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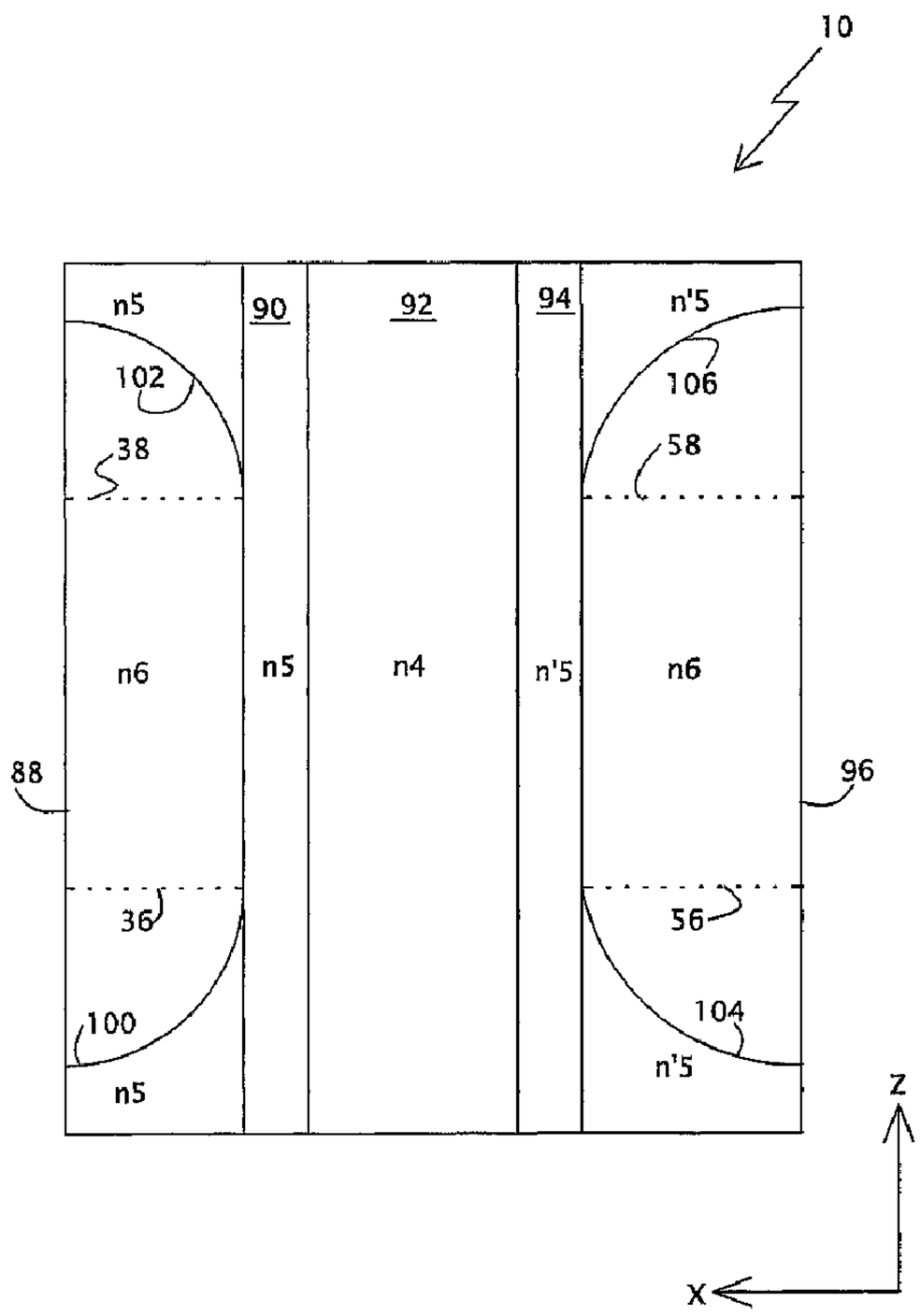
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(54) Titre : DISPOSITIFS DE COUPLAGE EN MODE OPTIQUE ET MATRICE DE COMMUTATION OPTIQUE BASEE SUR DE TELS DISPOSITIFS

(54) Title: OPTICAL MODE COUPLING DEVICES AND AN OPTICAL SWITCH MATRIX BASED THEREON



(57) Abrégé/Abstract:
The invention is a waveguide structure (10) that includes two waveguides (90, 94) flanking a coupling region (92) whose effective refractive index is less than those of the waveguides. Outboard of the waveguides are bounding regions (88, 96)

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(57) Abrégé(suite)/Abstract(continued):
whose effective refractive indices decrease inwards adiabatically at the proximal and distal ends of the bounding regions. The waveguides are coupled optically by periodic perturbations of the waveguide geometry, or by reversible uniform or periodic perturbations of the effective refractive indices. In an optical switch matrix based on the waveguide structure, all the waveguides are straight and parallel. A second aspect of the invention is a directional coupler comprising mechanisms for reversibly and quasiperiodically perturbing the effective refractive indices of the waveguides. The respective envelope functions vary monotonically in opposite senses. Light propagating in one waveguide, in the direction in which that waveguide's envelope function increases, is coupled into the other waveguide.

