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(54) **FIBER OPTIC DEVICES HAVING VOLUME BRAGG GRATING ELEMENTS**

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G03H 1/02 (2006.01)
G03H 1/04 (2006.01)
G02B 6/34 (2006.01)

(52) **U.S. Cl.** **430/1**; 430/2; 430/290; 385/37

(58) **Field of Classification Search** 385/16, 385/17, 27, 32; 398/81, 82, 84; 372/20; 359/15, 16; 430/1, 2, 290
See application file for complete search history.

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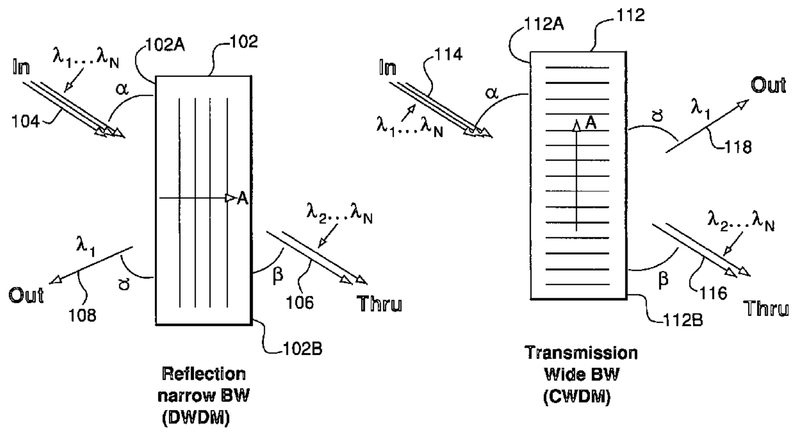
Primary Examiner—David A. Vanore
(74) *Attorney, Agent, or Firm*—Woodcock Washburn LLP

(57) **ABSTRACT**

Fiber optic devices including volume Bragg grating (VBG) elements are disclosed. A fiber optic device may include one or more optical inputs, one or more VBG elements, and one or more optical receivers. Methods for manufacturing VBG elements and for controlling filter response are also disclosed. A VBG chip, and fiber optic devices using such a chip, are also provided. A VBG chip includes a monolithic glass structure onto which a plurality of VBGs have been recorded.

14 Claims, 18 Drawing Sheets



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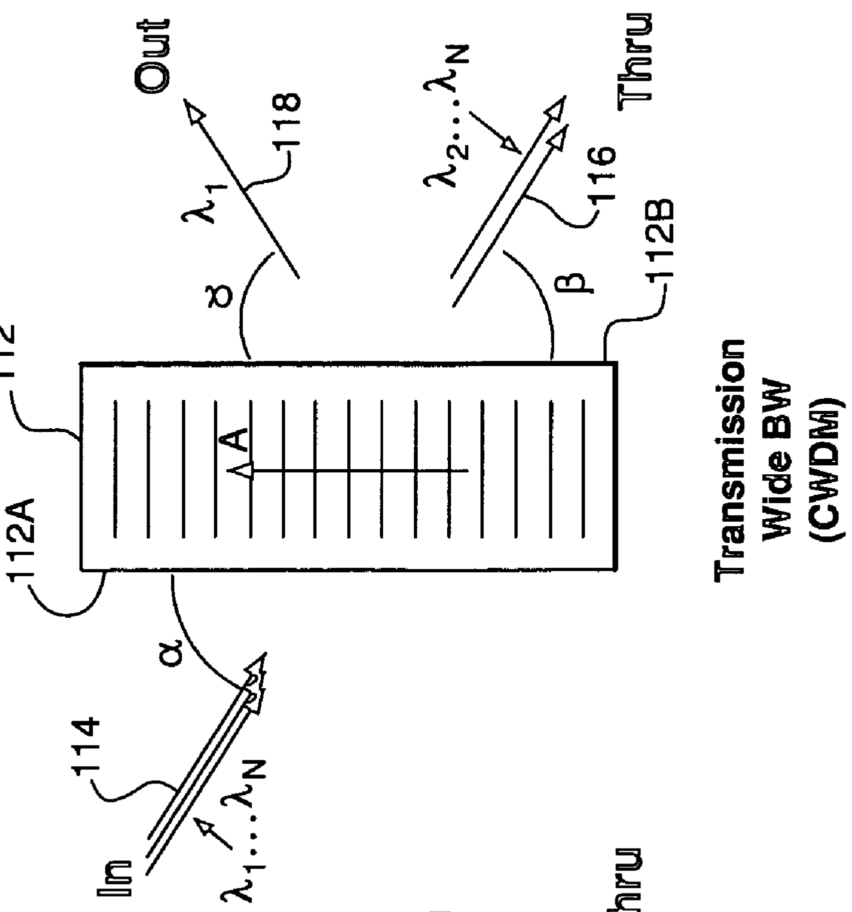

Out
118
λ1
γ
λ2...λN
Thru
116
β
112B
112
A
112A
α
114
In
λ1...λN
Transmission
Wide BW
(CWDM)

FIG. 1B

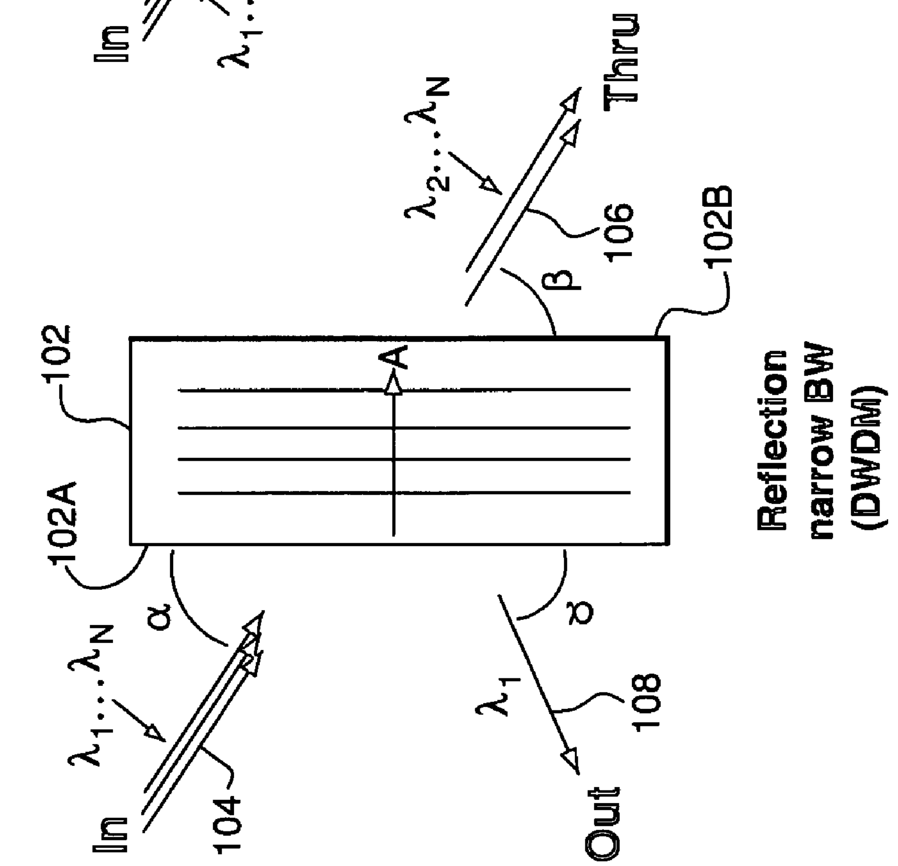

Thru
λ2...λN
106
β
102B
102
A
102A
α
λ1...λN
In
104
γ
λ1
108
Out
Reflection
narrow BW
(DWDM)

FIG. 1A

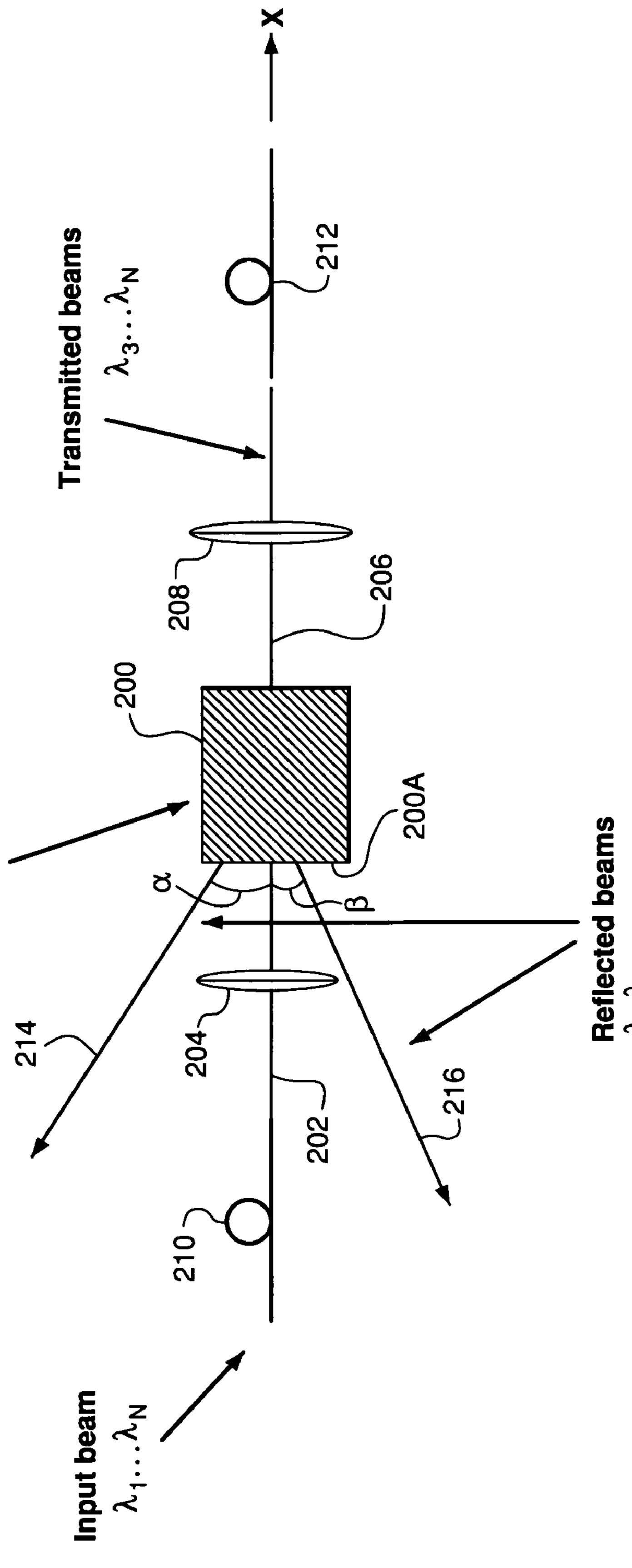

X
Transmitted beams
λ3...λN
212
208
206
200
VBG element
200A
α
β
Reflected beams
λ1λ2
214
204
216
202
210
Input beam
λ1...λN

