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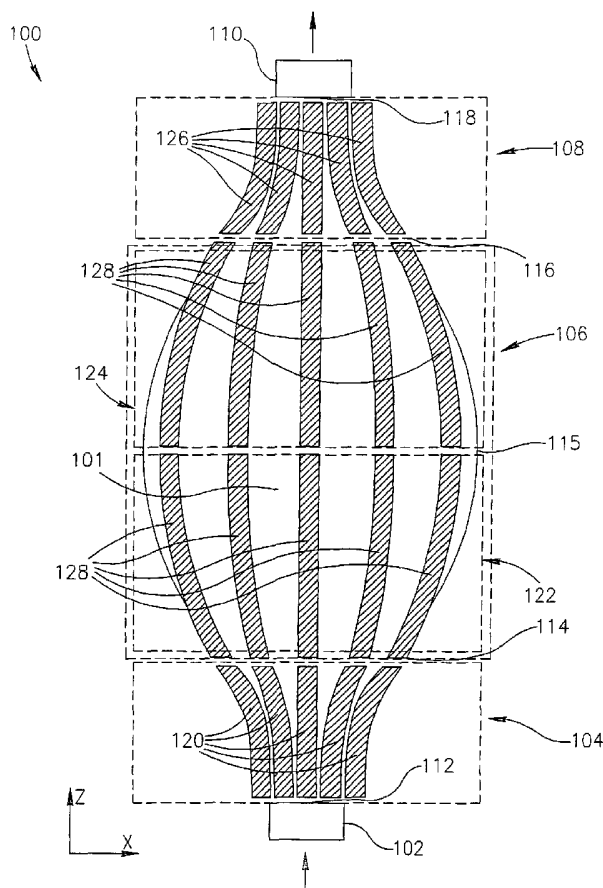
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[Continued on next page]

(54) Title: INDUCED OPTICAL WAVEGUIDE DEVICE



(57) Abstract: A waveguide arrangement for controlling one or more optical attributes of a light signal, including a 1Xn coupler section having n control elements, wherein n is equal or greater than one, a dynamic section associated with the 1Xn coupler section and having at least one control element, and an nX1 coupler section associated with the dynamic section and having n control elements, wherein the control elements, when activated according to a predetermined scheme, are able to produce at least one dynamically-controlled channel in at least one, respective, region of the waveguide arrangement by modifying a refractive index of the waveguide arrangement in the at least one region, respectively, and wherein the at least one dynamically-controlled channel, when produced, is able to guide at least a fraction of the light signal.



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INDUCED OPTICAL WAVEGUIDE DEVICE

FIELD OF THE INVENTION

[001] The present invention relates generally to the field of optical devices and,
5 more specifically, to optically controlling at least one attribute of a light signal.

BACKGROUND OF THE INVENTION

[002] In the field of integrated optics, there may be a need to use different devices, for example, devices designed to allow switching, mode converting,
10 and/or attenuating of a light signal propagating along one or more single-mode (SM) or multi-mode (MM) waveguides.

[003] U.S. Patent No. 5,623,566 to Hyung J. Lee, et al describes a device using thermo-optic deflection to transfer optical power between a single input waveguide and one of N output waveguides.

15 [004] European Patent Application EP-0513919-A1 to Van Der Tol describes a passive device for mode conversion of a first guided mode into a second pre-defined mode. The device is described to include a periodic geometrical structure consisting of a periodic sequence of two wave-guiding subsections within each period, wherein the lengths of the subsections and the number of
20 periods being matched to a pre-determined conversion fraction may be designed to allow coupling of a first pre-defined guided mode to a second

pre-defined guided mode. Similar devices are also described in U.S. Patent No. 5,703,977 to Pedersen et al and in European Patent Application EP0645650A1 to Van Der Tol. In such passive devices, the fraction of light being converted is pre-determined by the geometry of the device and, therefore, the activation and
5 operation of such devices cannot be selectively adjusted or controlled.

[005] U.S. Patent No. 5,574,808 to Van Der Tol et al describes a mechanism for activating and de-activating a mode-conversion device. The described device is activated by activating an electrode designed to disrupt the coupling between guided modes of the device, thereby to convert the coupling of a signal from a
10 first guided mode to a second guided mode.

[006] A Mach-Zehnder interferometer (MZI) as is known in the art may be used in conjunction with an optical switch or an optical mode converter. In existing devices, the MZI may split the power of a light signal between two light-guiding arms. A drawback of such devices is that even a slight error in the splitting of
15 power may result in a significant amount of cross talk. A MZI as is known in the art is based on a Y-splitter and a Y-combiner, connected in parallel with a two-arm structure. The splitter splits incoming light into both arms of the structure, and the combiner re-combines the light from both arms to produce outgoing light. The MZI may be connected to input and output multi-mode
20 waveguides, each capable of supporting two modes, namely, M1 and M2, respectively. A fabrication error in the splitter may result in uneven splitting of the amplitude of an input signal, e.g., $\frac{1}{\sqrt{2}} + \Delta$, $\frac{1}{\sqrt{2}} - \Delta$, between the two signals fed to the arms of the two-arm structure. This cross-talk may result in undesired

cross-talk between channels. If the combiner has a precise 1:1 combining ratio, assuming there is no phase difference between both arms, the mode in the MM waveguide resulting from a light signal entering one branch of the combiners

$\frac{1}{\sqrt{2}}(M_1 + M_2)$, and the mode in the MM waveguide resulting from light entering

5 the other branch of the combiner is $\frac{1}{\sqrt{2}}(M_1 - M_2)$. Therefore, without taking

into account splitter inaccuracy, the resulting mode in the MM waveguide would be the sum of contributions of both branches of the combiner,

$$\frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}(M_1 + M_2)\right) + \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}(M_1 - M_2)\right) = M_1, \text{ i.e., there is no second mode}$$

and, thus, no cross-talk between channels. However, if splitter inaccuracy results in

10 uneven splitting of the light, as is often the case, re-combination of the two signals,

$$\left(\frac{1}{\sqrt{2}} + \Delta\right)\left(\frac{1}{\sqrt{2}}(M_1 + M_2)\right) + \left(\frac{1}{\sqrt{2}} - \Delta\right)\left(\frac{1}{\sqrt{2}}(M_1 - M_2)\right) = M_1 + \sqrt{2}\Delta M_2,$$

introduces the second mode, resulting in undesired cross-talk.

SUMMARY OF THE INVENTION

15 [007] Embodiments of the present invention provide a dynamically controllable, multi-channel, optical apparatus to dynamically, e.g., tunably, control attributes of a signal of light, and a method of dynamically controlling attributes of light signals.

[008] The device in accordance with embodiments of the invention may include
20 a waveguide arrangement. The waveguide arrangement may include a 1XN

adiabatic coupler section, an N-channel dynamic section associated with the 1XN coupler section, and an NX1 adiabatic coupler section associated with the N-channel dynamic section.

[009] According to embodiments of the invention, the waveguide arrangement may include a tapered structure including a substantially narrow width at an input of the 1XN adiabatic coupler section, a maximum width at substantially a middle portion of the N-channel dynamic section, and a substantially narrow width at an output of the NX1 adiabatic coupler section.

[0010] According to embodiments of the invention, the device may also include at least one control element associated with the 1XN coupler section, at least one control element associated with the N-channel dynamic section, and at least one control element associated with the NX1 coupler section.

[0011] According to embodiments of the invention, the input-coupler control elements, the N-channel section control elements and/or the output-coupler control elements may be independently and/or jointly activated to change a predetermined optical property, e.g., an effective index of refraction, of at least one respective region of the waveguide arrangement, thereby to activate at least one dynamically-controlled, individually selected, channel associated with the at least one region, respectively. Further, in some embodiments of the invention, at least some of the control elements may be controllably activated to produce a predetermined, tunable, change in the predetermined optical property.

[0012] According to exemplary embodiments of the invention, at least some of the control elements may include heating elements.

[0013] Exemplary embodiments of the present invention may be implemented in the form of a Mode Converter (MC), a Mach-Zehnder Interferometer (MZI), a Variable Optical Attenuator (VOA), or any other optical device that may benefit from the functionalities provided by the invention.

[0014] Other exemplary embodiments of the invention provide a method for controlling one or more signal attributes of a light signal propagating through a waveguide. The method may include controllably modifying a pre-determined optical property, e.g., a refractive index of at least one region of the waveguide to controllably activate at least one, respective, dynamically-controlled, individually selected channel, coupling at least one fraction of the light signal to the at least one channel, respectively, controllably modifying at least one channel-attribute of the at least one channel, respectively, and coupling the at least one channel to an output of the waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, both as to organization and method of operation, together with objects, features and advantages thereof, may best be understood by

reference to the following detailed description when read with the accompanied drawings in which:

[0016] Fig. 1 is a schematic illustration of a top-view of an optical device, in accordance with exemplary embodiments of the present invention;

5 [0017] Fig. 2 is a schematic, conceptual, illustration of a top-view cross-section of the device of Fig. 1, in accordance with exemplary embodiments of the present invention;

[0018] Fig. 3 is a schematic illustration a front-view cross-section of the device of Fig. 1;

10 [0019] Fig. 4 is a schematic, conceptual, cross sectional illustration of a Multi-Mode (MM) waveguide, according to exemplary embodiments of the present invention;

[0020] Fig. 5 is a schematic illustration of graph depicting temperature increase as a function of location in a cross-section of the waveguide of Fig. 4, in an active state of operation, according to exemplary embodiments of the invention;

[0021] Fig. 6A is a schematic graph depicting effective refractive index and mode-order spectrum, respectively, as a function of horizontal location in the waveguide of Fig. 4, in an inactive state, according to exemplary embodiments of the invention;

20 [0022] Fig. 6B is a schematic graph depicting effective refractive index and mode-order spectrum, respectively, as a function of horizontal location in

the waveguide of Fig. 4, in an active state of operation, according to exemplary embodiments of the invention;

[0023] Fig. 7 is a schematic, simplified plane view illustration of a Mach-Zehnder interferometer (MZI) in accordance with an exemplary embodiment of the invention;

[0024] Fig. 8A is a schematic illustration of a numerical simulation of propagation of a light signal in an inactive state of the device of Fig. 7, in accordance with exemplary embodiments of the present invention;

[0025] Fig 8B is a schematic illustration of a numerical simulation of propagation of a light signal in the device of Fig. 7 producing a phase shift of π radians, in accordance with exemplary embodiments of the present invention;

[0026] Fig. 9 is a schematic, simplified, plane view illustration of a Mode Converter (MC) for conversion from a zero-order mode into a second-order mode, in accordance with an exemplary implementation of the invention;

[0027] Fig 10 is a schematic illustration of a numerical simulation of propagation of a light signal in the device of Fig. 9, in accordance with an exemplary embodiment of the present invention;

[0028] Fig. 11 is a schematic, simplified, plane view illustration of a Variable Optical Attenuator (VOA), in accordance with an exemplary implementation of the invention;

[0029] Fig. 12 is a schematic illustration of a numerical simulation of propagation of a light signal in the device of Fig. 11, in accordance with an embodiment of the present invention; and

[0030] Fig. 13 is a schematic block-diagram illustration of a method for controlling one or more attributes of a light signal in accordance with exemplary embodiments of the invention.