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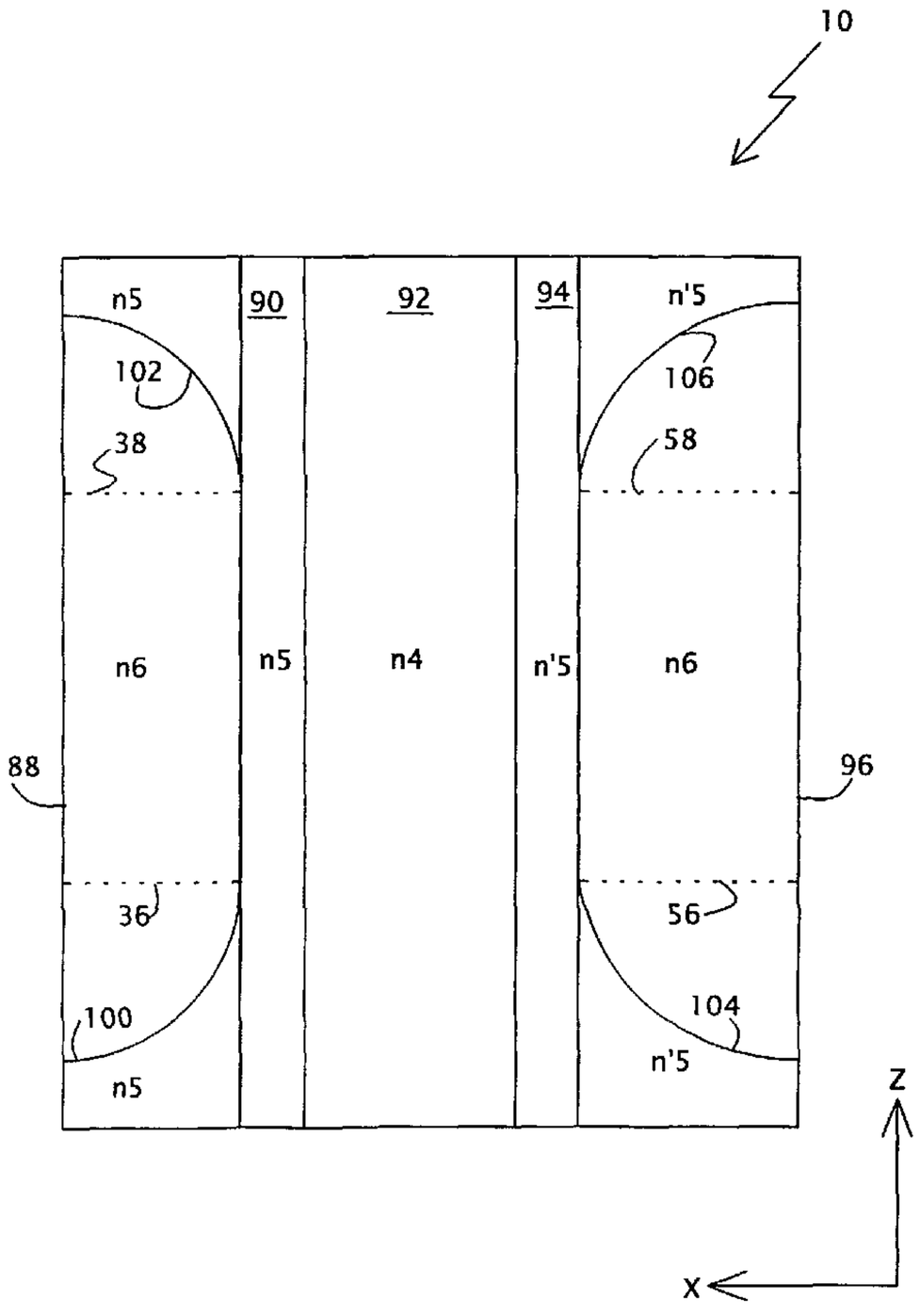
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(54) Title: OPTICAL MODE COUPLING DEVICES AND AN OPTICAL SWITCH MATRIX BASED THEREON