FIG. 2

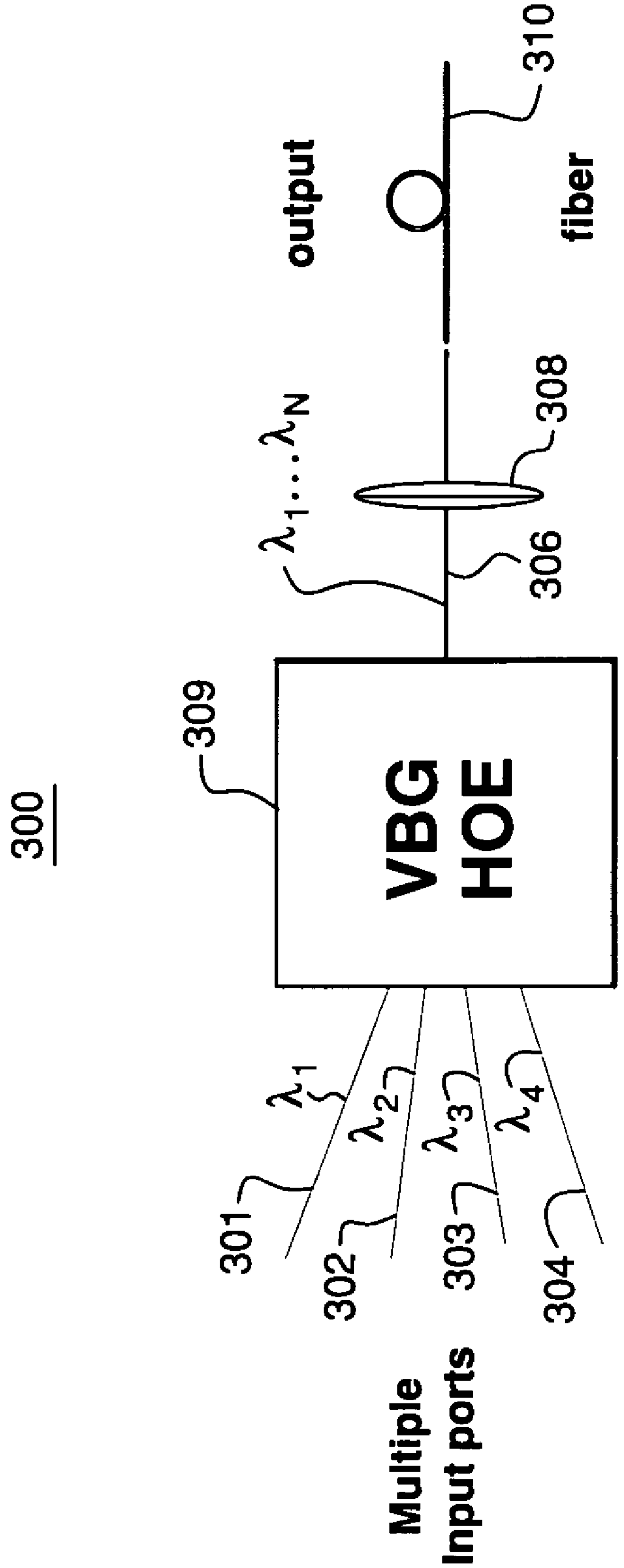

300
309
VBG
HOE
306
308
310
output
fiber
Multiple
Input ports
301
302
303
304

FIG. 3

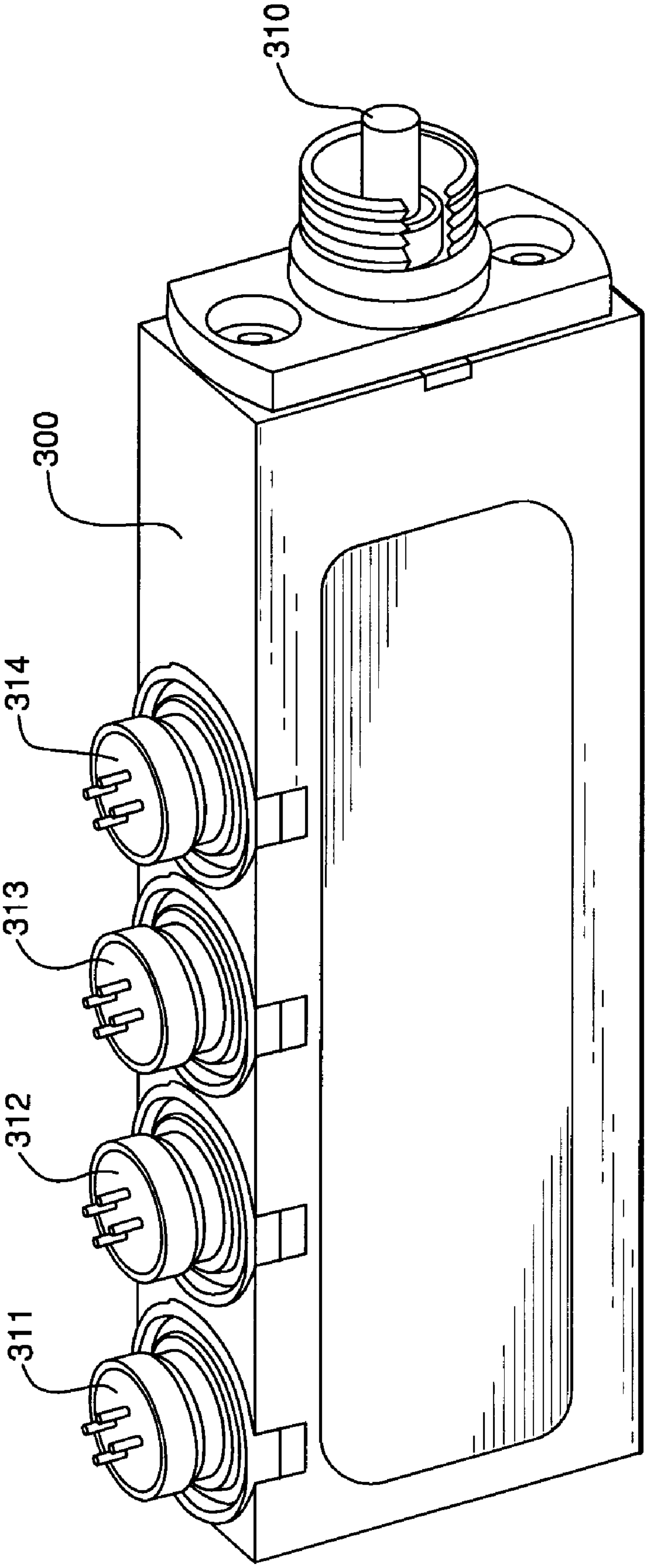


FIG. 4

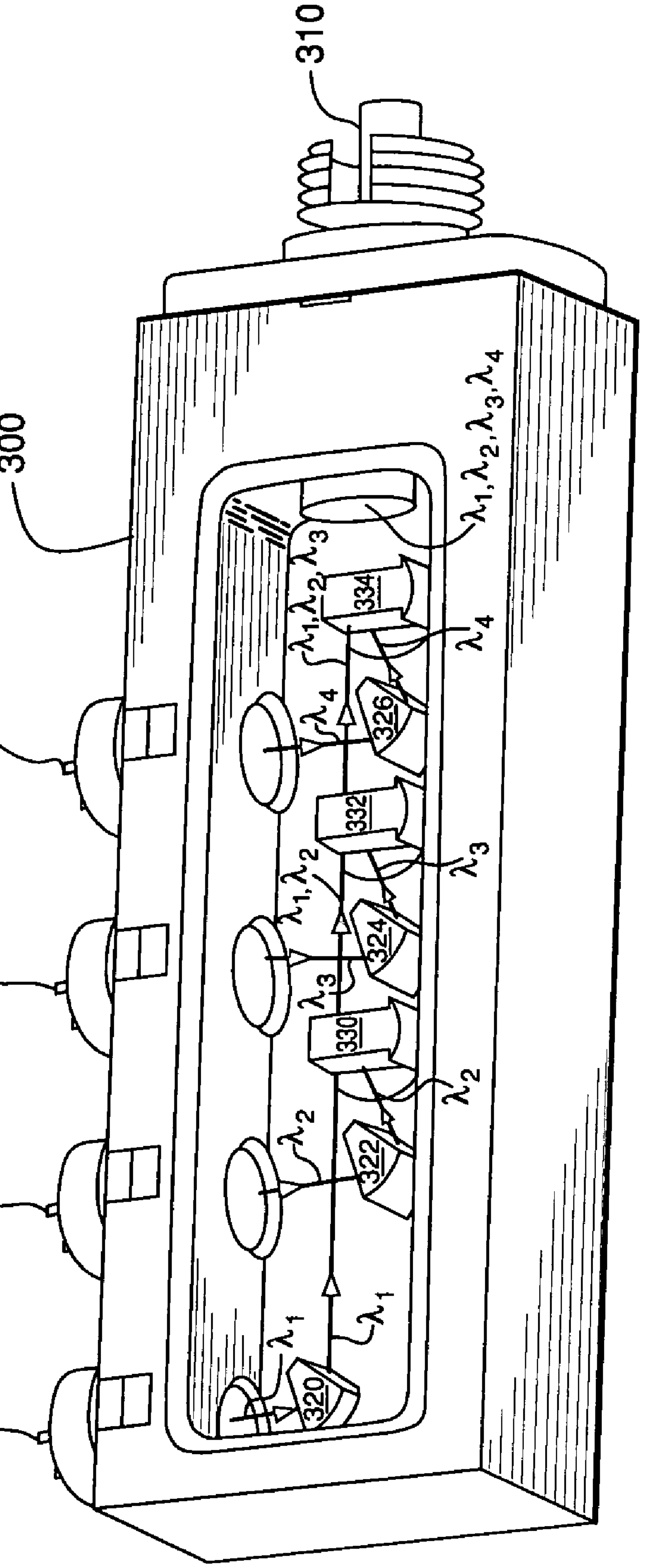

310
300
311
312
313
314
320
322
324
326
330
332
334
λ_1
λ_1
λ_2
λ_2
λ_3
λ_1, λ_2
λ_3
λ_4
$\lambda_1, \lambda_2, \lambda_3$
λ_4
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$