[0031] It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn accurately or to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity or several physical components included in one element. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements. It will be appreciated that these figures present examples of embodiments of the present invention and are not intended to limit the scope of the invention.

[0032] DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0033] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those of ordinary skill in the art that the present invention may be practiced without these specific details. In other instances, well-known methods, procedures, components and circuits may not have been described in detail so as not to obscure the present invention.

[0034] Reference is made to Fig. 1, which schematically illustrates a top-view of an optical device 100 in accordance with exemplary embodiments of

the present invention, and to Fig. 2, which is a schematic, conceptual, illustration of a top-view cross-section of the device of Fig. 1 depicting a plurality of dynamically-controlled channels 202, and a central non-activated channel 204, in accordance with embodiments of the invention.

5 [0035] According to exemplary embodiments of the invention, device 100 may include a Multi-Mode (MM) waveguide arrangement 101. Waveguide arrangement 101 may include a 1XN Dynamically Induced Adiabatic Coupler (DIAC) section 104, a Dynamically Induced N Channel (DINC) MM dynamic section 106, and an NX1 DIAC section 108.

10 [0036] According to exemplary embodiments of the invention, device 100 may receive input signals from a Single-Mode (SM) or a MM input waveguide 102 which may be connected to a leading edge 112 of 1XN DIAC section 104. A trailing edge 118 of NX1 DIAC section 108 may be connected to a SM or MM output waveguide 110.

15 [0037] According to embodiments of the invention, the combination of coupler section 104, dynamic section 106, and coupler section 108 may be designed to provide dynamically-controlled channels 202, as well as of non-activated channel 204, as described in detail below.

[0038] According to an exemplary embodiment of the invention, device
20 100 may accommodate an active state and an inactive state. When device 100 is in the inactive state, a light signal received from input waveguide 102 may propagate through central non-activated channel 204 and exit via output

waveguide 110, undergoing no change in mode order and without exciting other mode-orders of the light signal propagating in device 100.

[0039] According to a further exemplary embodiment of the invention, when device 100 is in the active state, a light signal received from input waveguide 102 may be at least partially coupled to one or more of dynamically-controlled channels 202. In embodiments of the invention, the signal population of each one of dynamically-controlled channels 202 may be separately and tunably controlled, as explained in detail below. Additionally or alternatively, in exemplary embodiments of the invention, channel-attributes of one or more of the dynamically-controlled channels 202, for example, a relative phase between the channels, may be separately controlled.

[0040] According to exemplary embodiments of the invention, waveguide 101 may be adiabatically tapered, so as to allow substantially unhindered propagation of light signals through central non-activated channel 204 with minimal loss and without exciting other mode-orders of the light signal propagating in device 100. According to these embodiments, waveguide 101 may have an input width, at leading edge 112, substantially compatible with the width of input waveguide 102, which width is significantly increased up to a maximum width at a middle portion 115 of dynamic section 106. The maximum width of waveguide 101 may be determined by the number of dynamically-controlled channels 202 required by the specific application of the device, and by a minimal width required for each channel 202 to allow coupling the input signal to one or more of channels 202, as described in detail below.

From middle portion 115, waveguide 101 may be adiabatically narrowed to substantially accommodate the width of output waveguide 110.

[0041] The adiabatic tapering of waveguide 101, as described above, may be achieved in the form of various tapered structures known in the art including but not limited to linear, polynomial, exponential, or hyperbolic tapered structures.

[0042] In exemplary embodiments of the invention, dynamically-controlled channels 202 may be activated and/or controlled by several methods known in the art for local modifying of index of refraction by an external process. These methods may include methods based on a heating effect, an electro-optic effect, an acousto-optic effect or any other suitable method of modifying the refractive index of a material.

[0043] According to embodiments of the invention, a plurality of refractive index control elements may be independently and/or jointly activated to controllably modify the optical properties, e.g., effective index of refraction, of at least one respective region of waveguide 101, thereby to controllably activate at least one dynamically-controlled channel 202 associated with the at least one region, respectively, as described below.

[0044] According to one embodiment of the invention, 1XN DIAC section 104 may include at least one control element 120 associated with waveguide 101. In an exemplary embodiment of the invention, a plurality of control elements 120 may be arranged, e.g., on top of waveguide 101, to fan out from narrow input waveguide 102 into coupler section 104.

[0045] According to embodiments of the invention, control elements 120 may include heating elements and/or any other suitable devices for affecting the refractive index of waveguide 101. According to some of these embodiments, control elements 120 may be implemented in the form of electrodes, for example, strips of material having a suitable electrical resistance capable of producing a predetermined increase in temperature in response to electrical current supplied thereto.

[0046] In some embodiments of the invention, the aggregated width of elements 120 at input 112 may be slightly greater than the width of input waveguide 102. In these embodiments, elements 120 may be arranged as closely as possible at input 112. However, the device may operate with some of control elements 120 positioned at least partly outside the cross-sectional area of waveguide 101. As the width of waveguide 101 increases, waveguide 101 becomes influenced by more of control elements 120, until all elements 120 are capable of activating dynamically-controlled channels 202 in device 100, as described below.

[0047] According to embodiments of the invention, control elements 120 may each have inactive and controllably active states of operation, as described herein. According to embodiments of the invention, each of control elements 120 may be activated independently to allow producing a desired coupling level between input waveguide 102 and one or more, respective, dynamically-controlled channels 202.

[0048] According to an embodiment of the invention, DINC MM dynamic section 106 may include a plurality of control elements 128. Control elements

128 may be arranged to conform to the shape of waveguide 101. A spacing between control elements 128 may be determined based on a minimal width of elements 128 that may be needed to activate and/or tune channels 202, as described below. According to embodiments of the invention, the center-to-center spacing, i.e., the minimal spacing between two centers of adjacent control elements 128, may be determined by the minimal required width of channels 202, as described above, such that control elements 128 may independently activate respective channels 202, allowing substantially no interference between adjacent channels 202. For example, for a channel 202 having a width of about 25 μ m, a center-to-center spacing of at least 25 μ m, e.g., about 30 μ m, may be used.

[0049] In exemplary embodiments of the invention, dynamic section 106 may include two control arrays, 122 and 124, each including a plurality of the control elements 128. In other embodiments of the invention, the number of control elements 128 and their arrangement may vary in accordance with the desired functionality of device 100, as described below.

[0050] According to embodiments of the invention, control elements 128 may include heating elements or any other suitable devices for affecting the refractive index of waveguide 101. According to some of these embodiments, control elements 128 may be implemented in the form of electrodes, for example, strips of material having a suitable electrical resistance capable of producing a predetermined increase in temperature in response to electrical current supplied thereto.

[0051] According to embodiments of the invention, control elements 128 may each have inactive and controllably active states of operation, as described herein. According to embodiments of the invention, each of control elements 128 may be activated independently to control and/or modify one or more attributes
5 of the dynamically-controlled channels 202, respectively, as described below.

[0052] According to one embodiment of the invention, NX1 DIAC section 108 may include at least one control element 126 associated with waveguide 101. In other exemplary embodiments of the invention, a plurality of N control element 126 may be arranged, e.g., on top of waveguide 101, to merge into
10 narrow output waveguide 110.

[0053] According to embodiments of the invention, control elements 126 may include heating elements or any other suitable devices for affecting the refractive index of waveguide 101. According to some of these embodiments, control elements 126 may be implemented in the form of electrodes, for
15 example, strips of material having a suitable electrical resistance capable of producing a predetermined increase in temperature in response to electrical current supplied thereto.

[0054] In some embodiments of the invention, the aggregated width of control elements 126 at output 118 may be slightly greater than the width of
20 output waveguide 110. In these embodiments, control elements 126 may be arranged as closely as possible at output 118. However, the device may operate with some of the control elements 126 positioned at least partly outside the cross-sectional area of output waveguide 110. As the width of waveguide 101 decreases, the waveguide becomes influenced by fewer control elements 126,

until some of control elements 126 may not be capable of activating dynamically-controlled channels 202 in MM waveguide 101, as described below.

[0055] According to embodiments of the invention, control elements 126 may each have inactive and controllably active states of operation, as described
5 herein. According to embodiments of the invention, each of control elements 126 may be activated independently and/or jointly to allow producing a desired coupling level between one or more of dynamically-controlled channels 202 and output waveguide 110.

[0056] According to some exemplary embodiments of the invention,
10 device 100 may have a total length, L, of between 2000 μ m and 40000 μ m, for example, about 20000 μ m; input 112 and output 118 may, respectively, have a width of between 6 μ m and 30 μ m, for example, about 18 μ m; middle portion 115 may have a width of between 30 μ m and 200 μ m, for example, about 100 μ m; heating elements 120, 128, and 126 may each have a width of between 5 μ m
15 and 30 μ m, for example, about 10 μ m; a center to center spacing between heating elements 128 may be between 30 μ m and 100 μ m, for example, about 50 μ m; DIAC section 104 may have a length of between 500 μ m and 5000 μ m, for example, about 2500 μ m; 1XN DIAC section 104 and NX1 DIAC section 108 may, respectively, have a length of between 500 μ m and 5000 μ m, for example,
20 about 2500 μ m; and dynamic section 106 may have a length of between 1000 μ m and 30000 μ m, for example, about 15000 μ m.

