formed.

**[0102]** Although many exemplary embodiments of the invention are described in terms of forming structures in circular optical fibers, it is contemplated that the exemplary structures described herein may be formed in optical waveguides of different cross-sectional shaped, including elliptical polarization-maintaining optical fibers.

**[0103]** Although illustrated and described above with reference to certain specific embodiments, the present invention is nevertheless not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention.

What is claimed is:

**1**. An optical fiber with an integral photonic crystal section, comprising:

an optical fiber core formed of a non-photosensitive material having an initial index of refraction, the optical fiber core includes;

a substantially cylindrical surface;

a longitudinal core axis;

a core radius; and

a plurality of index-altered portions having an altered index of refraction different from the initial index of refraction;

wherein the plurality of index-altered portions are arranged within the non-photosensitive material of the optical fiber core to form a photonic crystal structure.

**2**. An optical fiber according to claim **1**, wherein the non-photosensitive material of the optical fiber core includes at least one of: fused silica; borosilicate; quartz; zirconium fluoride; silver halide; chalcogenide glass; optical plastic; clear fused quartz; aluminosilicate; polymethylmeth-acrylate; polystyrene; acrylic; or arsenic trioxide.

**3**. An optical fiber according to claim **1**, wherein the optical fiber core is a multimode optical fiber core.

**4**. A optical fiber according to claim **3**, wherein the core radius of the multimode optical fiber core is in the range of about 10 μm to about 200 μm.

**5**. A multimode optical fiber according to claim **4**, wherein the core radius of the multimode optical fiber core is in the range of about 25 μm to about 31.25 μm.

**6**. An optical fiber according to claim **1**, wherein the altered index of refraction of the plurality of index-altered portions is altered by selective irradiation of the non-photosensitive material by pulses of ultrafast laser light.

**7**. An optical fiber according to claim **1**, wherein:

the non-photosensitive material of the optical fiber core has an initial crystallinity; and

the plurality of index-altered portions have an altered crystallinity which is less than the initial crystallinity of the non-photosensitive material.

**8**. An optical fiber according to claim **7**, wherein the altered crystallinity of the plurality of index-altered portions is altered by selective irradiation of the non-photosensitive material by pulses of ultrafast laser light.

**9**. An optical fiber according to claim **1**, wherein the photonic crystal structure formed in the optical fiber core is a one dimensional photonic crystal structure.

**10**. An optical fiber according to claim **1**, wherein the photonic crystal structure formed in the optical fiber core is a two dimensional photonic crystal structure.

**11**. An optical fiber according to claim **1**, wherein the photonic crystal structure formed in the optical fiber core is a three dimensional photonic crystal structure.

**12**. An optical fiber according to claim **1**, wherein the photonic crystal structure formed in the optical fiber core includes a defect.

**13**. An optical fiber with integral diffractive coupling optics, comprising:

an optical fiber core formed of a non-photosensitive material having an initial index of refraction, the optical fiber core includes;

a substantially planar end surface;

a substantially cylindrical surface;

a longitudinal core axis;

a core radius; and

a coupling section adjacent to the substantially planar end surface with a plurality of index-altered portions having an altered index of refraction different from the initial index of refraction;

wherein the plurality of index-altered portions are arranged within the coupling section of the optical fiber core to form the integral diffractive coupling optics.

**14**. An optical fiber according to claim **13**, wherein the non-photosensitive material of the optical fiber core includes at least one of: fused silica; borosilicate; quartz; zirconium fluoride; silver halide; chalcogenide glass; optical plastic; clear fused quartz; aluminosilicate; polymethylmeth-acrylate; polystyrene; acrylic; or arsenic trioxide.

**15**. An optical fiber according to claim **13**, wherein the optical fiber core is a multimode optical fiber core.

**16**. An optical fiber according to claim **15**, wherein the core radius of the multimode optical fiber core is in the range of about 10 μm to about 200 μm.

**17**. An optical fiber according to claim **13**, wherein the altered index of refraction of the plurality of index-altered portions is altered by selective irradiation of the non-photosensitive material by pulses of ultrafast laser light.

**18**. An optical fiber according to claim **13**, wherein:

the plurality of index-altered portions are a plurality of concentric circular annular portions centered on the longitudinal core axis of the optical fiber core; and

the plurality of concentric circular annular portions are sized and arranged such that the integral diffractive coupling optics formed in the coupling section of the optical fiber core is a circular two dimensional diffractive optical lens.

**19**. An optical fiber according to claim **13**, wherein:

the plurality of index-altered portions are a plurality of concentric elliptical annular portions centered on the longitudinal core axis of the optical fiber core;

the plurality of concentric elliptical annular portions are sized and arranged such that the integral diffractive coupling optics formed in the coupling section of the optical fiber core is an elliptical two dimensional diffractive optical lens.

**20**. An optical fiber according to claim **13**, wherein:

the plurality of index-altered portions are a plurality of parallel lines perpendicular to the longitudinal core axis of the optical fiber core;

the plurality of parallel lines are sized and arranged such that the integral diffractive coupling optics formed in the coupling section of the optical fiber core is a one dimensional diffractive optical lens.

* * * * *