FIG. 5

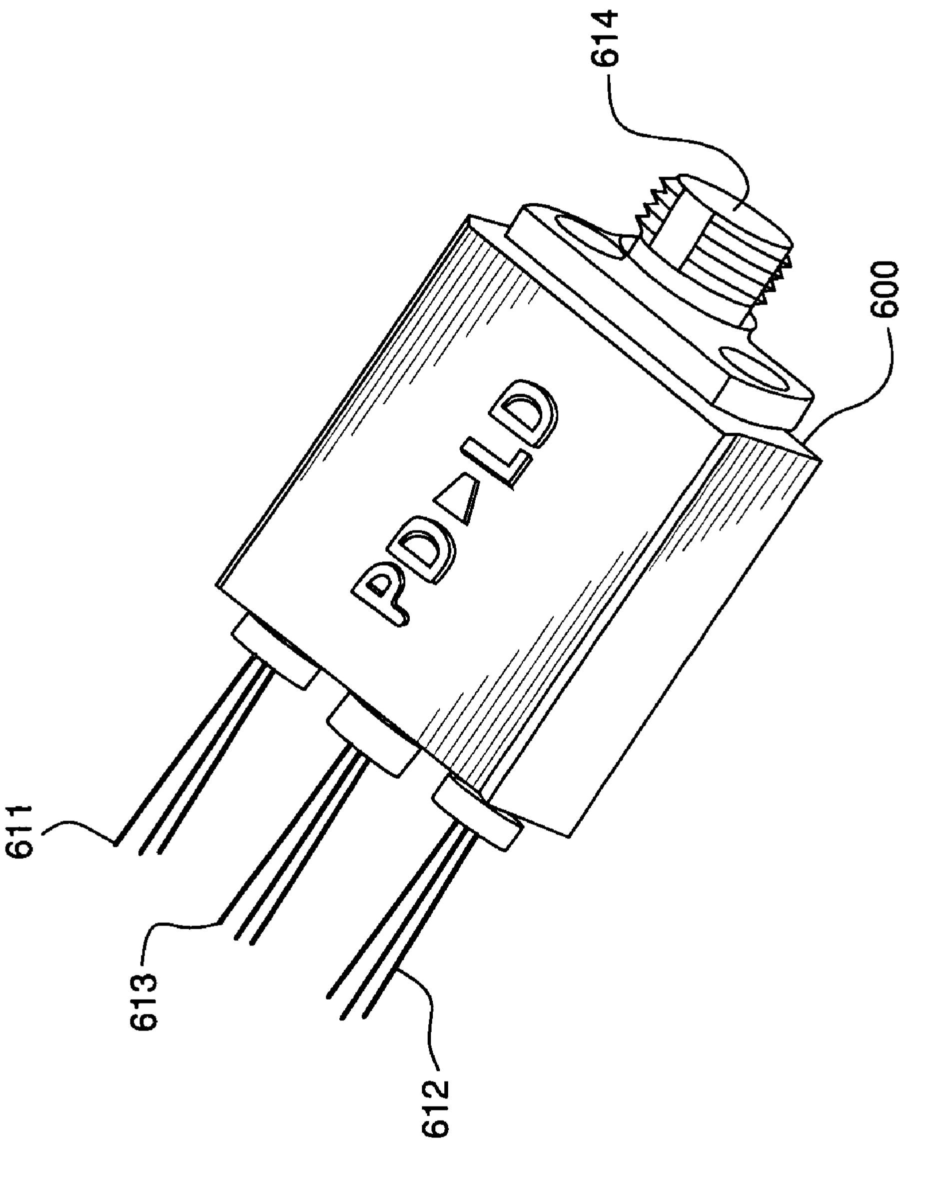


FIG. 6

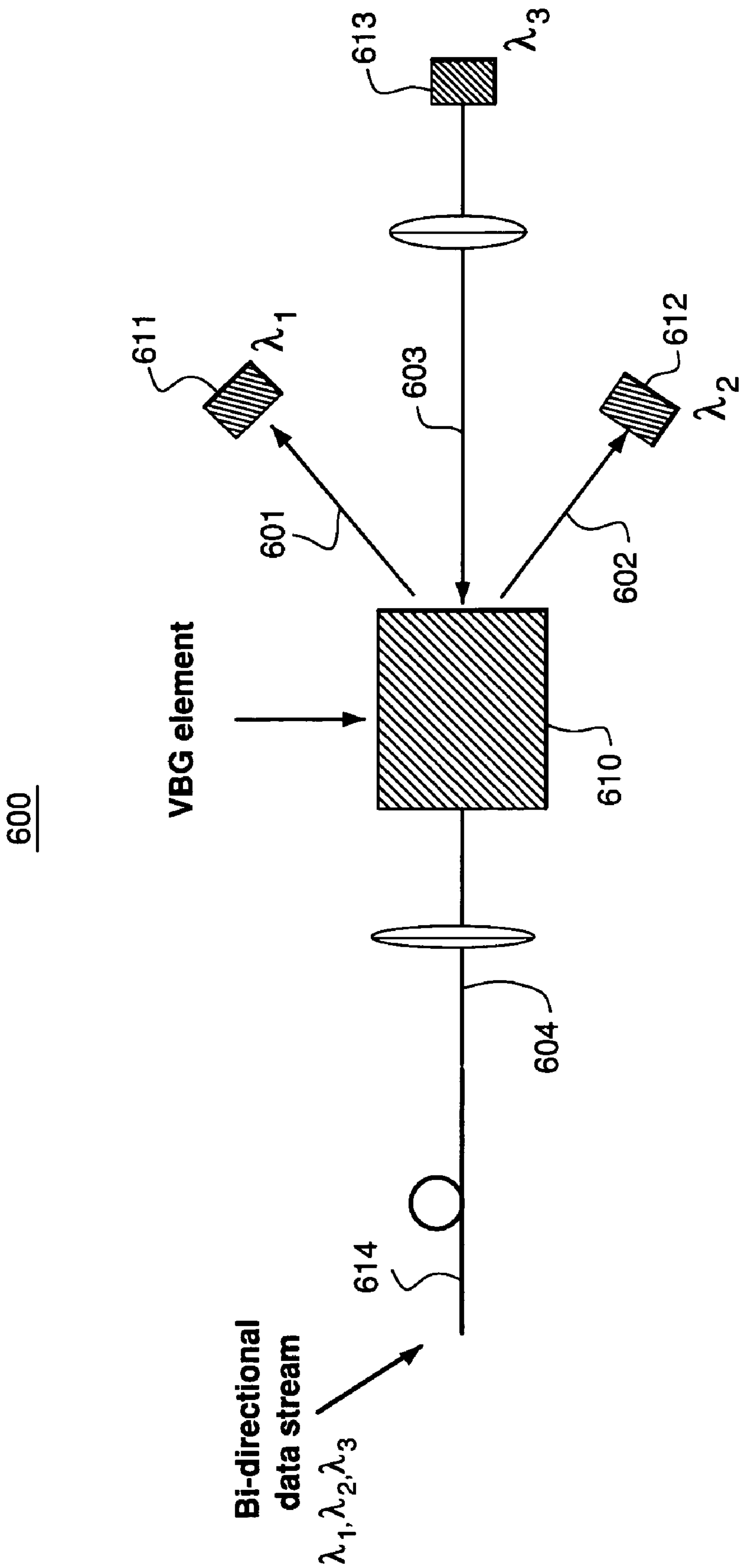

600
VBG element
610
601
602
603
604
611
λ1
612
λ2
613
λ3
614
Bi-directional
data stream
λ1,λ2,λ3

FIG. 7

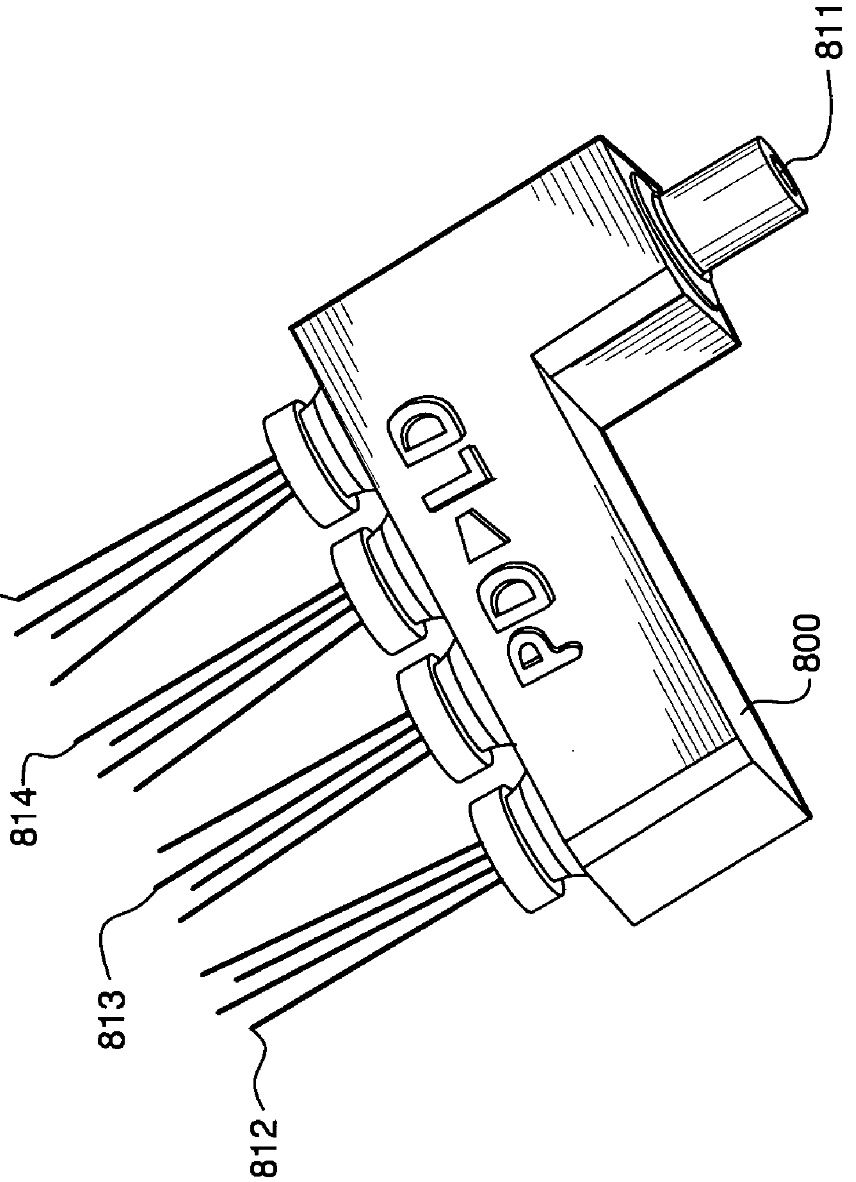


FIG. 8

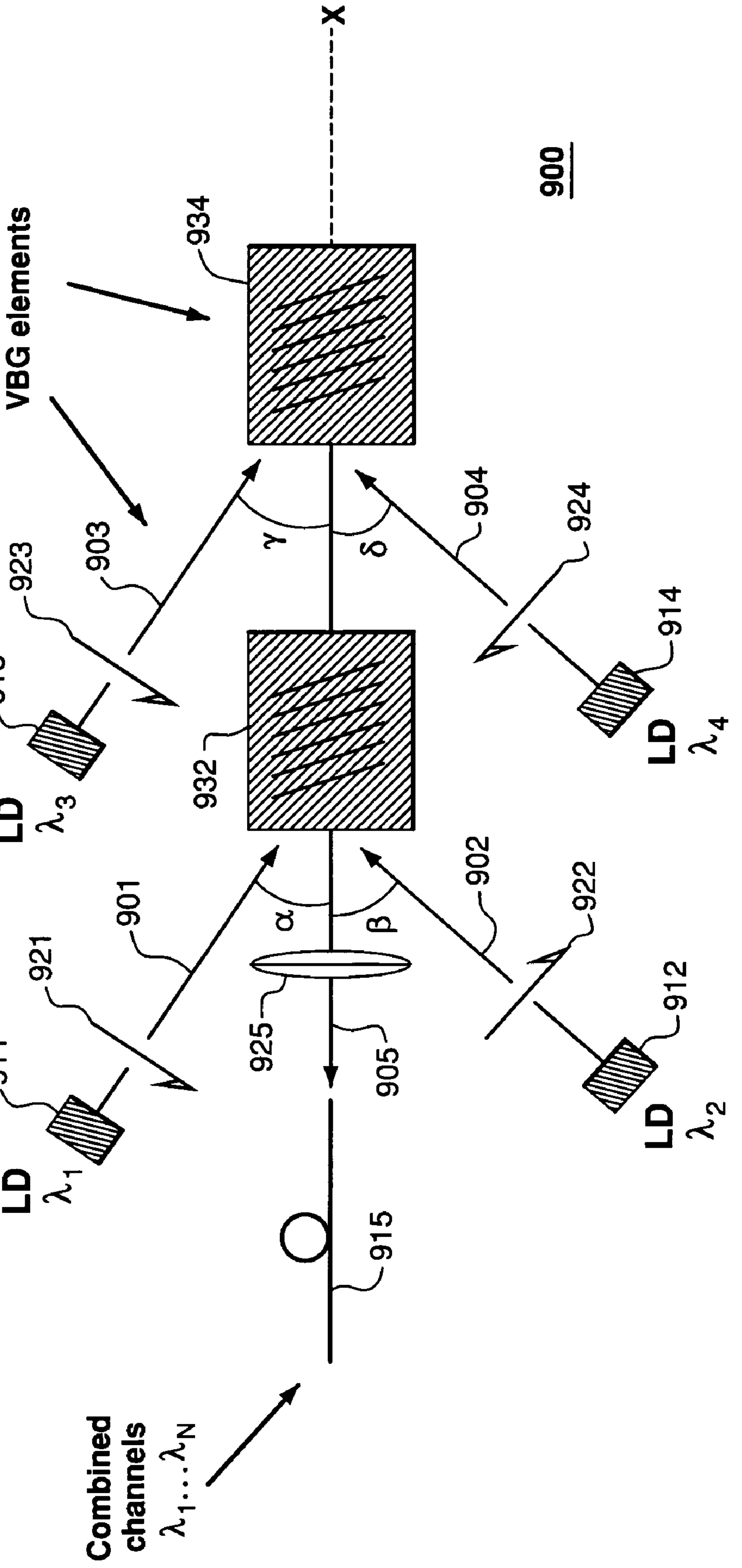

VBG elements
934
932
900
X
LD
λ_1
LD
λ_2
LD
λ_3
LD
λ_4
911
912
913
914
915
921
922
923
924
925
901
902
903
904
905
α
β
γ
δ
Combined
channels
$\lambda_1 \ldots \lambda_N$

FIG. 9

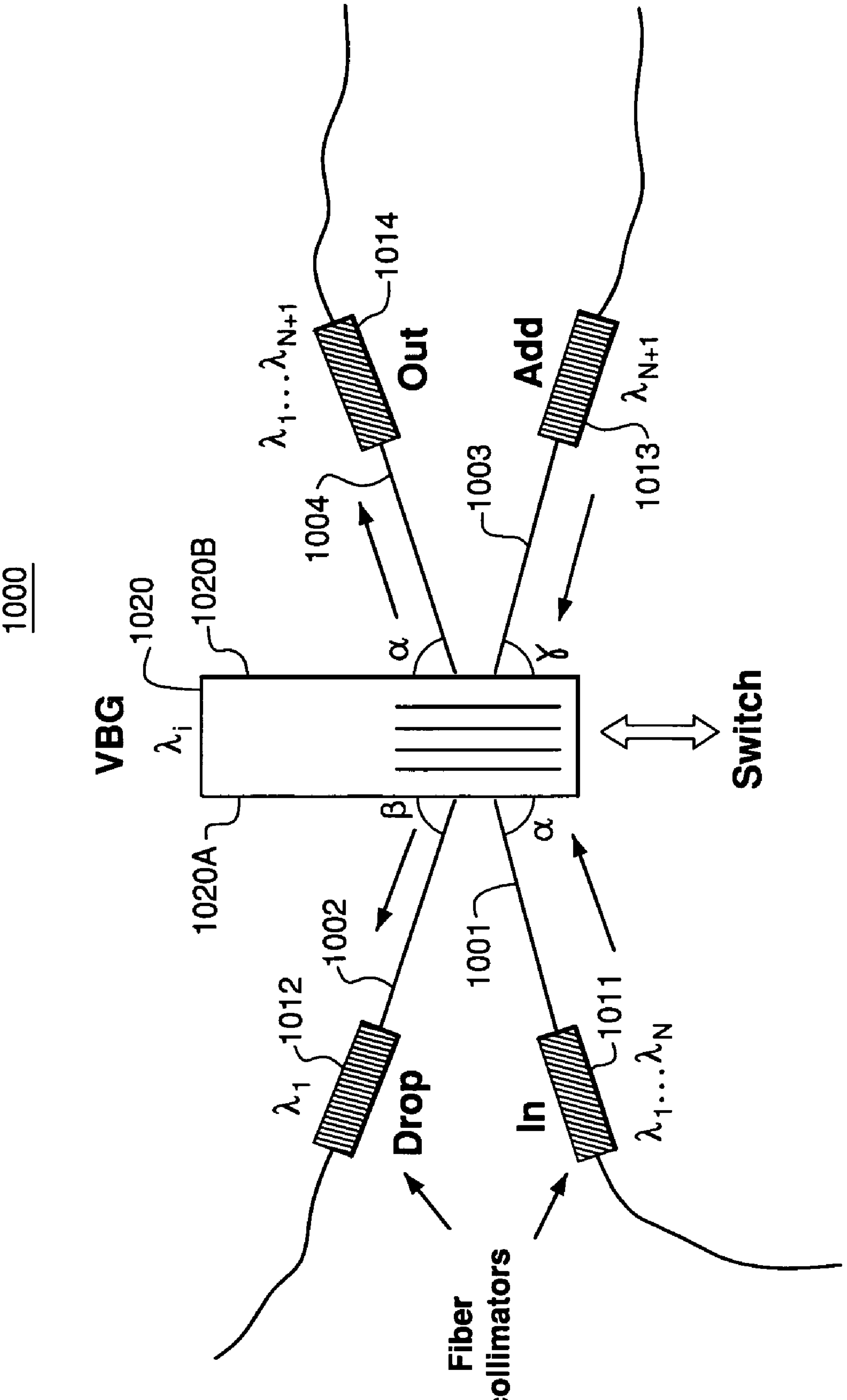

1000
VBG
λ_i
1020
1020B
1020A
α
β
α
γ
Switch
1004
1003
1002
1001
$\lambda_1 \ldots \lambda_{N+1}$
1014
Out
Add
λ_{N+1}
1013
λ_1
1012
Drop
In
1011
$\lambda_1 \ldots \lambda_N$
Fiber
collimators

FIG. 10

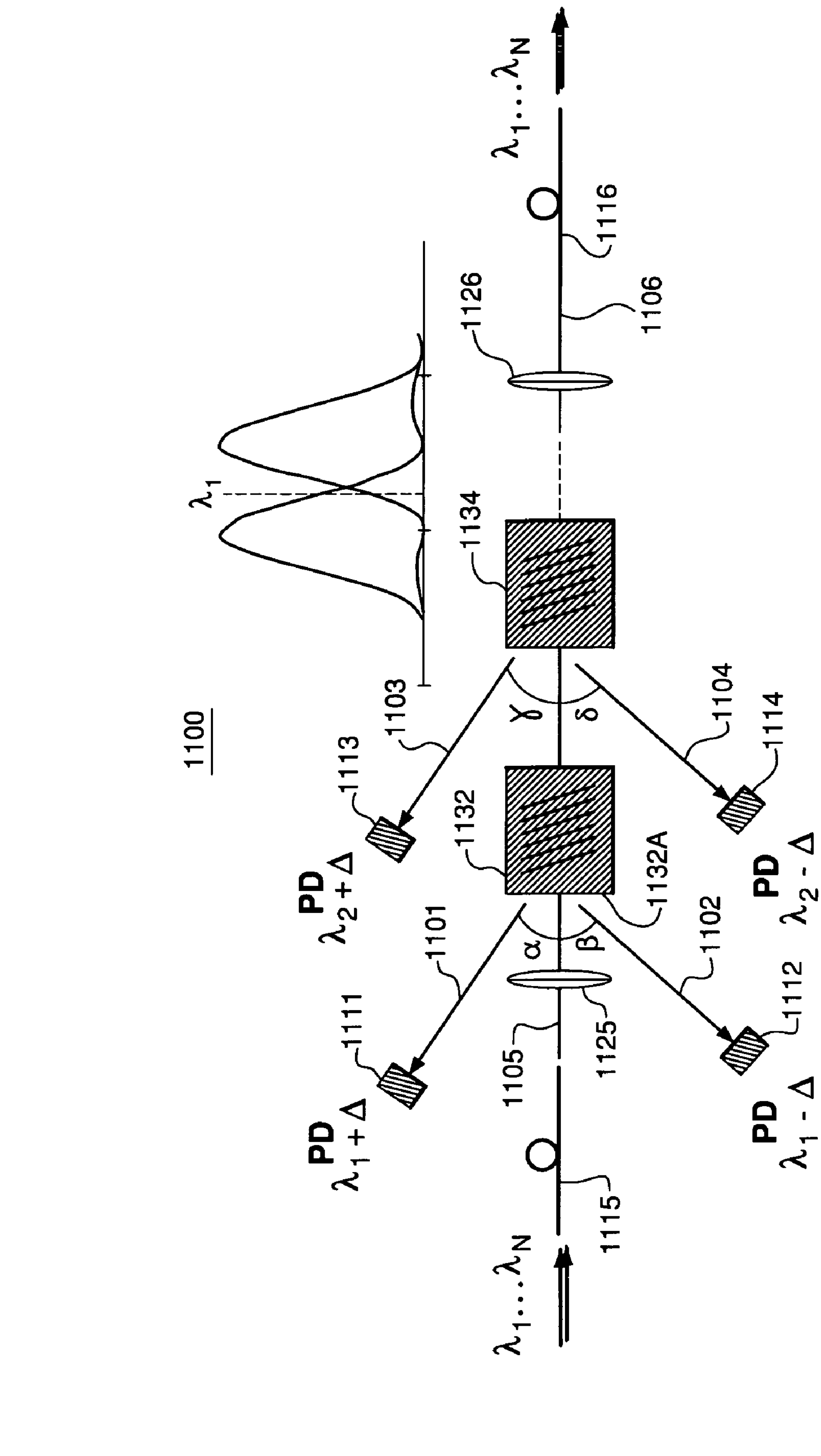

1100
λ1...λN
λ1...λN
λ1
1101
1102
1103
1104
1105
1106
1111
1112
1113
1114
1115
1116
1125
1126
1132
1132A
1134
α
β
γ
δ
PD λ1+Δ
PD λ1-Δ
PD λ2+Δ
PD λ2-Δ