[0057] According to embodiments of the invention, channels 202 may be used by DIAC section 104 to controllably couple, i.e. direct, an at least one fraction of the input light signal to at least one respective region of section 104,

by controlling the activation of control elements 120, as described below. Channels 202 may be further used by DINC section 106 to controllably couple the at least one fraction of the light signal to at least one respective region of section 106, e.g., by controlling the activation of control elements 128, as
5 described below. Elements 128 may also be controllably activated to create a desired phase shift between two or more channels 202, thereby to control an attribute of the at least one fraction of the light signal, as described below. Channels 202 may also be used by DIAC section 108 to controllably couple, i.e. direct, the at least one fraction of the light signal substantially to an output, e.g.,
10 by controlling the activation of control elements 126, as described below.

[0058] According to embodiments of the invention, device 100 may be substantially insensitive to manufacturing errors and/or defects. Dynamically-controlled channels 202 may be used to tune the device, as described below, in order to compensate for fabrication errors, thereby providing
15 an increase in production yield.

[0059] Reference is now also made to Fig. 3, which conceptually illustrates a front-view cross-section 300 of device 100, according to exemplary embodiments of the invention.

[0060] According to exemplary embodiments of the invention, each one of
20 sections 104, 106 and/or 108 (Fig. 1) may be used in conjunction with standard PLC technology, and may have a simple layer structure as conceptually depicted in Fig. 3.

[0061] According to an exemplary embodiment of the invention, structure 300 may include a base substrate layer 302, a bottom-cladding layer 304 having a refractive index n_{bc} , a core layer 310 having a refractive index n_{core} , a top cladding layer 308 having a refractive index n_{tc} , and at least one refractive index control element 312. Control element 312 may be used to activate and/or control at least one of dynamically-controlled channels 202 (Fig. 2), as described below. Control element 312 may be a thin film electrode heater or any other suitable device capable of affecting the refractive index of the core layer. Base substrate 302 may be formed of any suitable material known in the art, for example, silicon. In some embodiments, base substrate 302 may be used as a heat sink, and may be held at a substantially constant temperature, e.g., using a Thermo-Electric Cooler (TEC) or any other suitable device adapted to keep the substrate at a substantially constant temperature.

[0062] In exemplary embodiments of the invention, the effective refractive index of core layer 310 may be greater than the effective refractive index of top cladding layer 308, which may be similar, in turn, to the refractive index of the bottom cladding layer 304, as follows:

$$[0063] \quad n_{core} > n_{tc}, n_{core} > n_{bc}, n_{bc} \geq n_{tc}. \quad (1)$$

[0064] According to some exemplary embodiments of the invention, core 310 may have a height, of between $1\mu\text{m}$ and $10\mu\text{m}$, for example, about $6\mu\text{m}$; the refractive index, n_{core} , of core 310 may be, between 1.445 and 1.5, for example, about 1.46; top cladding 308 may have a height of between $6\mu\text{m}$ and $20\mu\text{m}$, for example, about $14\mu\text{m}$, and a refractive index, n_{tc} , of between 1.44 and 1.495, for

example, about 1.45; and bottom cladding 304 may have a height of between $6\mu\text{m}$ and $20\mu\text{m}$, for example, about $15\mu\text{m}$, and a refractive index, n_{bc} of between 1.44 and 1.495, for example, about 1.45.

[0065] Reference is made to Fig. 4, which is a schematic, conceptual, illustration of a cross-section of a MM waveguide, which may be used to activate dynamically-controlled channel 202 (Fig. 2) according to exemplary embodiments of the present invention.

[0066] Waveguide 400 may include a core 402 having a refractive index n_1 embedded in a cladding 404, which may have a lower refractive index, n_0 . Waveguide 400 may also include a base-substrate 408 and may be associated with a refractive index control element, e.g., a heating element 406.

[0067] According to exemplary embodiments of the invention, waveguide 400 may have a cross-section aspect ratio such that the width, w , of the waveguide may be much larger than the height, h , of the waveguide, for example, to support only one mode order in the y direction. However, the width of waveguide 400, w , may be sufficiently wide in a horizontal, x , dimension to support several mode orders. These dimensions may be calculated using approximation methods, for example, the approximation method described in paragraph 2.4 of chapter two of *K. Okamoto "Fundamentals of Optical Waveguides", San Diego, Academic Press (1992)*, which is incorporated herein by reference in its entirety. .

[0068] According to embodiments of the invention, control element 406 may have inactive and controllably active states of operation, as described herein.

[0069] Reference is also made to Fig. 5, which schematically illustrates a graph depicting temperature increase lines 502 as a function of location in a cross-section of the waveguide of Fig. 4 in an inactive state, in accordance with an exemplary embodiment of the invention.

[0070] According to one exemplary embodiment of the invention, heating element 406 may be activated by a power supply of between 0 Watts and 10 Watts, for example, 0-2 Watts. According to this exemplary embodiment, the activation of the heating element may create an increase in temperature in its vicinity as illustrated schematically in Fig. 5, where lines 502 represent isothermal lines. A maximal temperature increase of between 0°K and 400°K, for example, between 100°K and 150°K, may be obtained in a location 504 proximal to the heating element. The temperature variation may exponentially decrease as distance from the heating element increases, as illustrated in Fig. 5.

[0071] The refractive index of silica may increase by approximately 1.15×10^{-5} for each 1°K increase in temperature. Therefore, according to this exemplary embodiment of the invention, an increase in refractive index, Δn , in a given region of waveguide 400 may be proportional to a respective temperature increase, ΔT , in the given region, as illustrated in Fig. 5, wherein:

$$[0072] \quad \Delta n = 1.15 \times 10^{-5} \Delta T \quad (2)$$

Reference is also made to Fig. 6A, which schematically illustrates a graph depicting effective refractive index and mode-order spectrum, respectively, as a function of horizontal location in the waveguide of Fig. 4 in an inactive state, in accordance with an exemplary embodiment of the invention, and to

5 Fig. 6B, which schematically illustrates a graph depicting effective refractive index versus location in the waveguide of Fig. 4 in an active state of operation, in accordance with an exemplary embodiment of the invention.

[0073] As shown in Fig. 6A, waveguide 400 (Fig. 4) may support several bound modes 602 having effective refractive indexes 604.

10 [0074] According to an embodiment of the invention, when heating element 406 (Fig. 4) is activated, it may introduce increase Δn in the refractive index in its proximity, as described above. The refractive index increase Δn may create a protrusion 606 in the effective index of the waveguide. Since Δn exponentially decreases as distance from the heating element increases, as
15 explained above, protrusion 606 may have a generally Gaussian shape. The height and/or width of protrusion 606 may be relative to the temperature increase created by heating element 406. A larger increase in temperature may provide a higher and/or wider protrusion 606. Therefore, heating element 406 (Fig. 4) may be provided with an electrical power, sufficient to create a
20 temperature increase, e.g. 100°K, which may result in a sufficiently high and/or sufficiently wide protrusion 606 to create a localized mode 608, which may define one dynamically-controlled channel 202 (Fig. 2) in the proximity of heating element 406 (Fig. 4), e.g., substantially underneath heating element 406. According to embodiments of the invention, a width of

dynamically-controlled channel 202 (Fig. 2) may be related to the temperature increase provided by heating element 406, such that a higher temperature increase may allow activating a narrower channel. According to exemplary embodiments of the invention, a temperature increase of 100°K may provide a
5 dynamically-controlled channel having a 25µm width.

[0075] Reference is now made to Fig. 7, which schematically illustrates a simplified plane view of a Mach-Zehnder interferometer (MZI) in accordance with an exemplary implementation of the invention.

[0076] Implementation of device 100 (Fig. 1) as a MZI 700 may require, in
10 accordance with this embodiment of the invention, activating two dynamically-controlled channels 202 (Fig. 2), as described below.

[0077] According to an embodiment of the invention, a 1XN DIAC section 702 may be implemented in the form of a splitter, e.g. a 3db splitter, for splitting the signal of an input 701 into two signals propagating through dynamic
15 channels 202 (Fig. 2), respectively. This may be achieved by activating two control elements, 708, while maintaining a plurality of elements 710 inactive. According to some of the embodiments of the invention, a power splitting balance of the device may be fine-tuned, e.g., by varying the activation level of activated elements 708. This may be achieved by controllably varying the
20 electrical power supplied to each one of elements 708, which may include heating elements as described above.

[0078] DINC MM section 706 may be implemented, in this embodiment, in the form of a twin-arm phase-shifter, e.g., by activating at least control element

712 and at least one control element 714, while maintaining a plurality of elements 716 inactive. According to an embodiment of the invention, differential activation between element 714 and element 712 may introduce a phase shift between signals propagating via two respective channels 202 (Fig. 2), which are
5 activated in regions of the waveguide substantially near elements 712 and 714, respectively, as described above. Any amount of phase shift, as is known in the art, may be produced between the signals, for example, a phase shift of between 0 and π (pi) radians, or any other phase shift sufficient for a specific implementation of the MZI.

10 [0079] According to exemplary embodiments of the invention, 1XN DIAC section 704 may be implemented in the form of a coupler, e.g. a 3db coupler, for coupling the two signals from the two dynamic channels 202 (Fig. 2) to an output waveguide 722, e.g., by activating two control elements 718 while maintaining a plurality of control elements 720 inactive. According to a further embodiment of
15 the invention, a power splitting balance of the device may be fine-tuned, e.g., by varying the activation levels of activated elements 718. This may be achieved by controllably varying the electrical power supplied to active elements 718.

[0080] Fig. 8A schematically illustrates a numerical simulation of propagation of a light signal in an inactive state of the device of Fig. 7 in
20 accordance with an exemplary embodiment of the present invention.

[0081] According to embodiments of the invention, device 700 in its inactive state may act as an adiabatically shaped, e.g., tapered, waveguide as shown in Fig. 8A. As may be noted, a signal 802 of zero-order mode entering the device may propagate through non-activated channel 803, undergoing

substantially no modification and exiting the device as a signal 804 of zero-order mode, which may be similar to signal 802.

[0082] Fig 8B schematically illustrates a numerical simulation of propagation of a light signal in the device of Fig. 7 producing a phase shift of π (pi) radians in accordance with an exemplary embodiment of the present invention.