FIG. 11

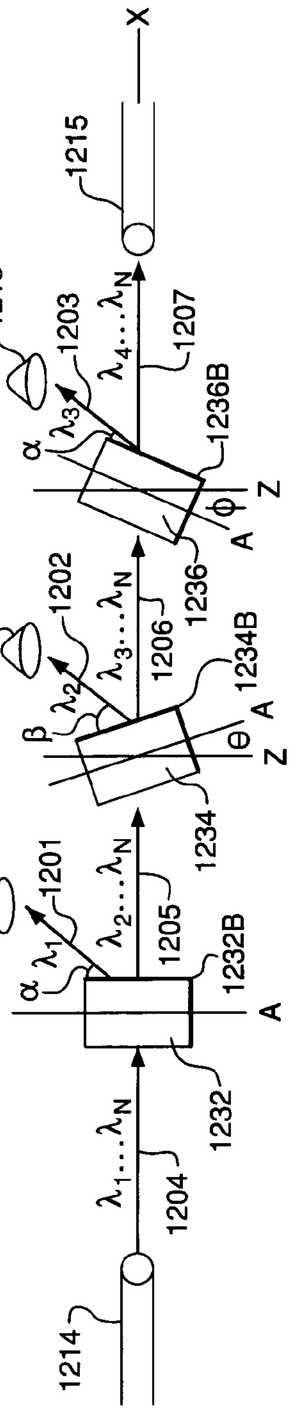


FIG. 12
CHAIN CASCADING

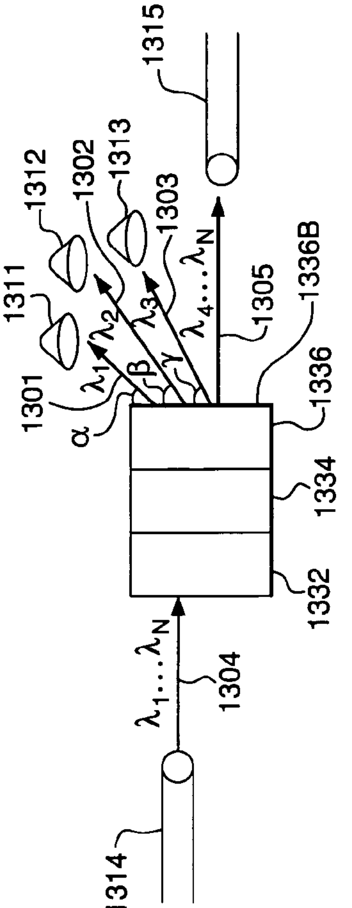


FIG. 13
LAMINATING

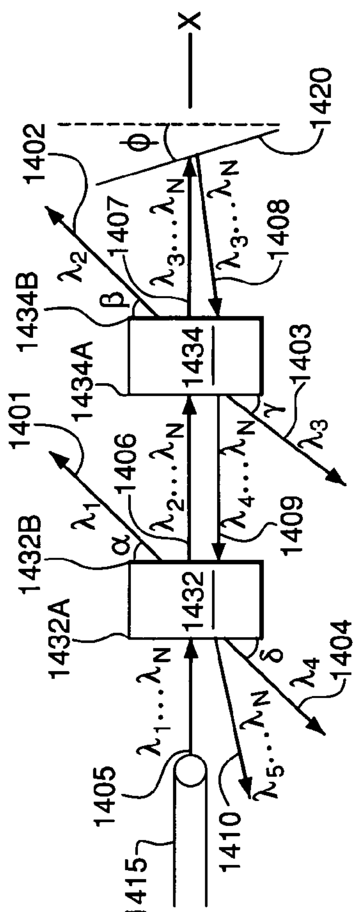


FIG. 14
MULTIPATH

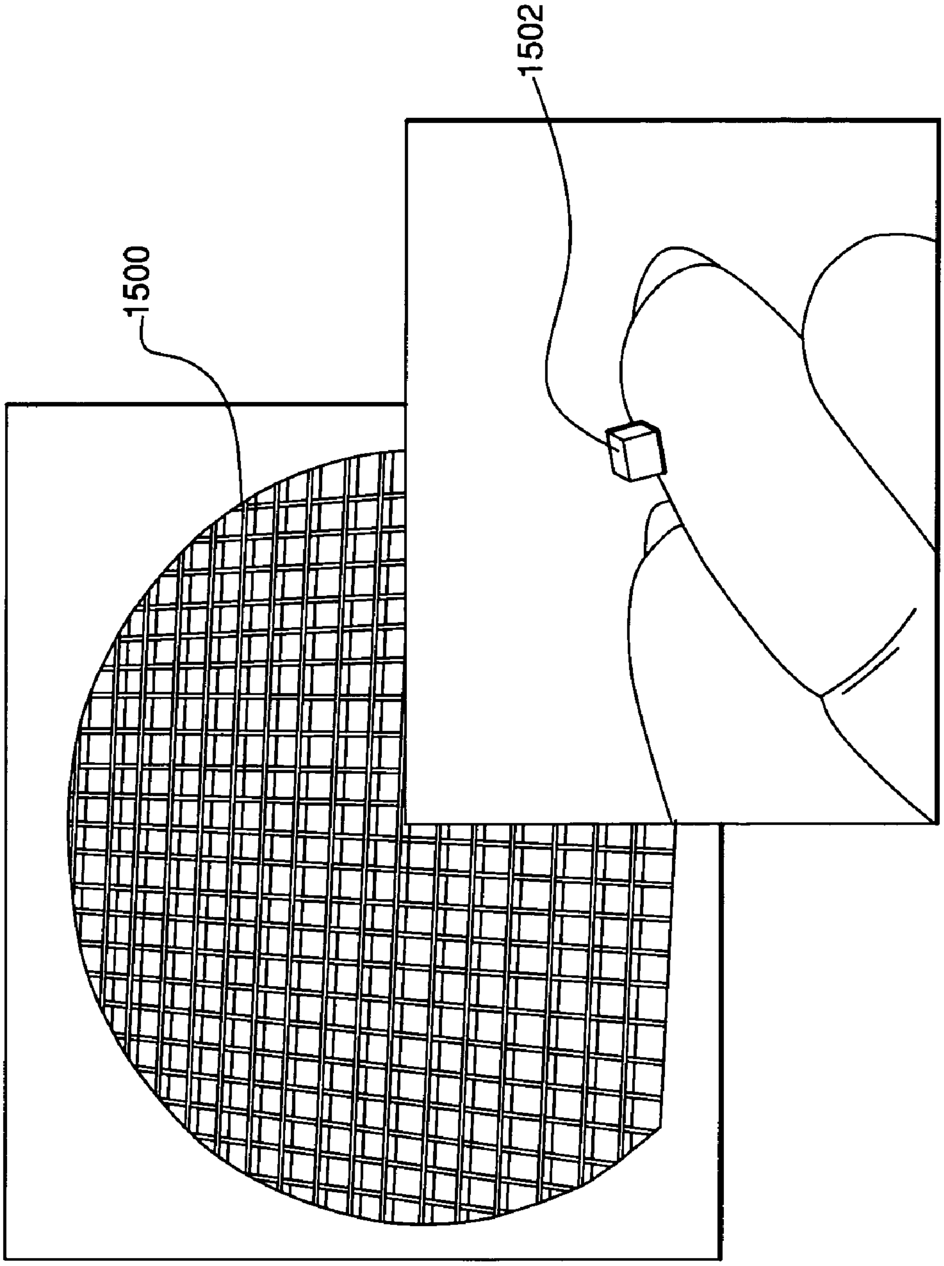


FIG. 15

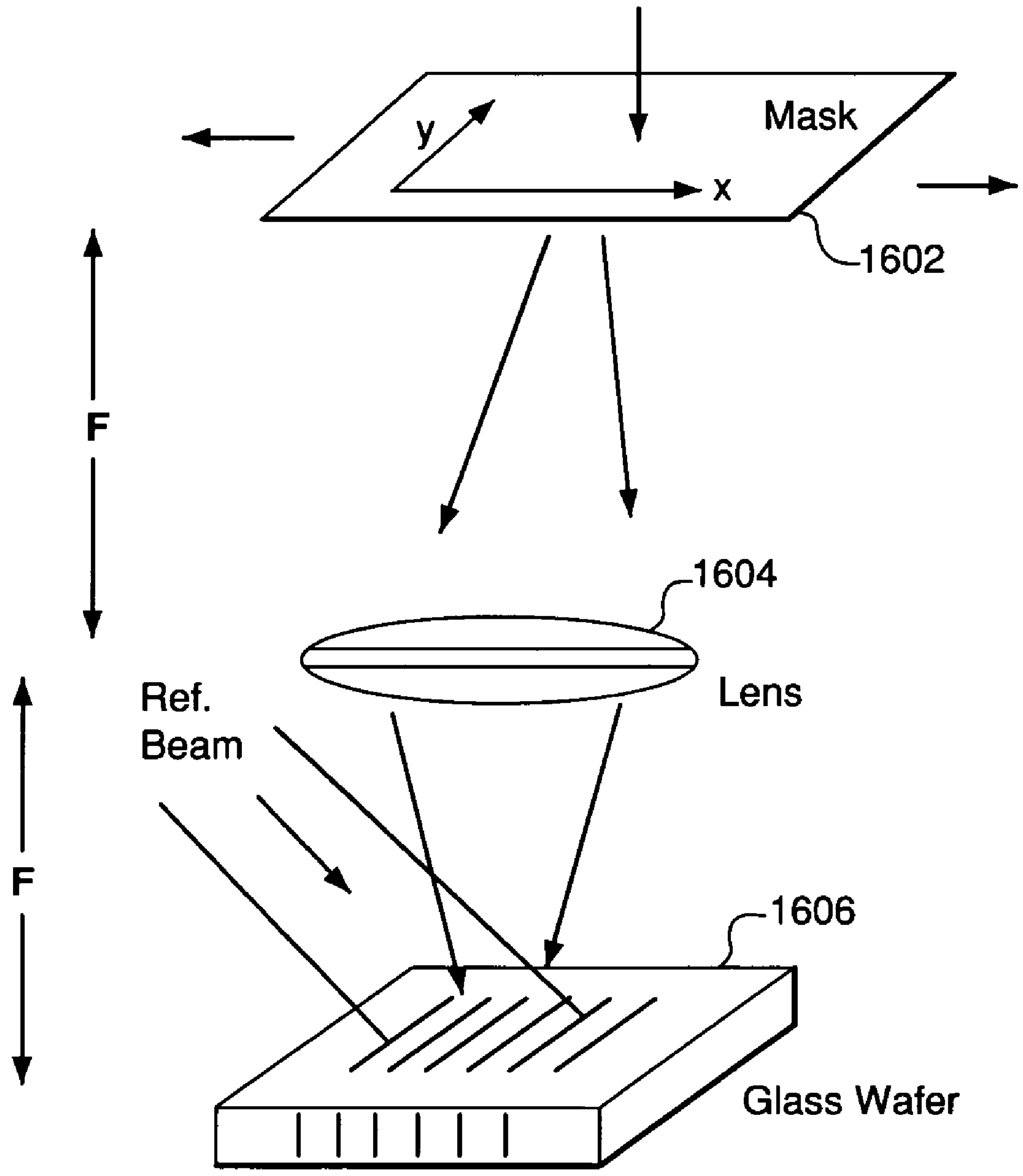
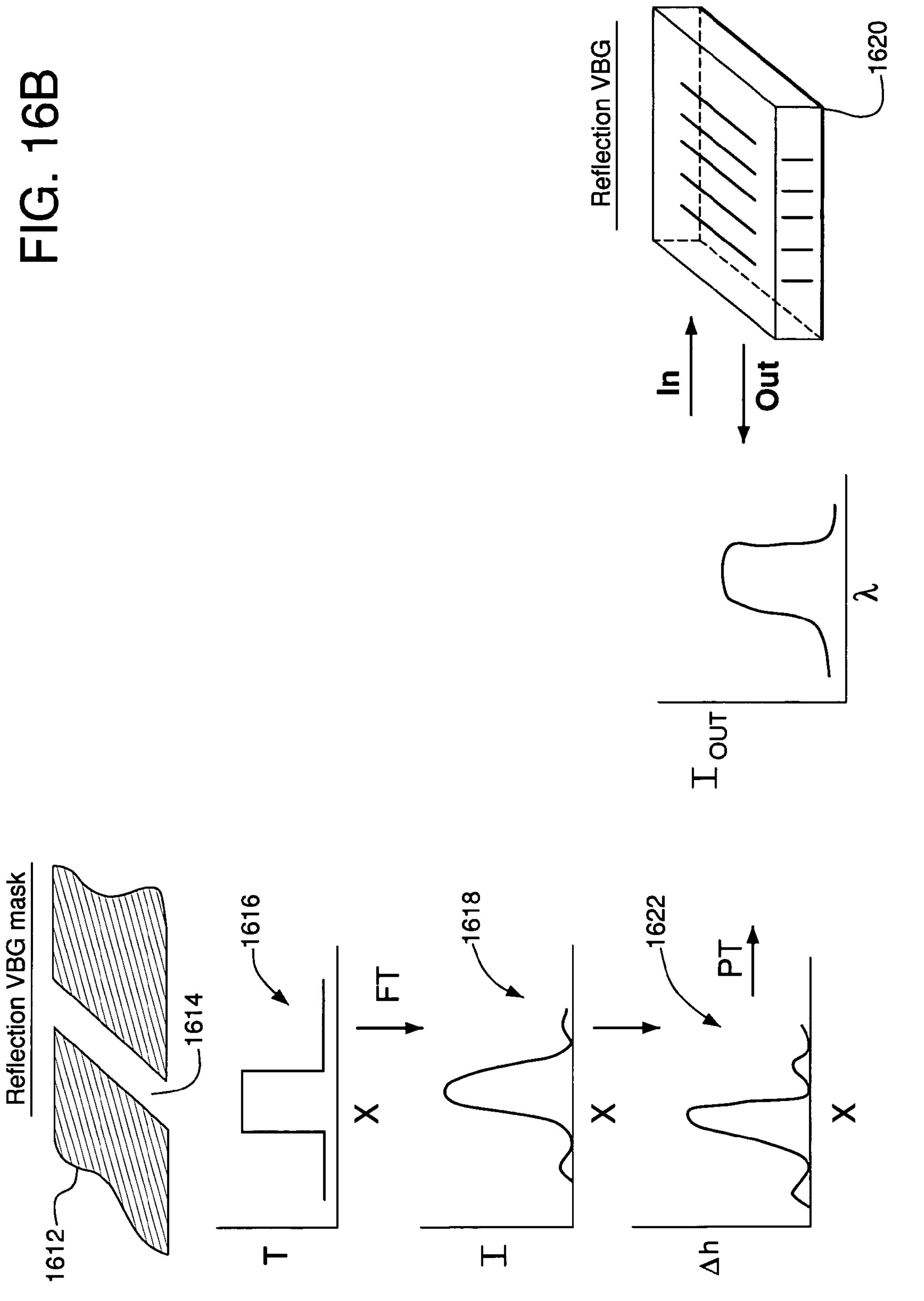


FIG. 16A

FIG. 16B


Reflection VBG mask
1612
1614
T
X
1616
FT
I
X
1618
Δh
X
1622
PT
Reflection VBG
1620
In
Out
I OUT
λ

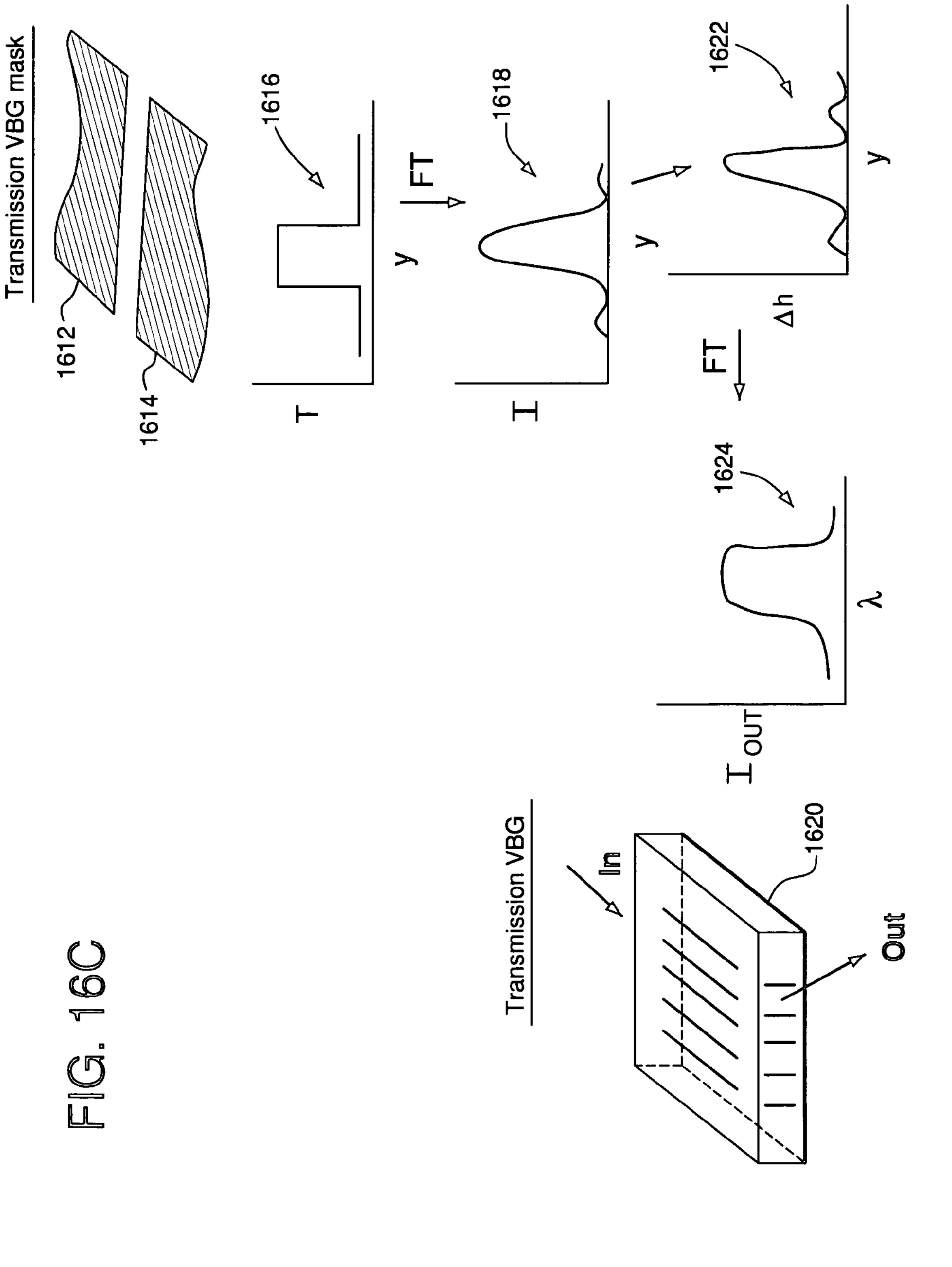
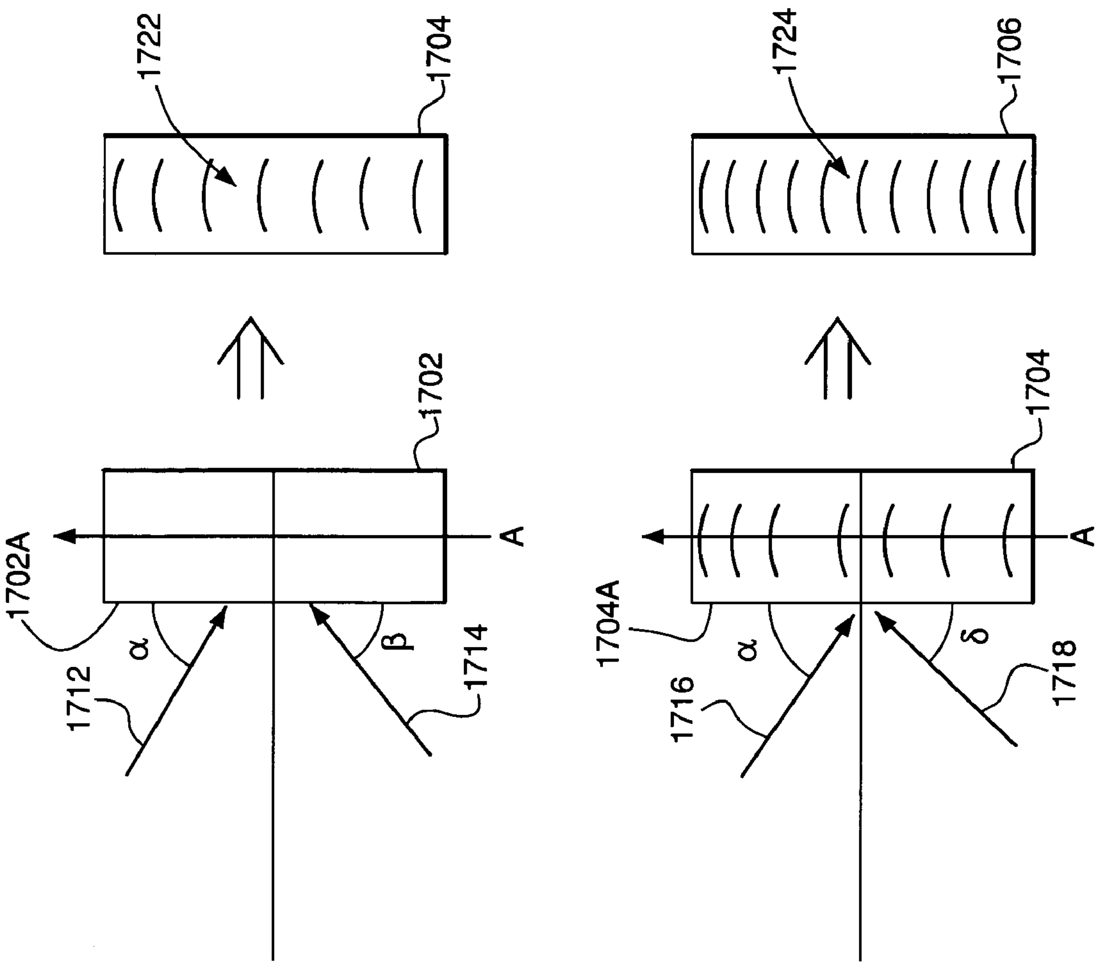

Transmission VBG mask
1612
1614
1616
T
y
FT
1618
I
y
FT
1622
Δh
y
1624
I_{OUT}
λ
Transmission VBG
In
1620
Out

FIG. 16C

FIG. 17


1722
1704
1724
1706
1702
1704
1702A
A
α
β
1712
1714
1704A
A
α
δ
1716
1718

VBG chip: DEMUX

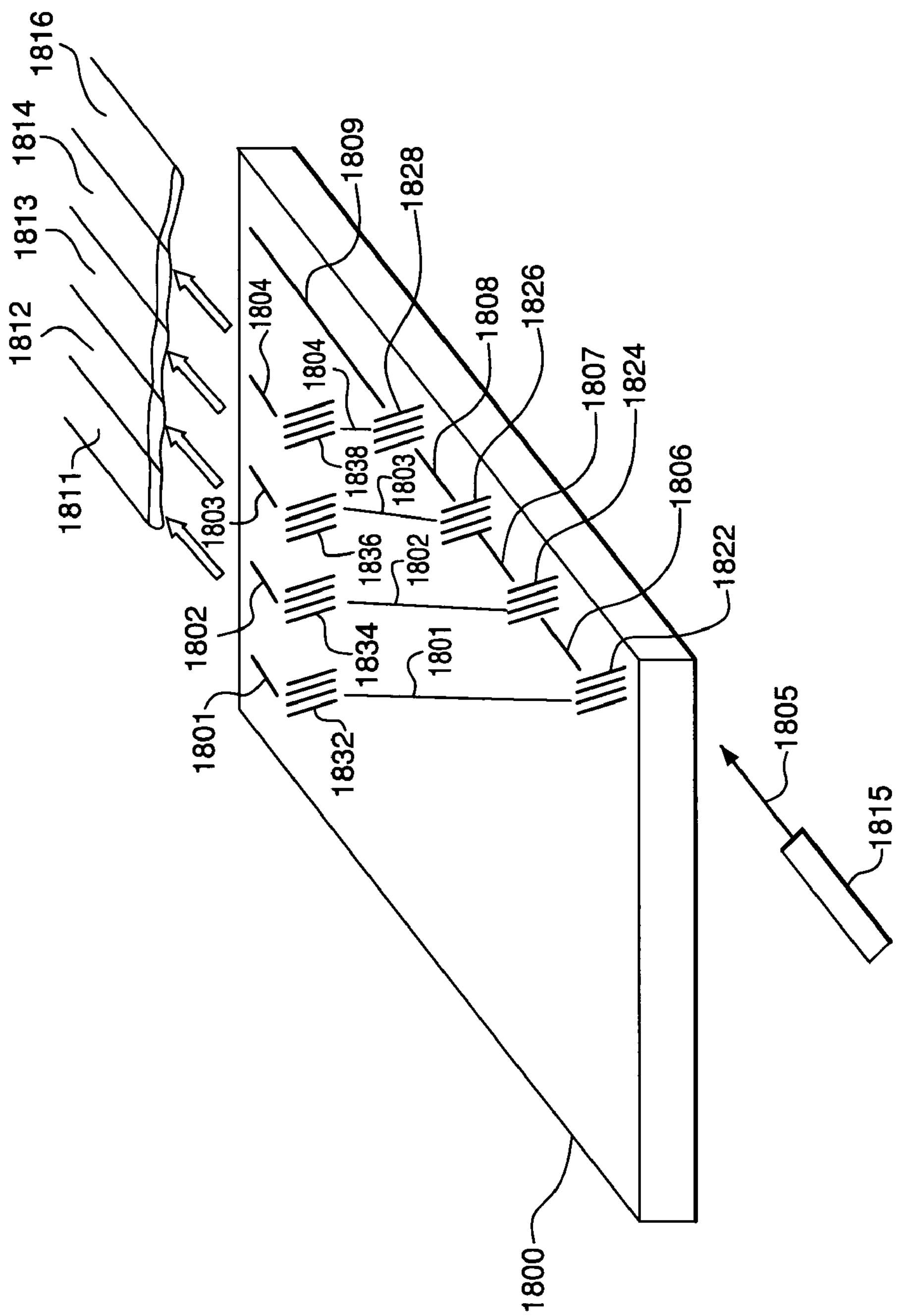


FIG. 18

FIBER OPTIC DEVICES HAVING VOLUME BRAGG GRATING ELEMENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit under 35 U.S.C. § 119(e) of U.S. Provisional patent application No. 60/365,032, filed Mar. 15, 2002, the disclosure of which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

The invention is related generally to fiber optic devices. In preferred embodiments, the invention provides fiber optic devices having one or more volume Bragg grating (VBG) elements, and methods for making such VBG elements.

BACKGROUND OF THE INVENTION

Light wavelength selectivity of thick periodic structures was, historically, studied first in x-ray diffraction on crystalline solids. It was recognized that such selectivity arises due to the coherent addition of the light energy diffracted by individual layers forming precisely spaced stacks, such as that of the atomic layers of a crystalline lattice. The name of phenomenon, "Bragg diffraction," was given in recognition of the studies of it performed by Bragg.

Later, largely the same behavior was observed during the diffraction of light at optical wavelengths on the acoustic waves of the appropriate frequencies created inside optically transparent solid media. Acoustic waves create a periodic modulation of the index of refraction of a dielectric material via perturbation of its density. As a result, an acoustic wave can be used to manipulate light based on its wavelength. Thus, it functions as a wavelength filter.

Acoustic perturbation, however, is of a temporal nature, and relaxes completely after its source is extinguished and with it disappears the filter. Long-lasting Bragg gratings were first utilized, perhaps, with the invention of full-color holography. It employed relatively thick films of dichromatic gelatins (DCG) for holographic recording of color-realistic images of 3-D objects by using lasers of different colors. Subsequent reconstruction of images with conventional white light sources became possible due to the wavelength selectivity property of volume Bragg gratings. However, to the inventors' knowledge, even though the wavelength selectivity of the volume Bragg gratings was the underlying mechanism that enabled white-light reconstruction of thick-layer DCG display holograms, their utility for separating, combining, or otherwise manipulating specific wavelengths of light with the intention of achieving practical device functionality has not been recognized.

Use of volume Bragg gratings (VBG) recorded in doped lithium niobate photorefractive crystals for filtering light at optical wavelengths was adopted in construction of solar and lidar filters used to isolate light at a particular wavelength from the broad band background. A principal issue, however, is that recording of such filters must be performed at the same wavelength at which the filter will subsequently operate. As a result, the use of these filters is limited to a very limited range of wavelengths where sufficiently powerful lasers exist. Furthermore, the list of appropriate recording materials is confined to two or three narrow classes of photorefractive materials, which often have physical properties that are unsuitable for their intended mode of operation. For example, no material is known to the inventors that would allow construction of practical functional fiber-optic devices that would utilize volume Bragg grating filters recorded at wavelengths in the range of about 800–1650 nm.

This drawback can be partially overcome in photorefractive lithium niobate crystals when a VBG filter is recorded through a different surface than that used for its operation. By using this approach, filters can be constructed in lithium niobate that can operate at wavelengths that are useful for practical photonic devices, such as, for example, fiber-optic devices. Nonetheless, this approach is still rather limited due to a number of factors. First, the usable wavelength range is limited to $\lambda_{op}>n*\lambda_{rec}$ on the one side, and the near infrared absorption edge of the lithium niobate on the other. Also, for practical devices, the bandwidth of the filter $\Delta\lambda$ is limited by the maximum refractive index modulation achievable in that material (or its dynamic range, Δn): $\Delta\lambda<(\lambda_{op})*\Delta n/2n$. This factor substantially limits the usefulness of this type of filter. This approach also requires the use of at least two (and typically four) polished surfaces that are orthogonal to each other, which increases the complexity of the filter manufacturing process and its cost. Additionally, the wavelength of the filter is substantially fixed to the value determined by the angle between the recording beams in the holographic setup. As a result, the wavelength must be controlled precisely for any practical device and is, therefore, unique for a particular wavelength or information-carrying "channel" of light, which complicates the issues in manufacturing of these elements.

SUMMARY OF THE INVENTION

An embodiment of the invention includes a fiber optic device comprising an optical input that provides input radiation having wavelength in a fiber optic range. A transmissive volume Bragg grating (VBG) element redirects the input radiation to an optical receiver. A second optical receiver may be provided to receive radiation transmitted through the VBG element, the transmitted radiation having a second wavelength in the fiber optic range. The device may include a second transmissive VBG element that redirects radiation transmitted through the first VBG element, the transmitted radiation having a second wavelength in the fiber optic range. A second optical receiver may be provided to receive the redirected transmitted radiation. A third optical receiver may be provided to receive radiation transmitted through the second VBG element, the second transmitted radiation having a third wavelength in the fiber optic range. The device may include a second optical input that provides second input radiation having another wavelength in the fiber optic range.