[0083] When activated, device 700 may operate as a MZI as shown in Fig 8B. As may be noted, a signal 806 of zero-order mode may enter the device. Two fractions 808 of the signal may propagate through two dynamically-controlled channels 202 (Fig. 2), respectively, as described above. Activation of the control elements, as described above, may shift the phase of signals 808, for example, by π (pi) radians. Signals 808 may then be coupled, as described above, to create an output signal 810 of second-order mode.

[0084] Reference is now made to Fig. 9, which schematically illustrates a simplified plane view of a Mode Converter (MC) 900 for conversion from a zero-order mode to a second-order mode, in accordance with an exemplary implementation of the invention

[0085] Implementation of an exemplary embodiment of device 100 (Fig. 1) as MC 900 may require, in accordance with this embodiment of the invention, selectively activating three dynamically-controlled channels 202 (Fig. 2). Further embodiments of the invention, e.g., for conversion between other order modes, may require selective activation of a different number of channels 202 (Fig. 2) in accordance with the number of phase-shifts required, as described below.

[0086] In an exemplary embodiment of the invention, conversion between a zero-order mode and a second-order mode may be accomplished by implementing a 1XN DIAC section 902 in the form of a coupler, e.g., a three-way input coupler, for coupling an input signal entering an input 908 to three dynamically controlled channels 202 (Fig. 2), respectively. In this embodiment, a DINC MM section 904 may be implemented in the form of a phase-shifter, e.g., a three-channel phase-shifter, which may be used to produce appropriate phase-shifts between the three dynamically-controlled channels, respectively, as described below.

[0087] In this embodiment, a NX1 DIAC section 906 may be implemented in the form of an output coupler, e.g., a three-way coupler, for re-coupling the three dynamically-controlled channels to an output 910.

[0088] According to an exemplary embodiment of the invention, 1XN DIAC section 902 may be implemented in the form of a three-way input coupler by activating a set of three DIAC control elements 912 while maintaining a plurality of control elements 914 inactive, thus activating three dynamically-controlled channels 202 (Fig. 2), as described above.

[0089] DINC MM section 904 may be implemented in the form of a three-channel phase-shifter, e.g., by controlling the activation of central control elements 920 and outer control elements 916 to activate and/or control three dynamically-controlled channels 202 (Fig. 2), as described above. A phase difference of π (pi) radian may be produced between a central channel (not shown), activated by central control elements 920, and two outer channels (not shown), activated by outer control elements 916, by differential activation of

central control elements 920 and outer control elements 916, which phase difference may also depend on the difference in length between the outer and central channels.

[0090] According to an embodiment of the invention, NX1 DIAC section 906 may be implemented in the form of an output three-way coupler by activating three control elements 922 while maintaining a plurality of control elements 924 inactive, thus activating respective dynamically-controlled channels 202.

[0091] Fig. 10 schematically illustrates a numerical simulation of propagation of a light signal in the device of Fig. 9, in accordance with an exemplary embodiment of the present invention.

[0092] It may be noted that a signal 1002 of a zero-order mode may enter the device. Two fractions 1004 of the signal may propagate through two dynamically-controlled channels 202 (Fig. 2), respectively. A third fraction 1006 of the signal may propagate through central non-activated channel 204 (Fig. 2). Signal 1004 may undergo a phase shift, by activating refractive index control elements 916, as described above. At the output of the device, channels 202 (Fig. 2) may be coupled to an output, such that signals 1004 and 1006 may form an output signal 1008 of a second-order mode.

[0093] It should be appreciated that according to other embodiments of the present invention, device 100 (Fig. 1) may be implemented to enable conversion between any varieties of modes, as described above. It will be understood by those of ordinary skill in the art, that it may be possible to use an

N-channel device, in accordance with embodiments of the invention, to allow conversion of a signal of any mode-order smaller than N-1.

[0094] Fig. 11 schematically illustrates a top-view of a Variable Optical Attenuator (VOA), in accordance with an exemplary implementation of the invention.

[0095] Implementation of device 100 (Fig. 1) as a VOA 1100 may include, in accordance with an exemplary embodiment of the invention, implementing DINC MM section 1102 as an orthogonal projection section, wherein two opposite outer control elements, 1104 and 1106, may be activated while other control elements, 1108 and 1110, may remain inactive.

[0096] In an input DIAC section 1109 and an output DIAC section 1103, outer control elements 1112 and 1114, which may correspond to activated control elements 1108 and 1110, respectively, may also be activated, while control elements 1116 and 1118 may remain inactive.

[0097] According to embodiments of the invention, control elements 1102 and 1104 may be used to activate a first dynamically-controlled channel (not shown) in a region of VOA 1100 substantially underneath control elements 1112 and 1104, respectively. Thus, an input light signal guided by a first mode and entering through an input 1101 of VOA 1100 may be coupled to the first dynamically-controlled channel. A second dynamically controlled channel (not shown), beginning 1114 substantially at a mid section 1113 of VOA 1100, may be activated by activating control elements 1106 and. A first fraction of the light signal exiting the first channel, substantially underneath an end 1111 of control

element 1104, may propagate through the second channel guided by the first mode. A second fraction of the light signal may propagate through other regions of VOA 1100 guided by other modes supported by the VOA. According to embodiments of the invention, an output waveguide 1107 of VOA 1100 may be adapted to support only the first mode order. Thus, the first fraction of the light signal, propagating through the second control channel, may exit the VOA, while the second fraction may be refracted, diffracted, scattered, diffused and/or otherwise dissipated in a cladding of output waveguide 1107. By controlling the level of activation of control elements 1112, 1104, 1106 and 1114, respectively, the first fraction of the light signal may be tuned to a desired level. Thus, an attenuation level of the light signal may be tuned by appropriately controlling the activation of the control elements.

[0098] Fig. 12 schematically illustrates a numerical simulation of propagation of a light signal in the device of Fig. 11, in accordance with an embodiment of the present invention. As may be noted from Fig. 12, a light signal 1202 entering the VOA may be coupled to a first dynamically-controlled channel (not shown). At substantially a mid-section 1212 of the VOA, a second dynamically controlled channel (not shown) may be activated, such that a first fraction 1206 of the signal, guided by a first mode-order, may be coupled to the second channel. a second fraction 1208 of the signal, guided by other mode-orders, may propagate through different regions of the VOA, i.e., different from those of the second channel. At the output of the VOA only fraction 1206 of the signal may exit the VOA, while the second fraction may be refracted, diffracted, scattered, diffused and/or otherwise dissipated in the cladding.

[0099] Reference is now made to Fig. 13, which schematically illustrates a block-diagram of a method for controlling one or more signal attributes of a light signal propagating through a waveguide, in accordance with exemplary embodiments of the invention.

5 [00100] According to exemplary embodiments of the invention, the method may include modifying a pre-determined optical property of at least one region of the waveguide to controllably activate at least one, respective, dynamically-controlled channel, as indicated at block 1302.

[00101] The method may also include coupling at least one fraction of the
10 light signal to the at least one channel, respectively, as indicated at block 1304;

[00102] The method may further include controllably modifying at least one channel-attribute of the at least one channel, respectively, as indicated at block 1306.

[00103] As indicated at block 1308, the method may include coupling the at
15 least one channel to an output of the waveguide.

[00104] While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made. Embodiments of the present invention may include other apparatuses for
20 performing the operations herein. Such apparatuses may integrate the elements discussed, or may comprise alternative components to carry out the same purpose. It will be appreciated by persons skilled in the art that the

appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

CLAIMS

1. A waveguide arrangement for controlling one or more optical attributes of a light signal, comprising:

a $1 \times n$ coupler section having n control elements, wherein n is equal or greater than one;

a dynamic section associated with said $1 \times n$ coupler section and having at least one control element; and

an $n \times 1$ coupler section associated with said dynamic section and having n control elements,

wherein said control elements, when activated according to a predetermined scheme, are able to produce at least one dynamically-controlled channel in at least one, respective, region of said waveguide arrangement by modifying a refractive index of said waveguide arrangement in said at least one region, respectively, and wherein said at least one dynamically-controlled channel, when produced, is able to guide at least a fraction of said light signal.

2. The device of claim 1 wherein one or more of said control elements is activated independently of others of said control elements.

3. The device of claim 1 or claim 2 wherein one or more of said control elements is controllably activated to produce a desired change in said refractive index.
4. The device of any of claims 1-3 wherein said waveguide arrangement comprises a base substrate, a cladding, and a core embedded in said cladding, and wherein at least some of said control elements are associated with said cladding.
5. The device of any of claims 1-4 wherein at least one of said control elements comprises a heating element able to controllably modify the temperature of a respective region of said waveguide arrangement in response to a controllable supply of electric power.
6. The device of claim 5, wherein said heating element comprises a thin film electrode heater.
7. The device of any of claims 1-6 wherein said waveguide arrangement comprises an adiabatically-shaped structure.
8. The device of claim 7 wherein said adiabatically-shaped structure comprises a tapered structure having a relatively narrow width at an input of said $1 \times n$ coupler section of said waveguide arrangement, a maximal width in said n -channel section of said waveguide arrangement, and a relatively narrow width at an output of said $n \times 1$ coupler section of said waveguide arrangement.

9. A mode converter comprising a device as in any of claims 1-8,
wherein said one or more optical attributes comprise a mode-order
of said light signal.
10. The device of any of claims 1-8 wherein said one or more optical
attributes comprise a phase of said light signal.
11. The device of any of claims 1-10 able to operate in accordance
with one or more active states of operation and having one or
more inactive states.
12. The device of claim 10 wherein, at each of said one or more
inactive states, said waveguide arrangement substantially does
not affect said one or more optical attributes of the light signal.
13. The device of any of claims 1-12 wherein said at least one control
element of said dynamic section comprises a first control array,
interfacing said $1 \times n$ coupler section, and a second control array
interfacing said first control array and said $n \times 1$ coupler section, and
wherein said first control array is able to be activated
independently of said second control array.
14. A variable optical attenuator comprising a device as in claim 9,
wherein n is equal to two, and further comprising an input
waveguide associated with said $1 \times n$ coupler section and an output
waveguide associated with said $n \times 1$ coupler section, and wherein

said output waveguide is able to support at least one mode order supported by said input waveguide.