Another embodiment of the invention provides a fiber optic device comprising an optical input that provides input radiation having a plurality of wavelengths in a fiber optic range, and a volume Bragg grating (VBG) element made of sensitized silica glass. The VBG element receives the input radiation and redirects radiation having a first wavelength to an optical receiver.

In another embodiment, a fiber optic device comprising an optical input and a plurality of VBG elements is provided. A first VBG element receives input radiation and redirects first redirected radiation having a first wavelength in the fiber optic range. A second VBG element receives first transmitted radiation from the first VBG element and redirects second redirected radiation having a second wavelength in the fiber optic range. A first optical receiver receives the first redirected radiation and a second optical receiver receives the second redirected radiation. The VBG elements may be disposed along an optical axis of the fiber optic device. A face of the first VBG element may be laminated to a face of the second VBG element.

A fiber optic device according to the invention may include an optical input, a VBG element, and a reflector that reflects transmitted radiation received from the VBG back into the VBG such that the VBG redirects second redirected radiation to a first optical receiver.

A method for controlling filter response is also provided. Such a method includes providing a mask that corresponds to a desired filter response of a volume Bragg grating (VBG) element, and transmitting a recording beam through the mask. The recording beam is transmitted through a lens to a glass that is sensitive to a wavelength of the recording beam. The lens is adapted to perform an optical Fourier transform of a transfer function associated with the mask. A second recording beam may be transmitted to the glass in combination with the first recording beam. The second recording beam may have generally the same wavelength as the first recording beam, such that the first and second recording beams are coherent.

A method for manufacturing a VBG element by forming a large-wafer VBG and segmenting the large-wafer VBG into a plurality of individual VBG elements is also provided. Each of the individual VBG elements retains the index vector of the large-wafer VBG. The large-wafer VBG may-be segmented by dicing the large-wafer VBG into the plurality of individual VBG elements.

Another method for manufacturing a VBG element includes forming a first VBG element using a pair of recording beams and using a single recording beam to replicate the first VBG to form a second VBG.

A VBG chip, and fiber optic devices using such a chip, are also provided. A VBG chip includes a monolithic glass structure onto which a plurality of VBGs have been recorded. The VBG chip may include a first grating recorded at a first location on the glass, wherein the first grating is adapted to receive incident light having a plurality of wavelengths in a fiber optic range and to redirect first redirected light having a first wavelength in the fiber optic range. A second grating may be recorded at a second location on the glass to receive the first redirected light. The second grating may be adapted to redirect the first redirected light out of the glass structure. Another grating at another location on the glass may be adapted to receive transmitted light from the first VBG, and to redirect light having a second wavelength in the fiber optic range.

BRIEF DESCRIPTION OF THE DRAWINGS

Certain preferred embodiments of the invention will now be described in detail with reference to the figures. Those skilled in the art will appreciate that the description given herein with respect to the figures is for exemplary purposes only and is not intended in any way to limit the scope of the invention.

FIGS. **1**A and **1**B depict reflective and transmissive VBGs, respectively.

FIG. **2** demonstrates the transparency property of a VBG.

FIG. **3** is a schematic of a device according to the invention for combining a plurality of optical inputs into a single optical fiber output.

FIG. **4** is a perspective view of a preferred embodiment of a device according to the invention.

FIG. **5** depicts the interior of a device such as shown in FIG. **4**.

FIG. **6** is a perspective view of another preferred embodiment of a device according to the invention.

FIG. **7** is a schematic diagram of a device such as shown in FIG. **6**.

FIG. **8** is a perspective view of another preferred embodiment of a device according to the invention.

FIG. **9** is a schematic diagram of a DWDM multi-source combiner according to the invention.

FIG. **10** is a schematic diagram of an optical add-drop multiplexer according to the invention.

FIG. **11** is a schematic diagram of a multi-channel wavelength monitor according to the invention.

FIG. **12** depicts chain cascading of a plurality of VBGs in a fiber optic device according to the invention.

FIG. **13** depicts lamination cascading of a plurality of VBGs in a fiber optic device according to the invention.

FIG. **14** depicts a multiple path device according to the invention.

FIG. **15** depicts a method according to the invention for fabricating VBGs.

FIGS. **16**A–C depict another method according to the invention for fabricating VBGs.

FIG. **17** depicts yet another method according to the invention for fabricating VBGs.

FIG. **18** depicts an integrated VBG "chip" according to the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Using Sensitized Silica Glasses for Manufacturing of VBG Filters

One of the major problems in developing and using any kind of permanent VBG filters for practical applications has been the unavailability of a material or a class of materials possessing physical properties that are adequate for the practical applications. For example, the photorefractive electro-optic crystals, in which much of the research was conducted on the subject of VBGs, among other problems, are incapable of providing truly permanent, stable recording across a wide temperature range. Furthermore, these crystals are strongly anisotropic, which limits their usage substantially. For these reasons, an entire range of applications of VBG filters in general has not been substantially explored. In fact, to the inventors' knowledge, there is not a single photonic device now in the market that uses VBG elements.

According to the invention, a previously unexplored class of materials, the silicate photorefractive glasses (PRG), can be used to enable the design and manufacturing of practical devices based on VBGs, with special emphasis on photonic devices for fiber-optic applications. This type of materials substantially overcomes all of the above-mentioned drawbacks of the previously studied materials and possesses all the required properties to manufacture devices for demanding applications exemplified by the fiber optics. These properties include, but are not limited to, the following: a) optical transparency in the entire optical window from UV to mid-infrared; b) outstanding longevity of the recorded gratings; c) outstanding thermal stability (<200 C); d) adequate dynamic range; e) excellent optical quality, including the achievable polishing quality of the elements made of this material; f) low manufacturing costs; g) ability to be formed and processed in the adequate shapes and sizes (e.g., flat disks or wafers); h) refractive index isotropy.

Compositions and processes for manufacturing such PRGs are described in U.S. Pat. No. 4,057,408 ("the 408 patent"), the disclosure of which is hereby incorporated herein by reference in its entirety. The 408 patent discloses photosensitive glasses, i.e., glasses which, after an exposure to high energy or actinic radiations, can be heat treated in a certain manner to develop a colored transparent article, or which can be thermally opacified to produce a colored opal glass. More particularly, the **408** patent is directed to alkali halide silver halide-containing photosensitive glasses which, through a sequence of shortwave radiation exposures and heat treatments, exhibit the total range of colors seen in the visible spectrum either in the transparent or in the opacified state and in three dimensions. As described in the **408** patent, the base glass composition can be varied widely, but the presence of silver, alkali oxide, fluorine, at least one of the group consisting of chlorine, bromine, and iodine, and, where ultra-violet radiations comprise the actinic radiations, cerium oxide may be required.

Manufacturing of VBG Elements in Silica Glasses by Recording Holographically at a Specific Wavelength and Using Them in Fiber-Optic Devices at an Arbitrary Wavelength

As described in the literature on the theory of Bragg diffraction in thick holograms (see, e.g., Kogelnik, H., "Coupled wave theory for thick hologram gratings," The Bell System Technical Journal, November 1969, 48(9), 2909–2947), there are two basic types of the VBGs—transmission and reflection, which are different in their mode of operation (see Kogelnik FIG. **4**).

FIG. **1**A depicts a reflective VBG **102** having a grating wave vector, A, in the horizontal direction as shown. An input light beam **104** composed of light of a plurality of wavelengths $\lambda_1, \ldots \lambda_N$ is directed toward the VBG **102** at a first angle α to the input face **102**A of the VBG **102**. The VBG **102** is formed such that it is transparent to all but one of the wavelengths $\lambda_1, \ldots \lambda_N$. That is, the light beam propagates through the grating relatively unaffected, except that the light having a certain wavelength, λ_1, is filtered out of the beam. As a result, only that light **106** having wavelengths $\lambda_2, \ldots \lambda_N$ continues through the VBG **102** and exits the VBG. **102** at a second angle β to the output face **102**B of the VBG **102**. Preferably, the VBG **102** is fabricated so that the angle β at which the beam exits the VBG **102** is as near as possible to the angle α at which it entered the VBG **102** (i.e., the beam continues along in a generally straight line). Light **108** having wavelength λ_1, however, is reflected back at an angle γ from the input face **102**A of the VBG **102** because of the holography within the VBG **102**. That is, the VBG **102** is fabricated such that the index of refraction varies within the VBG **102** to allow light having wavelengths $\lambda_2, \ldots \lambda_N$ to continue through the VBG **102**, and light having wavelength λ_1 to be reflected back at a known angle. Methods for fabricating such VBGs are discussed in detail below.

FIG. **1**B depicts a transmissive VBG **112** having a grating wave vector, A, in the vertical direction as shown. An input light beam **114** composed of light of a plurality of wavelengths $\lambda_1, \ldots \lambda_N$ is directed toward the VBG **112** at a first angle α to the input face **112**A of the VBG **112**. The VBG **112** is formed such that it is transparent to all but one of the wavelengths. That is, the light beam propagates through the grating relatively unaffected, except that the light having a certain wavelength, λ_1, is filtered out of the beam. As a result, only that light **116** having wavelengths $\lambda_2, \ldots \lambda_N$ continues through the VBG **112** and exits the VBG **112** at a second angle β to the output face **112**B of the VBG **112**. Preferably, the VBG **112** is fabricated so that the angle β at which the beam **116** exits the VBG **112** is as near as possible to the angle α at which it entered the VBG **112** (i.e., it continues along in a generally straight line). Light **118** having wavelength λ_1, however, exits the VBG **112** at a third angle γ to the output face **112**B because of the holography within the VBG **112**. That is, the VBG **112** is fabricated such that the index of refraction varies within the VBG **112** to allow light having wavelengths $\lambda_2, \ldots \lambda_N$ to continue relatively straight through the VBG **112**, and light having wavelength λ_1 to be deflected as it passes through the VBG **112** such that it exits the VBG **112** at a known angle β to the output face.

Wavelength filtering properties of transmission and reflection VBGs are different primarily in the width of the filter that can be constructed in an element of practical size. Generally, reflection thick volume holograms have very narrow wavelength bandwidth, with the upper limit determined by the dynamic range of the material, as described above in connection with the example of lithium niobate VBG filters. Conversely, transmission thick volume holograms generally have wider bandwidth, which, historically, has precluded their use for the generation of white light color display holograms.

Nonetheless, when recorded in a sufficiently thick slab of a transparent material (e.g., >1 mm), a method can be devised to record transmission VBGs that can achieve bandwidths sufficiently narrow for practical photonic devices (e.g., bandwidth of 30 nm or less).

Another principal difference between reflection VBGs and transmission VBGs is that the transmission type allows tuning of the central wavelength of the filter by adjusting the incident angle of light upon the VBG. For that reason, a VBG filter can be recorded at one wavelength (e.g., in the UV range where silicate PRGs are sensitive) and operate at another (e.g., in the 850 nm to 1650 nm range typically employed in various fiber-optic devices). This can be achieved without the limitations of recording through an orthogonal side of the element, described above for the case of the lithium niobate VBG filters. This means that: a) the range of the usable wavelengths is practically unlimited; b) wider bandwidths are readily available; c) there is no need for polishing additional surfaces.

The use of permanent transmission VBGs as band-pass filters for manipulation of wavelengths in photonic devices, exemplified by the fiber-optic active and passive components, has not been explored so far probably for one or more of the following reasons: a) strong anisotropy of the material (e.g., inorganic electro-optic photorefractive crystals); b) impossible to manufacture in sufficiently thick layers (>1 mm, e.g., DCG); c) impossible to achieve sufficient optical quality of the bulk material and/or polishing quality of the surfaces (e.g., photo-polymers); d) insufficient temperature stability.

FIG. **2** demonstrates the transparency property of a VBG **200** in which an input light beam **202** composed of light of a plurality of wavelengths $\lambda_1, \ldots \lambda_N$ is directed toward the VBG **200**, through a lens **204**, along an optical axis, x, of the device. As shown, the input light beam **202** can be emitted from an optical fiber **210**. The VBG element **200** is fabricated such that the index of refraction varies within the VBG **200** to allow light **206** having wavelengths $\lambda_3, \ldots \lambda_N$ to continue relatively straight through the VBG **200**, through a lens **208**, and into a receiver **212**, which can be another output optical fiber, for example, as shown. Light **214** having wavelength λ_1, however, is reflected back at a first angle α from the input face **200**A of the VBG **200**. Similarly, light **216** having wavelength λ_2 is reflected back at a second angle β from the input face **200**A of the VBG **200** because of the holography within the VBG **200**.

FIGS. **3**–**5** depict a preferred embodiment of a fiber optic device **300** according to the invention for combining a plurality of optical inputs **311**–**314** into a single optical output **310**. As shown, the device **300** includes four optical inputs **311**–**314**, which can be laser diodes, as shown, or optical fibers, for example. Each optical input **311**–**314** carries light **301**–**304** of a different wavelength λ_1–λ_2. The device **300** also includes three VBG elements **330**, **332**, **334**. Light **301** from the first input **311**, having wavelength λ_1, is transmitted into the interior of the device **300**, where it is deflected via a first deflector **320** (such as a mirror, for example) such that it enters the first VBG element **330** at a known angle. As shown, the light travels along the optical axis of the device, and enters the VBG **330** at a known angle to the input face of the VBG **330**. The first VBG **330** is transparent to light having wavelength λ_1, so the light having wavelength λ_1 exits the first VBG **330** without being deflected by the VBG.

Light **302** from the second input **312**, having wavelength λ_2, is transmitted into the interior of the device **300**, where it is deflected via a second deflector **322** such that it enters the first VBG element **330** at a known angle. The first VBG **330** deflects the light having wavelength λ_2 such that the light having wavelength λ_2 exits the first VBG **330** without being deflected by the VBG and, therefore, is combined with the light having wavelength λ_1.

Similarly, light **303** from the third input **313**, having wavelength λ_3, is transmitted into the interior of the device **300**, where it is deflected via a third deflector **324** such that it enters the second VBG element **332** at a known angle. The second VBG **332** deflects the light having wavelength λ_3 such that the light having wavelength X3 exits the second VBG **332** without being deflected by the second VBG **332**. The second VBG **332** is transparent to light having wavelength λ_1 or λ_2. Consequently, the light having wavelength λ_3 is combined with the light having wavelength λ_1 and λ_2.

Similarly, light **304** from the fourth input **314**, having wavelength λ_4, is transmitted into the interior of the device **300**, where it is deflected via a fourth deflector **326** such that it enters the third VBG element **334** at a known angle. The third VBG **334** deflects the light having wavelength λ_4 such that the light having wavelength λ4 exits the third VBG **334** without being deflected by the third VBG **334**. The third VBG **334** is transparent to light having wavelength λ1, λ2, or λ3. Consequently, the light having wavelength λ4 is combined with the light having wavelength λ1, λ2, and λ3.