15. A Mach-Zehnder interferometer comprising a device as in any of claims 1-12, wherein n is equal to two, wherein said at least one region of said waveguide arrangement comprises two regions, wherein said at least one fraction of said signal comprises first and second fractions, and wherein said at least one control element of the dynamic section comprises first and second control elements that, when activated, produce a desired phase shift between said first and second fractions, respectively.

16. A method for controlling one or more attributes of a light signal propagating through a waveguide, the method comprising:

controllably modifying a predetermined optical property of at least one region of said waveguide to controllably activate at least one, respective, dynamically-controlled channel;

directing at least one fraction of said light signal to propagate in said at least one channel, respectively; and

coupling said at least one channel to an output of said waveguide.

17. The method of claim 16 comprising causing said at least one channel to shift a phase of said at least one fraction, respectively, of said signal.

18. A mode-converting waveguide arrangement for converting an input light signal from a first mode order to a second mode-order, the waveguide arrangement comprising:

a $1 \times n$ coupler section having n control elements, wherein n is equal or greater than one;

a dynamic section associated with said $1 \times n$ coupler section and having at least one control element; and

an $n \times 1$ coupler section associated with said dynamic section and having n control elements,

wherein said control elements, when activated in accordance with a predetermined scheme, are able to produce at least one dynamically-controlled channel in at least one, respective, region of said waveguide arrangement by modifying a refractive index of said waveguide arrangement in said at least one region, respectively, and wherein said at least one dynamically-controlled channel, when produced, is able to convert at least a fraction of said light signal from said first mode to said second mode.

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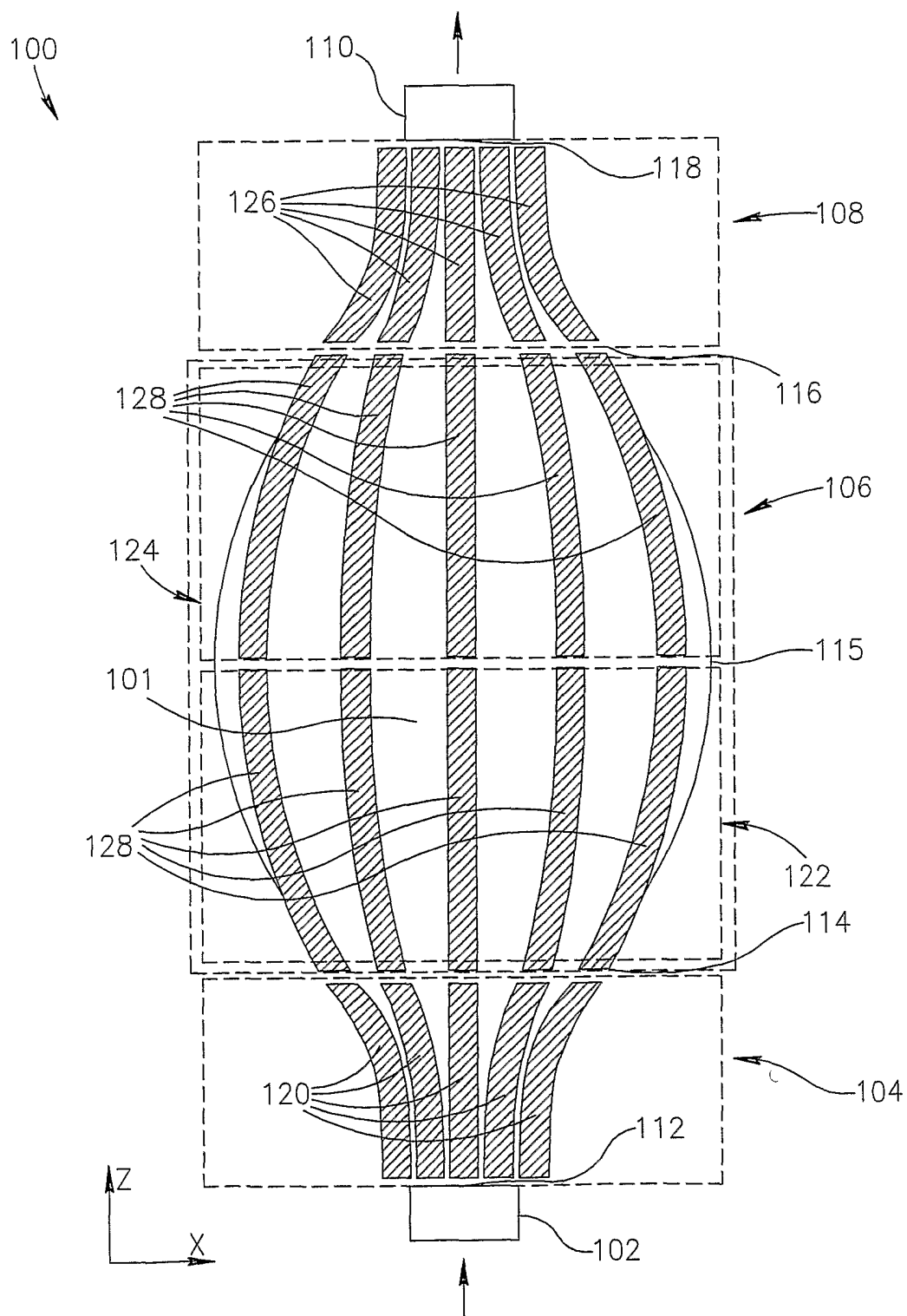


FIG.1

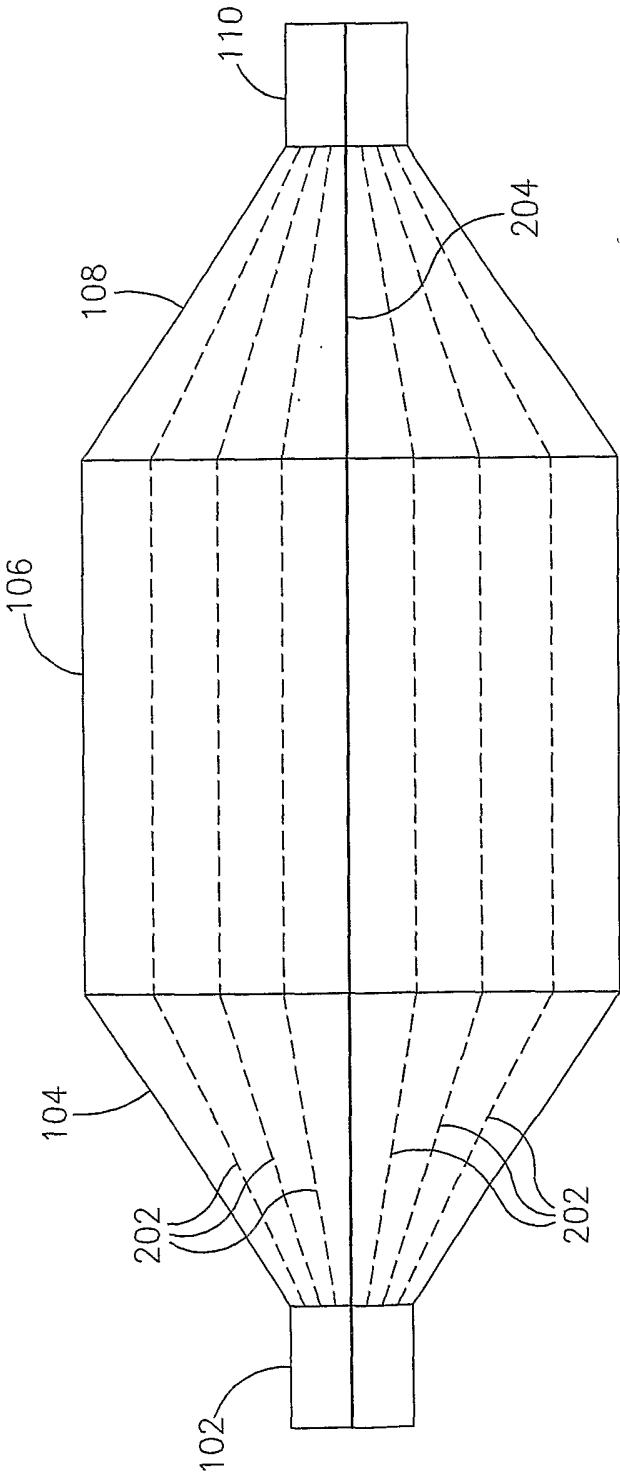


FIG. 2

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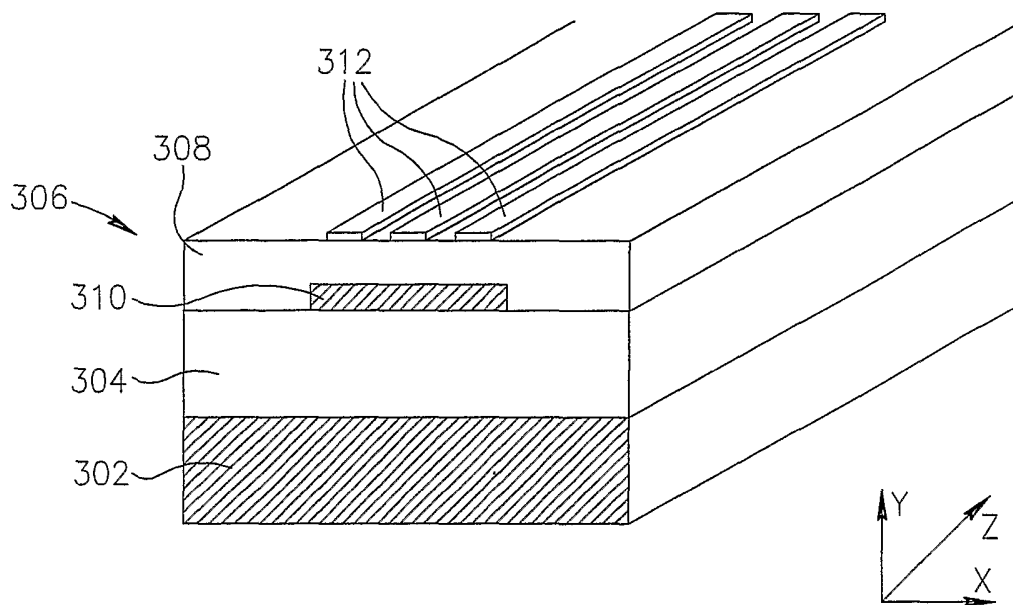