FIGS. **6** and **7** depict a preferred embodiment of a triplexer bi-directional transmitter/receiver **600** according to the invention. As shown, the device **600** includes an optical input **613**, two optical outputs, such as receivers **611**, **612**, and a bi-directional optical carrier **614**, each of which can be an optical fiber, for example. The bi-directional carrier **614** carries light **604** having wavelengths $\lambda_1 \ldots \lambda_3$ as shown. The first output **611**, which may be a photodiode, for example, as shown, receives light **601** of wavelength λ_1 The second output **612**, which may also be a photodiode, for example, as shown, carries light **602** of wavelength λ_2. The optical input **613**, which may be a laser diode, for example, as shown, transmits light **603** of wavelength λ_3.

The VBG **610** is fabricated such that it is transparent to light having wavelength λ_3, which is transmitted to the VBG **610** via the optical input **613**. The VBG **610** can also be fabricated such that it deflects light **601** having wavelength λ_1 and light **602** having wavelength λ_2. The light **601** having wavelength λ_1 can be received by the first optical output **611**, and the light having wavelength X2 can be received by the second optical output **612**. The bi-directional carrier **614** carries light **604** having wavelength λ_1 and wavelength λ_2 in a first direction (toward the VBG) and wavelength λ_3 in a second direction (away from the VBG).

FIG. **8** depicts a preferred embodiment of a Xenpak form-factor CWDM transmitter **800** according to the invention. As shown, the device **800** includes an optical input **811** and four optical outputs **812**–**815**, each of which can be a laser diode, as shown, or an optical fiber, for example. The optical input carries light having wavelengths $\lambda_1 \ldots \lambda_4$. The first output **811** carries light of wavelength λ_1; the second output **812** carries light of wavelength λ_2; the third output **813** carries light of wavelength λ_3; and the fourth output **814** carries light of wavelength λ_4.

FIG. **9** is a schematic diagram of a DWDM multi-source combiner **900** according to the invention. As shown, the multi-source combiner **900** includes four optical inputs **911**–**914**, such as optical fibers, for example. Each optical input **911-914** carries light of a different wavelength $\lambda_1, \ldots \lambda_4$ as shown. The device **900** also includes two VBG elements **932**, **934**. Light **901** from the first input **911**, having wavelength λ_1, is transmitted, preferably through a lens **921**, such that it enters the first VBG element **932** at a first known angle α. The first VBG **932** is fabricated such that the light **901** having wavelength λ_1 is deflected from the first VBG **932** along the optical axis x of the device **900**. Similarly, light **902** from the second input **912**, having wavelength λ_2, is transmitted, preferably through a lens **922**, such that it enters the first VBG element **932** at a second known angle β. The first VBG **932** is fabricated such that the light **902** having wavelength λ_2 is also deflected from the first VBG **932** along the optical axis x of the device **900**.

Light **903** from the third input **913**, having wavelength λ_3, is transmitted, preferably through a lens **923**, such that it enters the second VBG element **934** at a third known angle γ. The second VBG **934** is fabricated such that the light **903** having wavelength λ_3 is deflected from the VBG **934** along the optical axis x of the device **900**. Similarly, light **904** from the fourth input **914**, having wavelength λ_4, is transmitted, preferably through a lens **924**, such that it enters the second VBG element **934** at a fourth known angle δ. The second VBG **934** is fabricated such that the light **904** having wavelength λ_4 is also deflected from the second VBG **934** along the optical axis x of the device **900**. The first VBG **932** is transparent to light having wavelength λ_3 and λ_4. Thus, light beams having respective wavelengths λ_1, λ_2, λ_3, and λ_4 can be combined into a single optical beam **905**, which can then be transmitted, preferably through a lens **925**, to an optical receiver **915**, such as an optical fiber, for example.

FIG. **10** is a schematic diagram of a free-space optical add-drop multiplexer (OADM) **1000** according to the invention. As shown, the OADM **1000** includes an optical input **1011** , such as an optical fiber, for example, that carries light **1001** having wavelengths $\lambda_1, \ldots \lambda_N$ as shown. As shown in FIG. **10**, the OADM **1000** includes a VBG element **1020** that is fabricated to reflect light **1002** having wavelength λ_1. The VBG **1020** is transparent to light having wavelengths $\lambda_2, \ldots \lambda_N$. The light beam **1001** from the first input **1011** is incident onto the VBG **1020** at a first angle α to a first face **1020**A of the VBG element **1020**. Consequently, a light beam **1002** having wavelength λ_1 is deflected at a second angle β from the face **1020**A of the VBG element **1020**. The light beam **1002** having wavelength λ_1 is thus "dropped" from the input signal, and can be directed to an optical receiver **1012**, such as another optical fiber, for example.

The OADM **1000** also includes an additional input **1013**, which can be an optical fiber, for example, that carries a light beam **1003** having wavelength λ_{N+1}. The light beam **1003** having wavelength λ_{N+1} is incident onto the VBG **1020** at an angle γ to a second face **1020**B of the VBG **1020**. The VBG element **1020** is fabricated to reflect light having wavelength λ_{N+1} from the second face **1020**B such that the light **1003** from the additional input **1013** is combined with the light from the first input to form an output light beam **1004** having wavelengths $\lambda_2, \ldots \lambda_{N+1}$. The output light beam **1004** can be directed to an optical receiver **1014**, such as another optical fiber, for example.

FIG. **11** is a schematic diagram of a multi-channel wavelength monitor **1100** according to the invention. As shown, the multi-channel wavelength monitor **1100** includes an optical input **1115** that carries light **1005** having wavelengths $\lambda_1, \ldots \lambda_N$. The monitor **1100** also includes two VBG elements **1132**, **1134**. The input light beam **1105** is transmitted, preferably through a lens **1125**, such that it enters the first VBG element **1132** at a first known angle (preferably, along the optical axis x of the device **1100**, that is, 90° to the face **1132**A of the first VBG **1132**). The first VBG **1132** is fabricated such that the light **1101** having wavelength $\lambda_1+\Delta$ is deflected from the first VBG **1132** at a first angle α, and light **1102** having wavelength $\lambda_1-\Delta$ is deflected from the first VBG **1132** at a second angle β. The first VBG **1132** is transparent to the rest of the wavelengths in the input beam **1105**. Light **1101** having wavelength $\lambda_1+\Delta$ may be received by an optical receiver **1111**, and light **1102** may be received by an optical receiver **1112**.

The light beam is then transmitted to the second VBG element **1134**, which is fabricated such that the light **1103** having wavelength $\lambda_2+\Delta$ is deflected from the second VBG **1134** at a first angle γ, and light **1104** having wavelength $\lambda_2-\Delta$ is deflected from the second VBG **1134** at a second angle δ. Light **1103** having wavelength $\lambda_2+\Delta$ may be received by an optical receiver **1113**, and light **1104** having wavelength $\lambda_2-\Delta$ may be received by an optical receiver **1114**. The second VBG **1134** is transparent to the rest of the wavelengths in the beam. The output beam **1106** can then be received, preferably through a lens **1126**, by an optical receiver **1116**, which can be another optical fiber, for example.

Methods for Packaging Devices With Large Channel Counts Using VBG Filters

One of the main advantages of VBG filters and, indeed, their unique property is the ability to record multiple filters sharing the same volume of the material. This allows for the fabrication of devices of very small size and unique functionality. Nevertheless, the number of gratings that can share the same volume, known as the multiplexing number, or the M/#, in the holographic memory field, is limited by the dynamic range of the material. For that reason, for practical materials suitable for manufacturing of VBG filters, that number will typically be rather limited (a realistic estimate is around 4 filters for a 4 mm thick element). Furthermore, fabrication of VBG filters with a larger number of gratings becomes progressively more complex, while at the same time reducing the flexibility in packaging them in a device. In addition, when sharing the same volume, the combined effect of the VBGs can be obtained via the coherent addition of the effects of the individual gratings, which results in the appearance of cross-terms, leading sometimes to undesirable side effects. It is, therefore, desirable to have a practical method for manufacturing devices with sufficiently large channel count. According to one aspect of the invention, fiber optic devices can be fabricated which can have a basically unlimited number of channels while using very simple VBG elements as building blocks.

FIG. **12** depicts a device according to the invention in which any number of transmissive VBG filters can be combined to construct a device with an arbitrary channel count and for an arbitrary set of wavelengths. Preferably, the VBG filters are identical, thereby reducing the cost of fabrication. In this approach, the individual VBG elements are positioned on the main optical axis of the device and their tilt angles are adjusted individually in order to tune it to the peak wavelength of the desired channel. This approach may be referred to as "chain cascading."

As shown in FIG. **12**, an optical input **1214** carries light **1204** having wavelengths $\lambda_1, \ldots \lambda_N$. Light **1204** is incident on a first VBG element **1232** along the optical axis x of the device. The first VBG **1232** is fabricated such that the light **1201** having wavelength λ_1 is deflected from the first VBG **1232** at a first angle α to the exit face **1232**B of the VBG **1232**. As shown, the VBG **1232** is positioned such that its grating vector A and exit face **1232**B are perpendicular to the optical axis x of the device. Thus, the light **1201** having wavelength λ_1 is deflected from the first VBG **1232** at an angle 90-α to the optical axis x of the device. The device may include a first optical receiver **1211** that receives the deflected beam **1201**. The first VBG **1232** is transparent to the rest of the wavelengths $\lambda_2, \ldots \lambda_N$ in the input beam **1204**, such that a transmitted beam **1205** having wavelengths $\lambda_2, \ldots \lambda_N$ is transmitted through the VBG **1232** along the optical axis x.

The transmitted beam **1205** is incident on a second VBG element **1234**. The second VBG **1234** may be fabricated, like the first VBG **1234**, such that light having wavelength λ_1 would be deflected from the second VBG **1234** at a first angle α to the exit face **1234**B of the VBG **1234**. As shown, the VBG **1234** is positioned such that its grating vector A and exit face **1234**B are at a known angle θ (>90°) to the optical axis x of the device. Light **1202** having wavelength λ_2 is deflected from the second VBG **1234** at a known angle β to the exit face **1234**B of the VBG **1234** (and, therefore, at a known angle to the optical axis x). The device may include a second optical receiver **1212** that receives the deflected beam **1202**. The second VBG **1234** is transparent to the rest of the wavelengths $\lambda_3, \ldots \lambda_N$ in the transmitted beam **1205**, such that a second transmitted beam **1206** having wavelengths $\lambda_3, \ldots \lambda_N$ is transmitted through the VBG **1234** along the optical axis x.

The transmitted beam **1206** is incident on a third VBG element **1236**. The third VBG **1236** may be fabricated, like the first VBG **1232**, such that light having wavelength λ_1 would be deflected from the third VBG **1236** at a first angle α to the exit face **1236**B of the VBG **1236**. As shown, the VBG **1236** is positioned such that its grating vector A and exit face **1236**B are at a known angle ϕ (<90°) to the optical axis x of the device. Light **1203** having wavelength λ_3 is deflected from the third VBG **1236** at a known angle γ to the exit face **1236**B of the VBG **1236** (and, therefore, at a known angle to the optical axis x). The device may include a third optical receiver **1213** that receives the deflected beam **1203**. The third VBG **1236** is transparent to the rest of the wavelengths $\lambda_4, \ldots \lambda_N$ in the transmitted beam **1206**, such that a third transmitted beam **1207** having wavelengths $\lambda_4, \ldots \lambda_N$ is transmitted through the VBG **1236** along the optical axis x. The device may include a fourth optical receiver **1215** that receives the transmitted beam **1207**.

FIG. **13** depicts a device according to the invention that includes a complex VBG filter element that has been fabricated from a number of simple, possibly identical, VBG elements. In function it is similar to the device described above in connection with FIG. **12** but instead of being positioned and adjusted individually in the package, the elements can be properly positioned in a suitable fixture in direct physical contact with one another and then permanently bonded together, using suitable bonding materials that are well known in the art, thus creating a single compounded element with complex functionality.

The positioning of the individual VBG elements with respect to one another in such an arrangement can be important to the usefulness of the assembly. Methods of exercising such control can include: a) proper surface preparation of the wafers of the recording material, such as polishing, parallelism of the surfaces etc.; b) proper rotational orientation of the elements with respect to each other during the bonding procedure; c) use of calibrated spacers to the adjust relative angle between the individual VBG elements; d) precise control of the tilt angle of the wafer with respect to the recording laser beams during the holographic recording process.

This approach, referred to as "lamination cascading," enables the achievement of the same density of the grating packing in the same package volume as the direct multiplexing of the filters during the recording process, but without the need of multiple exposures and without the physical overlap, and thus interference, of the individual filters in the bulk of the material.

As shown in FIG. **13**, an optical input **1314** carries light **1304** having wavelengths $\lambda_1, \ldots \lambda_N$. Light **1304** is incident on a series of VBG elements **1332**–**1336** along the optical axis x of the device. The VBG elements **1332**–**1336** are fabricated such that light **1301** having wavelength λ_1 is deflected from the third VBG **1336** at a first angle α to the exit face **1336**B of the VBG **1336**, light **1302** having wavelength λ_2 is deflected from the third VBG **1336** at a second angle β to the exit face **1336**B of the VBG **1336**, and light **1303** having wavelength $\lambda_3$is deflected from the third VBG **1336** at a third angle γ to the exit face **1336**B of the VBG **1336**. The device may include a first optical receiver **1311** that receives the deflected beam **1301**, a second optical receiver **1312** that receives the deflected beam **1302**, and a third optical receiver **1313** that receives the deflected beam **1303**. The VBGs **1332**–**1336** may be transparent to the rest of the wavelengths $\lambda_4, \ldots \lambda_N$ in the input beam **1304**, such that a transmitted beam **1305** having wavelengths $\lambda_4, \ldots \lambda_N$ is transmitted through the VBGs **1332**–**1336** along the optical axis x. The device may include a fourth optical receiver **1315** that receives the transmitted beam **1305**.

FIG. **14** depicts a device according to the invention in which any simple, individual VBG element can be used for processing several wavelength channels by allowing multiple paths through it in different directions. In its simplest form, the so-called "double pass configuration" functions as follows:

A series of simple individual VBG elements is positioned in line as described above in connection with FIG. **12**. A mirror is placed at the end of the chain of the elements, which reflects the transmitted light back onto the same elements. This has the effect of folding the chain of the elements back onto itself. The mirror angle is adjusted slightly, so that the angle of the back-reflected light is somewhat different than the forward-propagating light. This angle is adjusted in such a way as to tune the center wavelength of the VBG filters to the desired value.

In such an implementation, the method allows using each of the VBG elements more than once, thus effectively increasing the number of filters without increasing the number of VBG elements, and thereby enabling the overall size of the package to remain practically the same. Multiple path folding is also possible if an additional mirror is used in the beginning of the chain of the VBG elements, slightly offset from the axis in angle and space.