FIG. 3

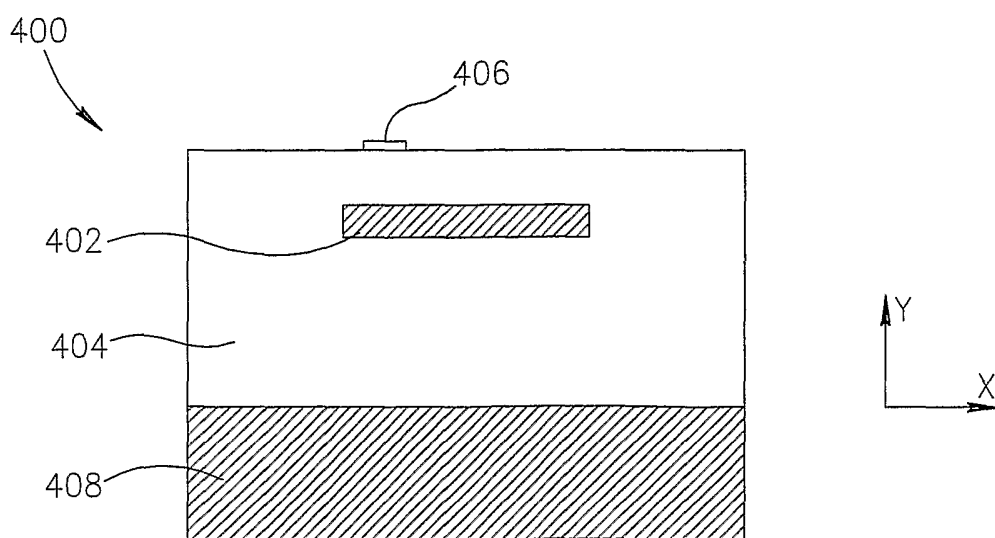


FIG. 4

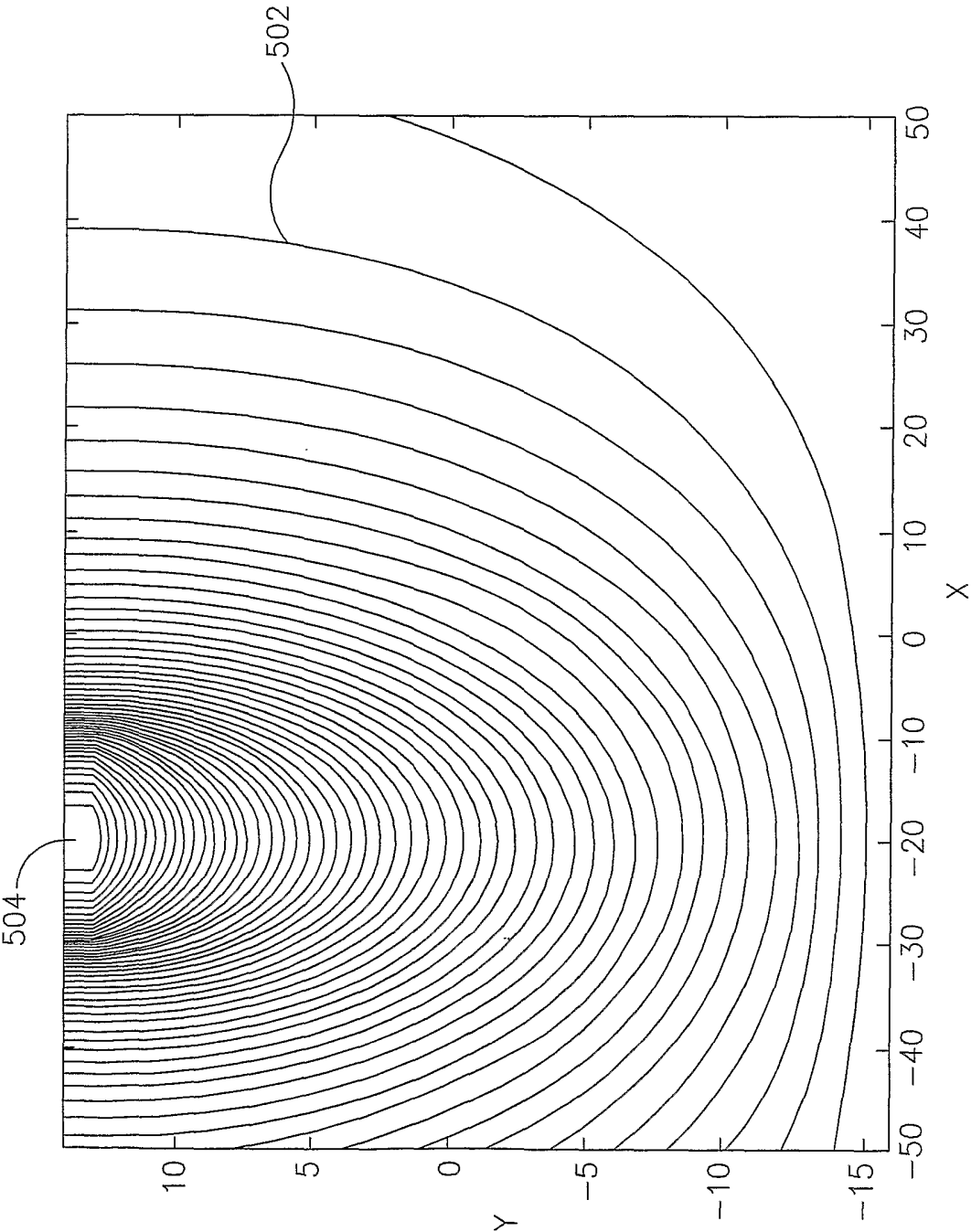


FIG.5

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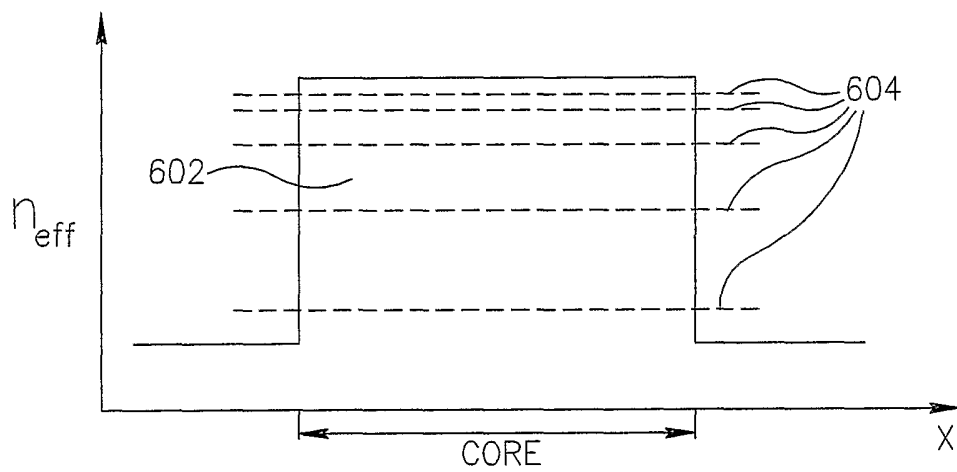


FIG. 6A

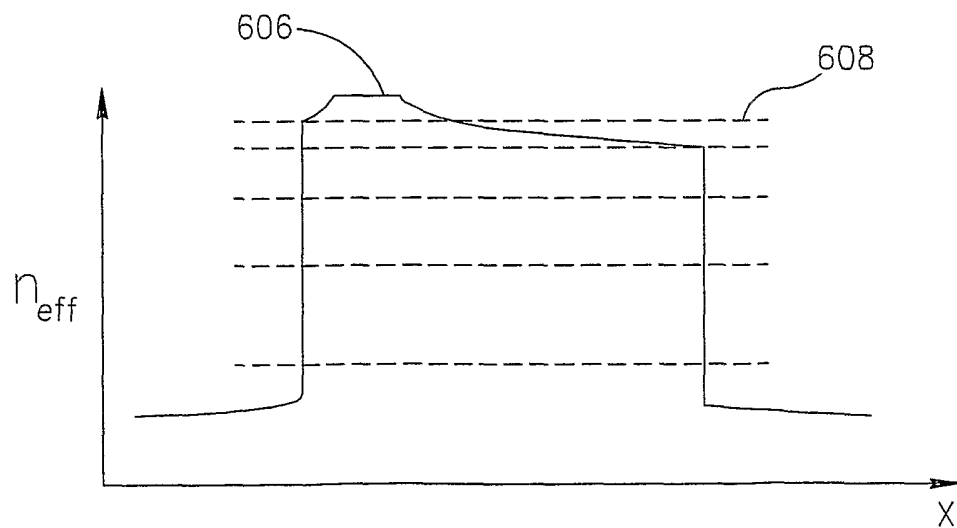


FIG. 6B

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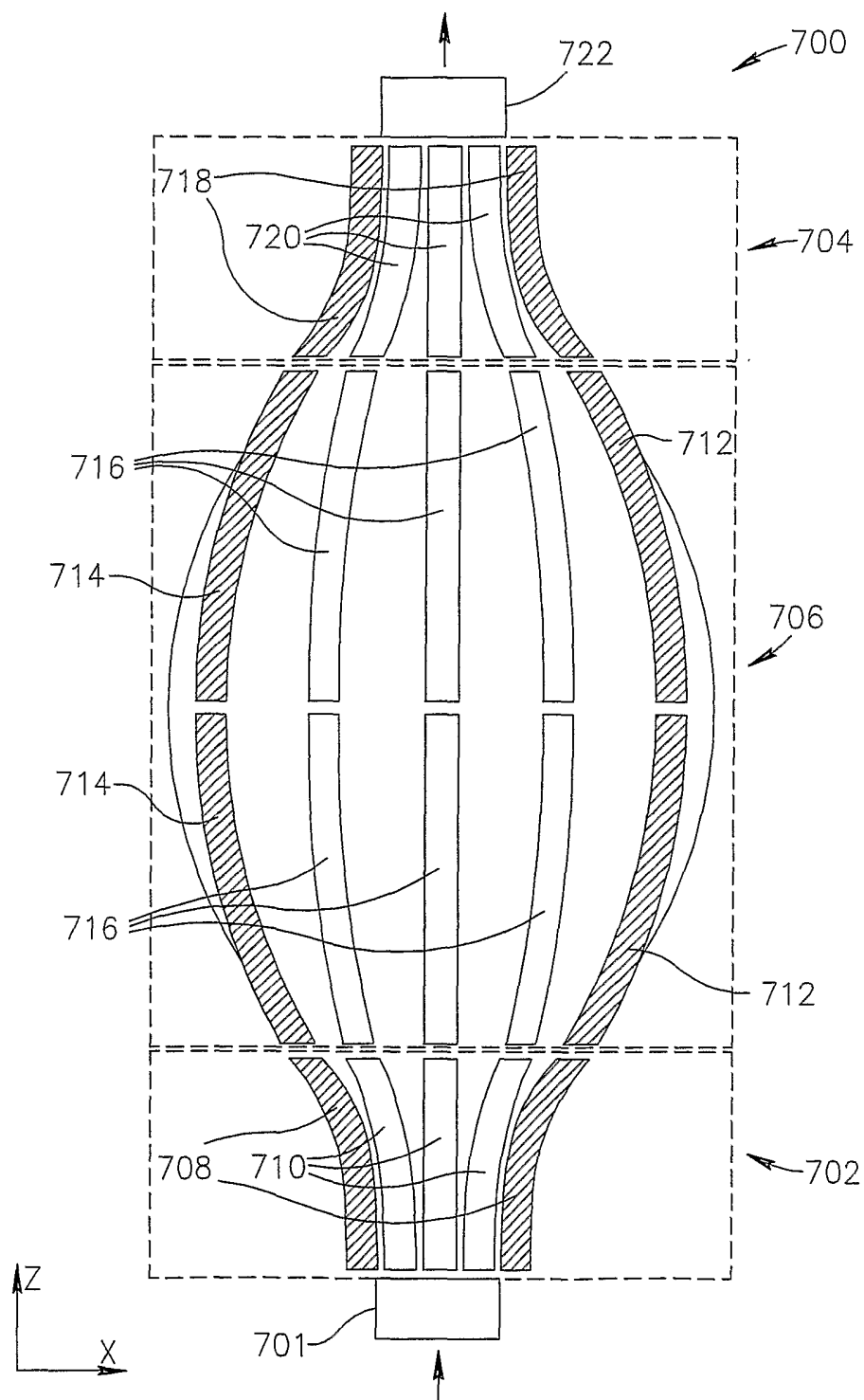


FIG. 7

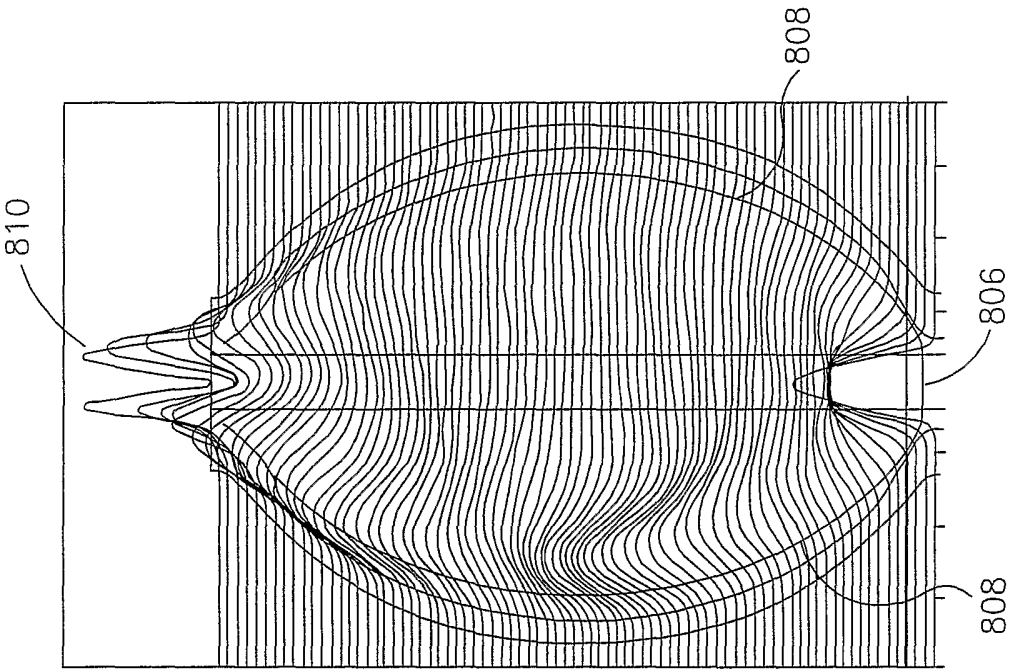


FIG. 8A

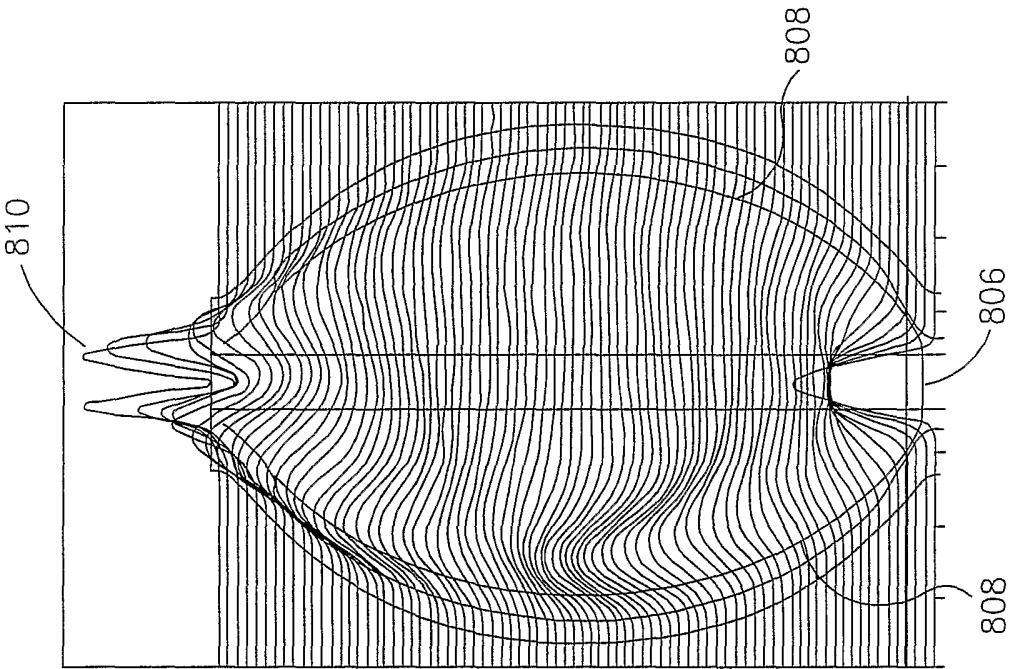


FIG. 8B

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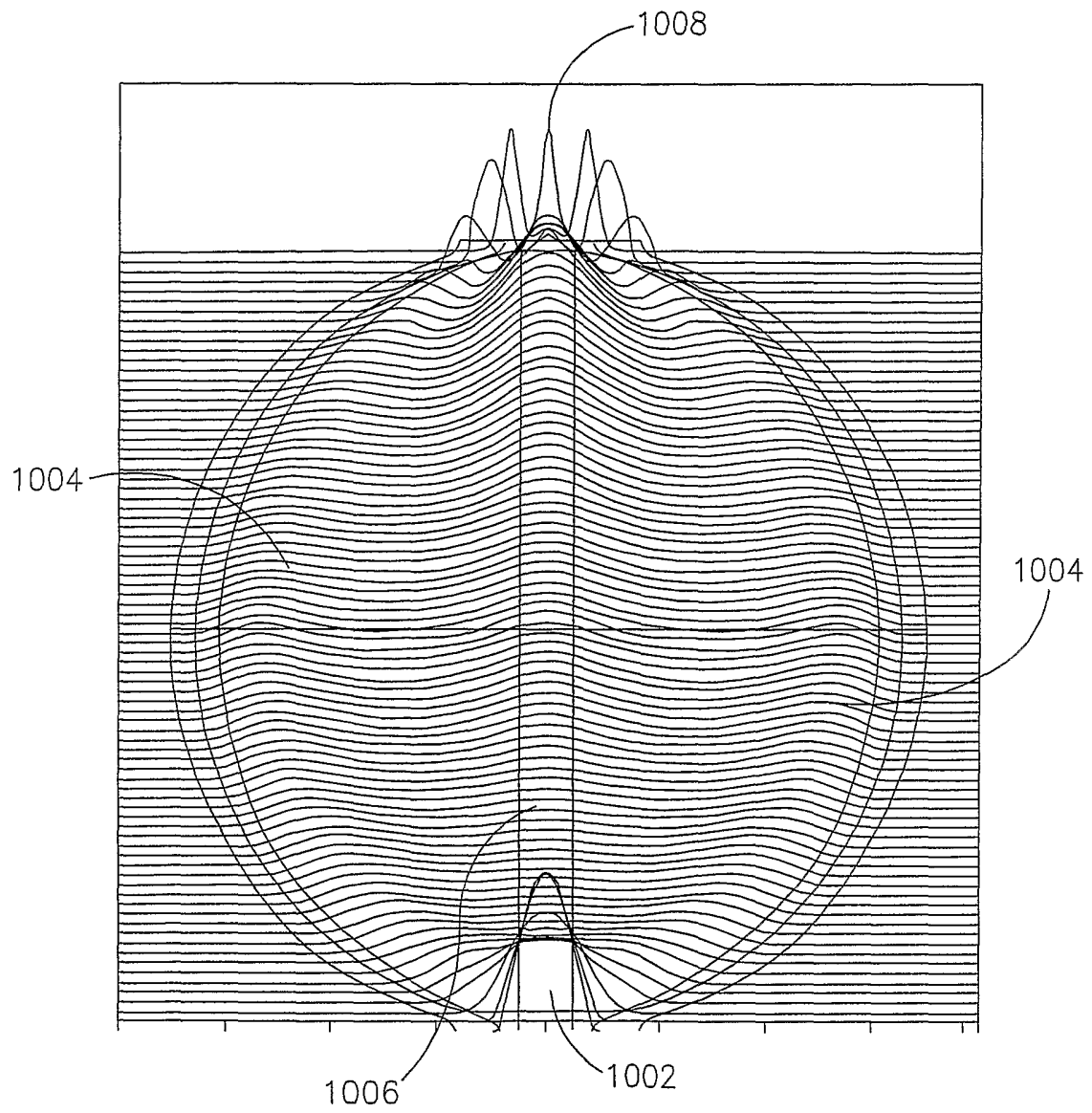