As shown in FIG. **14**, an optical input **1415** carries light **1405** having wavelengths $\lambda_1, \ldots \lambda_N$ Light **1405** is incident on a first VBG element **1432** along the optical axis x of the device. The first VBG **1432** is fabricated such that light **1401** having wavelength λ_1 is deflected from the first VBG **1432** at an angle α to the exit face **1432**B of the first VBG **1432**. The first VBG **1432** is transparent to the rest of the wavelengths $\lambda_2, \ldots \lambda_N$ in the input beam **1405**, such that a transmitted beam **1406** having wavelengths $\lambda_2, \ldots \lambda_N$ is transmitted through the VBG **1432** along the optical axis x.

The transmitted beam **1406** is incident on a second VBG element **1434**. The second VBG **1434** is fabricated such that light **1402** having wavelength λ_2 is deflected from the second VBG **1434** at an angle β to the exit face **1434**B of the second VBG **1434**. The second VBG **1434** is transparent to the rest of the wavelengths $\lambda_3, \ldots \lambda_N$ in the transmitted beam **1406**, such that a transmitted beam **1407** having wavelengths $\lambda_3, \ldots \lambda_N$ is transmitted through the VBG **1434** along the optical axis x.

The transmitted beam **1407** is directed toward a mirror **1420**, which is disposed at an angle ϕ to the optical axis x of the device. The reflected beam **1408** is incident on the second VBG **1434** at an angle ϕ to the exit face **1434**B. The second VBG **1434** is fabricated such that light **1403** having wavelength λ_3 is deflected from the second VBG **1434** at an angle γ to the entrance face **1434**A of the second VBG **1434**. The second VBG **1434** is transparent to the rest of the wavelengths $\lambda_4, \ldots \lambda_N$ in the reflected beam **1408**, such that a reflected beam **1409** having wavelengths $\lambda_4, \ldots \lambda_N$ is transmitted through the VBG **1434**.

The reflected beam **1409** is incident on the first VBG **1432** at an angle ϕ to the exit face **1432**B. The first VBG **1434** is fabricated such that light **1404** having wavelength λ_4 is deflected from the first VBG **1432** at an angle δ to the entrance face **1432**A of the first VBG **1432**. The first VBG **1432** is transparent to the rest of the wavelengths $\lambda_5, \ldots \lambda_N$ in the reflected beam **1409**, such that a reflected beam **1410** having wavelengths $\lambda_5, \ldots \lambda_N$ is transmitted through the VBG **1432**.

The device may include a first optical receiver that receives the deflected beam **1401**, a second optical receiver that receives the deflected beam **1402**, and a third optical receiver that receives the deflected beam **1403**, and a fourth optical receiver that receives the deflected beam **1404**. The device may also include a fifth optical receiver that receives the reflected beam **1410**.

It should be understood that any of the techniques described above can be optimized to take maximum advantage of VBG properties such as: transparency to all but one wavelength, angular tunability, functionality distributed over the volume of a thick material, material rigidity and dimensional stability, excellent polishing qualities, and the like.

Methods for Economically Manufacturing VBG Elements

In the manufacturing of VBG elements, it is typically desirable to minimize the costs of production of such elements. For that reason, holographic recording of each element individually is likely to be cost-prohibitive for most or all of the high-volume applications. A number of methods according to the invention for cost-effective production of such elements will now be described.

A first such method, depicted in FIG. **15**, exploits the unique property of a hologram, whereupon each fractional piece of the recorded hologram possesses full and complete information about the recorded object. When applied to the VBG filters recorded on the PRG plates, it means that each piece of such plate, or wafer, should have the same filtering properties as the wafer in whole. For that reason, a large-size wafer **1500** can be diced, using a suitable cutting device, such as a saw, for example, into a large number of relatively small individual VBG elements **1502**, each with complete filter functionality. In following this process, one could significantly reduce the number of recording and testing operations, thereby reducing the manufacturing costs of the VBG elements.

A second cost-reduction method according to the invention applies to the repetitive fabrication of the filter with identical properties. Such an approach is particularly suitable for high-volume production environments. In such circumstances reproduction of a filter with a complex shape, which may require, for example, multiple exposure steps to achieve the complete control over its spectral shape, may result in a prohibitively long and complex manufacturing operations. However, since holography allows true and complete reconstruction of the recorded wavefront, it is, therefore, possible to record a hologram of the reconstructed wavefront, rather than the true original, to achieve the same result.

This approach includes: a) placing a "virgin" recording wafer directly behind a recorded "master" hologram; and b) directing the reference beam onto the master hologram in exactly the same fashion as during the recording of the master. The transmitted reference wave and the reconstructed object wave interfere again behind the master hologram. Consequently, a new hologram is recorded on the virgin wafer, which is an exact replica of the master.

The advantages of this method include but are not limited to the following: a) better stability (not sensitive to the phase fluctuations); b) simpler setup (no filter shape control required); c) no polishing on the virgin wafer is required, if it is placed in direct contact with the master and an index matching fluid is used on the interface; and d) shorter cycle times (higher throughput).

Methods to Control the Filter Response Function

When used in practical applications such as in fiber-optic devices, for example, the spectral shape of a filter can be used to manipulate the wavelengths of light in a desired fashion. The filter shape can determine such device parameters as adjacent channel isolation, cross-talk, suppression ratio, etc. The ability to control the spectral shape of the VBG filters, therefore, can make the difference between a practically usable device and a practically useless one.

As follows from the general theory of Bragg diffraction (see Kogelnik), the spectral shape of the filter created by a VBG is related via a Fourier transform to the amplitude and phase envelope of the VBG along the general direction of propagation of the affected light wave. It is, therefore, desirable to be able to control both in order to create a filter with a desired spectral shape.

A method according to the invention for controlling the spectral shape of a VBG filter relates to the use of the Fourier transform property of a lens and the phase capturing ability of the holographic recording method. As depicted in FIG. **16**A, a method **1600** for creating a VBG filter with any desired spectral shape can be performed as follows. A mask **1602** representing the desired filter shape is placed in the front focal plane of a lens **1604** situated in the object arm of the holographic recording setup. The recording media sample **1606** (e.g., a glass wafer) is placed in the back focal plane of the same lens. The plane-wavefront reference beam of the holographic recording setup overlaps with the object beam on the sample, subtending it at an angle required by the target operational wavelength of the VBG filter being recorded.

When positioned as described, the lens creates a true Fourier transform of the mask directly on the recording medium. Via a coherent interference with the plane reference wave, both the amplitude and the phase of the Fourier transform are transferred to the amplitude and phase envelope of the VBG imprinted on the recording material. When reconstructed, or "read," with a light beam nearly normal to the recorded grating planes, the spectral response of the VBG filter thus recorded will take the shape of the masks placed in the front focal plane of the lens.

This method allows for a single exposure recording of a filter with practically arbitrary complexity of the shape of the spectral response function and is referred to as the "parallel method" or the "holographic filter imprinting method."

A holographic filter imprinting method according to the invention can be similarly applied to the task of shaping the filter response function of transmission VBG filters. It may be accomplished by choosing a proper orientation of the apodizing mask relative to the direction of the grating planes and, similarly, by choosing the proper entrance and exit faces on the VBG element.

Exemplary methods for creating transmissive and reflective VBGs are depicted in FIGS. **16**B and **16**C respectively. As shown, a mask **1612** having a slit **1614** can be placed in the front focal plane of the lens. Light shone through the mask will generate a square amplitude profile **1616**. As the light passes though the lens, the Fourier transform **1618** of the square amplitude profile will be imprinted on the sample **1620**. When reconstructed, the spectral response of the pattern **1622** recorded on the VBG filter **1620** will take the shape of a square amplitude profile **1624**. Depending on the orientation of the mask relative to the grating plane, the VBG can be made reflective (as shown in FIG. **16**B) or transmissive (as shown in FIG. **16**C).

Method for Controlling the Shape of Transmissive VBG Filters

Furthermore, when dealing with VBG filters functioning in the transmission geometry, a different approach can be taken in order to manipulate the spectral shape of the filter. In this case, the method, which is depicted in FIG. **17**, comprises multiple, sequential exposures of the same volume of the recording material. Each exposure would produce a simple plane VBG, but after recording multiple gratings a filter of an arbitrary shape will be constructed via coherent addition of the recorded VBGs. Volume Bragg gratings are physical representations of sinusoidal waves, and, therefore, their coherent sum is a Fourier transform of an envelope function.

For that reason, a close representation of an arbitrary amplitude and phase envelope function can be constructed via a series of holographic exposures, provided appropriate control is exercised over both the amplitude and the relative phase of the gratings recorded in such series of exposures.

Such control can be achieved via employing techniques for active measurement and stabilization of the phase of the recorded VBGs.

As shown in FIG. **17**, a virgin sample **1702** is subjected to a first pair of incident beams **1712** and **1714**. Beam **1712** is incident on the entrance face **1702**A of the virgin sample **1702** at an angle α relative to the entrance face **1702**A (and, as shown, relative to the grating vector A). Beam **1714** is incident on the entrance face **1702**A of the virgin sample **1702** at an angle β relative to the entrance face **1702**A (and, as shown, relative to the grating vector A). Thus, a first holographic sample **1704** is formed having a first holographic image **1722**.

The first holographic sample **1704** is then subjected to a second pair of incident beams **1716** and **1718**. Beam **1716** is incident on the entrance face **1704**A of the first holographic sample **1704** at an angle γ relative to the entrance face **1704**A (and, as shown, relative to the grating vector A). Beam **1718** is incident on the entrance face **1704**A of the first holographic sample **1704** at an angle δ relative to the entrance face **1704**A (and, as shown, relative to the grating vector A). Thus, a second holographic sample **1706** is formed having a second holographic image **1724**.

VBG Chip

FIG. **18** depicts an integrated VBG "chip" according to the invention. As shown, the VBG chip **1800** is a monolithic glass structure into which a plurality of holographic images or "gratings" have been recorded. An optical input **1815** carries light **1805** having wavelengths $\lambda_1, \ldots \lambda_N$. Light **1805**, which may be collimated, is incident on a first grating **1822**. Grating **1822** is recorded such that light **1801** having wavelength λ_1 is deflected at an angle such that it is received by grating **1832**. Grating **1832** is recorded such that it deflects the light **1801** out of the chip **1800** toward an optical receiver **1811**. Grating **1822** is transparent to the rest of the wavelengths $\lambda_2, \ldots \lambda_N$ in the input beam **1805**, such that a transmitted beam **1806** having wavelengths $\lambda_2, \ldots \lambda_N$ is transmitted through the grating **1822**.

The transmitted beam **1806** is incident on grating **1824**, which is recorded such that light **1802** having wavelength λ_2 is deflected at an angle such that it is received by grating **1834**. Grating **1834** is recorded such that it deflects the light **1802** out of the chip **1800** toward an optical receiver **1812**. Grating **1824** is transparent to the rest of the wavelengths $\lambda_3, \ldots \lambda_N$ in the beam **1806**, such that a transmitted beam **1807** having wavelengths $\lambda_3, \ldots \lambda_N$ is transmitted through the grating **1824**.

Similarly, the transmitted beam **1807** is incident on grating **1826**, which is recorded such that light **1803** having wavelength λ_3 is deflected at an angle such that it is received by grating **1836**. Grating **1836** is recorded such that it deflects the light **1803** out of the chip **1800** toward an optical receiver **1813**. Grating **1826** is transparent to the rest of the wavelengths $\lambda_4, \ldots \lambda_N$ in the beam **1807**, such that a transmitted beam **1808** having wavelengths $\lambda_4, \ldots \lambda_N$ is transmitted through the grating **1826**.

The transmitted beam **1808** is incident on grating **1828**, which is recorded such that light **1804** having wavelength X_4 is deflected at an angle such that it is received by grating **1838**. Grating **1838** is recorded such that it deflects the light **1804** out of the chip **1800** toward an optical receiver **1814**. Grating **1828** is transparent to the rest of the wavelengths $\lambda_5, \ldots \lambda_N$ in the beam **1808**, such that a transmitted beam **1809** having wavelengths $\lambda_5, \ldots \lambda_N$ is transmitted through the grating **1828**. The transmitted beam **1809** is directed toward an optical receiver **1816**. As shown, each of the optical receivers **1811**- **1814** and **1816** can be an optical fiber, for example. Any or all of the optical receivers **1811**-**1814** and **1816** can be bundled together to form an optical fiber ribbon, for example.

A VBG chip as shown can be made according to the following method. One or more incident beams are directed toward a first location of a virgin sample (to form grating **1822**, for example). Then, the beams are turned off, and either the sample or the source of illumination is positioned (e.g., the sample may be moved laterally and/or rotationally as necessary) such that the incident beam(s) may now be directed toward a second location on the sample (to form grating **1824**, for example). This process is repeated until all desired gratings have been recorded.

Thus, there have been described fiber optic devices comprising volume Bragg gratings and methods for fabricating the same. Those skilled in the art will appreciate that numerous changes and modifications can be made to the preferred embodiments of the invention, and that such changes and modifications can be made without departing from the spirit of the invention. Examples of devices that can be made in accordance with the invention include, without limitation, 1×N laser source combiners, multi-channel transmit/receive modules (including triplexers), optical add-drop multiplexers, terminal multiplexers, network monitors, wavelength lockers, tunable filters, tunable gain equalizers, dispersion compensators, and the like.

What is claimed:

1. A method for manufacturing a Bragg grating element, the method comprising:

forming a Bragg grating wafer having a Bragg grating recorded therein, said Bragg grating being characterized by a grating wave vector; and

segmenting the Bragg grating wafer into a plurality of individual Bragg grating elements, wherein each of the individual Bragg grating elements retains the grating wave vector of the Bragg grating wafer.

2. The method of claim **1**, wherein segmenting the Bragg grating wafer comprises dicing the Bragg grating wafer into the plurality of individual Bragg grating elements.

3. The method of claim **1**, wherein the Bragg grating wafer is made of a photosensitive glass.

4. The method of claim **3**, wherein the Bragg grating wafer is made of a photosensitive glass containing at least one of the group consisting of silicon oxide, aluminum oxide, and zinc oxide.

5. The method of claim **3**, wherein the photosensitive glass includes silver, an alkali oxide, fluorine, and at least one of the group consisting of chlorine, bromine, and iodine.

6. The method of claim **5**, wherein the photosensitive glass includes cerium oxide.

7. The method of claim **1**, wherein the Bragg grating wafer contains a reflective Brag grating.

8. The method of claim **7**, wherein the individual Bragg grating elements are reflective Bragg grating elements.

9. The method of claim **1**, wherein the Bragg grating wafer contains a transmissive Bragg grating.

10. The method of claim **9**, wherein the individual Bragg grating elements are transmissive Bragg grating elements.

11. The method of claim **1**, wherein the Bragg grating wafer contains an apodized Bragg grating.

12. The method of claim **1**, wherein the Bragg grating wafer has a dimension of three or more individual Bragg grating elements.

13. The method of claim **1**, wherein segmenting the Bragg grating wafer comprises sawing the Bragg grating wafer into the plurality of individual Bragg grating elements.

14. The method of claim **12**, wherein dicing the Bragg grating wafer comprises dividing the Bragg grating wafer along each of a first direction and a second direction.

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