FIG.10

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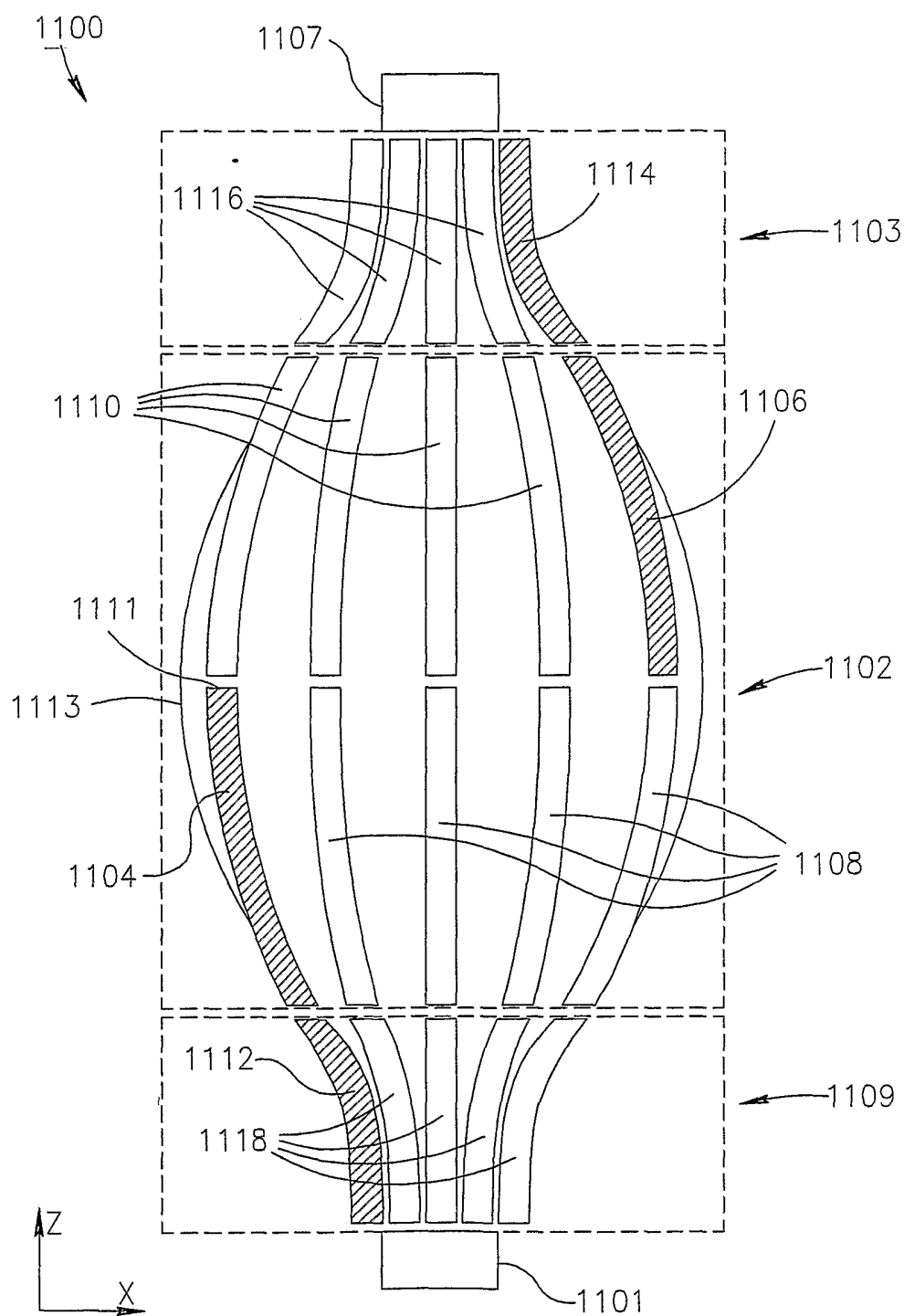


FIG.11

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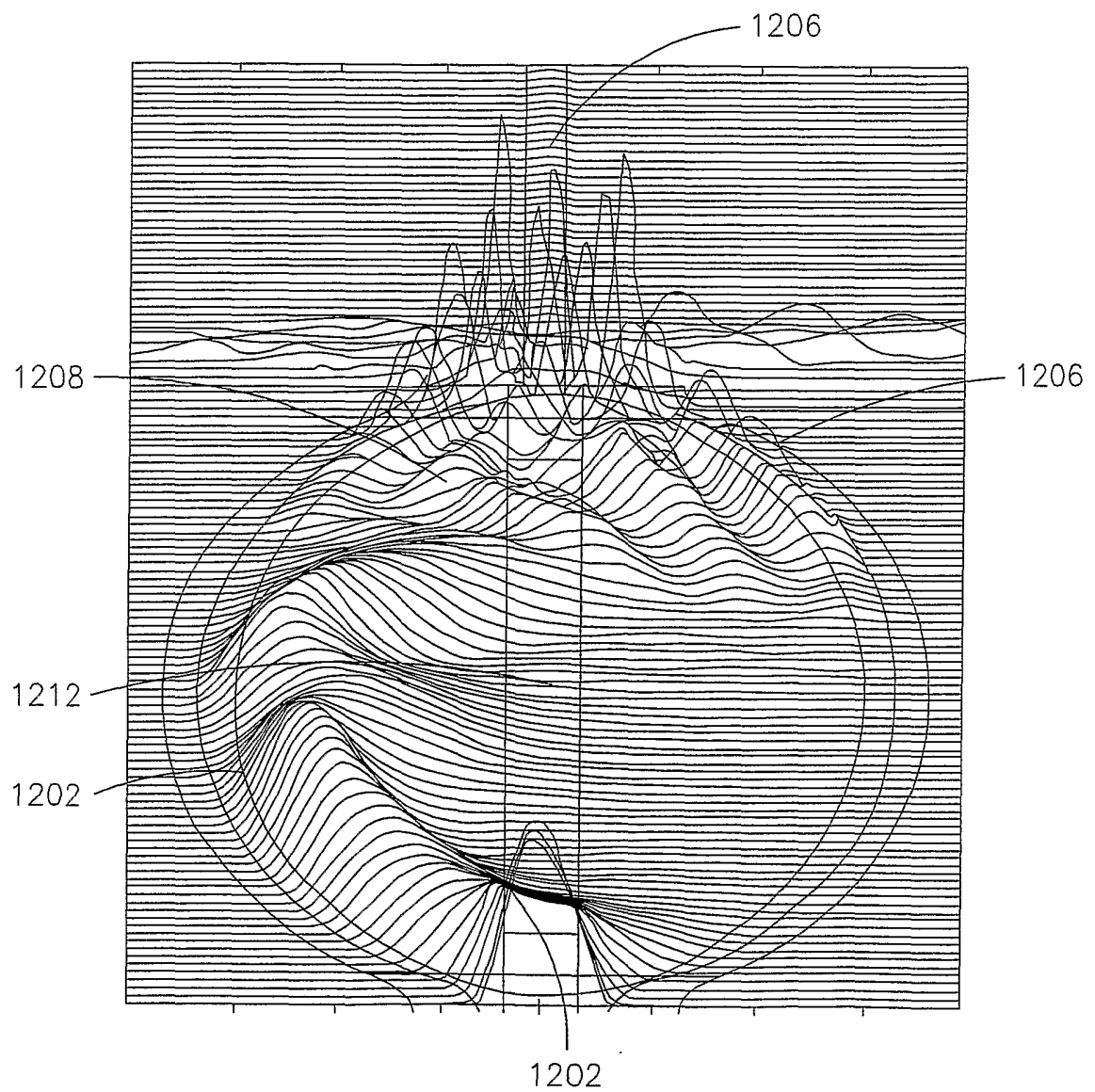


FIG.12

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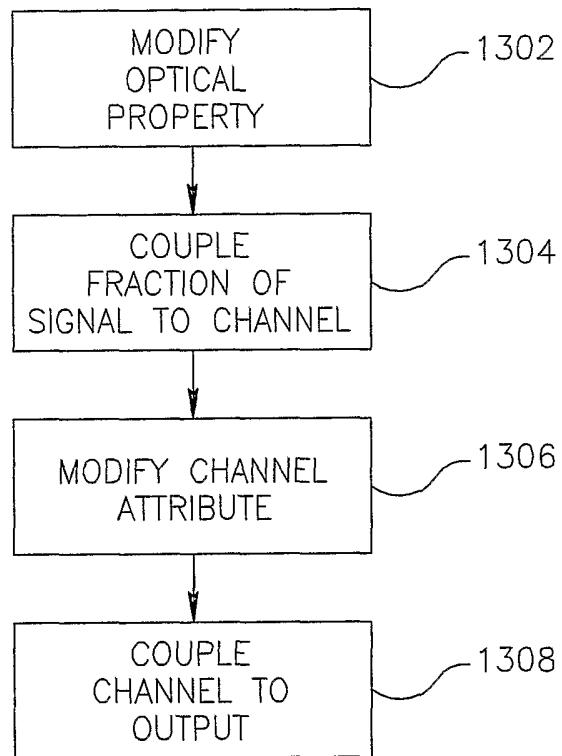


FIG.13

INTERNATIONAL SEARCH REPORT

PCT/IL 03/00447

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02F1/01 G02F1/225

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	abstract; figures 3-5, 17 ---	16, 17
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Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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- *&* document member of the same patent family

Date of the actual completion of the international search

20 August 2003

Date of mailing of the international search report

28/08/2003

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INTERNATIONAL SEARCH REPORT

PCT/IL 03/00447

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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