(57) Abstract: The invention is a waveguide structure (10) that includes two waveguides (90, 94) flanking a coupling region (92) whose effective refractive index is less than those of the waveguides. Outboard of the waveguides are bounding regions (88, 96) whose effective refractive indices decrease inwards adiabatically at the proximal and distal ends of the bounding regions. The waveguides are coupled optically by periodic perturbations of the waveguide geometry, or by reversible uniform or periodic perturbations of the effective refractive indices. In an optical switch matrix based on the waveguide structure, all the waveguides are straight and parallel. A second aspect of the invention is a directional coupler comprising mechanisms for reversibly and quasiperiodically perturbing the effective refractive indices of the waveguides. The respective envelope functions vary monotonically in opposite senses. Light propagating in one waveguide, in the direction in which that waveguide's envelope function increases, is coupled into the other waveguide.

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OPTICAL MODE COUPLING DEVICES AND AN OPTICAL SWITCH MATRIX BASED THEREON

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to optical communications devices and, more particularly, to optical couplers.

An optical coupler is a device for exchanging light between two optical waveguides. An optical waveguide is a device for transmitting light over long distances with low losses. It consists of a linearly extended guide portion, having a relatively high index of refraction, encased in a cladding having a lower index of refraction. Light is confined to the guide portion by total internal reflection. Common examples of optical waveguides include planar waveguide structures, which, for the transmission of infrared light, often are made from semiconductors in the same way as integrated circuits, and optical fibers. In an optical fiber, the guide portion conventionally is called a "core".

A directional coupler, in particular, consists of two parallel waveguides in close proximity to each other. The theory of directional couplers is described in D. Marcuse, Theory of Dielectric Optical Waveguides, Academic Press, Second Edition, 1991, Chapter 6, which is incorporated by reference for all purposes as if fully set forth herein. Two identical waveguides, far apart from each other, have identical propagation modes, with identical propagation constants. As the two waveguides are brought closer to each other, pairs of corresponding modes become coupled. The solutions of Maxwell's equations are, to a close approximation, sums (even symmetry) and differences (odd symmetry) of the corresponding uncoupled modes, each solution having its own propagation constant that is slightly different from the propagation constants of the corresponding uncoupled modes. Monochromatic light entering a directional coupler via the guide portion of one of the waveguides in one uncoupled mode thus is a linear combination of two coupled modes. Therefore, this light is exchanged between the guide portions of the two waveguides. After propagating through the directional coupler for a distance called the "beat length", the light has been transferred entirely to the guide portion of the other waveguide. Of course, if the directional coupler is longer than the beat length, the light returns to the guide portion of the first waveguide. The beat length is inversely proportional to the difference between the coupled propagation constants. Specifically, the beat length

$L=\pi/(\beta_e-\beta_o)$, where β_e is the propagation constant of the coupled even mode and β_o is the propagation constant of the coupled odd mode. These propagation constants are functions of the indices of refraction of the guide portions and of the intervening optical medium, and of the wavelength of the light.

The closer the guide portions are to each other, the larger the difference between the coupled propagation constants. In practical optical couplers of this type, in order to keep the beat length, and hence the length of the device, on the order of centimeters, the distance between the coupled guide portions often must be on the order of micrometers. This dimensional restriction increases the cost and complexity of the couplers.

Vorobeichik et al., in US Patent No. 6,088,495, which is incorporated by reference for all purposes as if fully set forth herein, describe a directional coupler in which the separately propagating modes in the two waveguides are coupled via one or more higher order mode that, rather than being localized to the guide portions of the waveguides, are spread over both the waveguides and the optical medium between the waveguides. Coupling is achieved by periodic perturbation of the indices of refraction of the waveguides.

SUMMARY OF THE INVENTION

The directional coupler described by Vorobeichik et al. is based on coupled optical fibers. A first aspect of the present invention is a similar directional coupler that is based on a planar waveguide structure.

The optical mode coupling, that is achieved by uniform periodic modulation or perturbation of the effective refractive indices of the waveguides, is sensitive to minor variations of various parameters, such as modulation period, wavelength, and coupling strength ratio. A second aspect of the present invention is a directional coupler, with adiabatic optical mode coupling, in which the modulation strength is not uniform in the propagation direction, and whose performance is relatively insensitive to minor variations of these parameters.

According to the present invention there is provided a waveguide structure including: (a) a first waveguide, having a proximal end, and having a first waveguide effective index of refraction $\overline{n}_1$; (b) a second waveguide, substantially parallel to the first waveguide, having a proximal end, and having a second waveguide effective

index of refraction $\overline{n}_2$; (c) a coupling region, situated between the waveguides, having a coupling region effective index of refraction $\overline{n}_3$ that is less than $\overline{n}_1$ and that also is less than $\overline{n}_2$; (d) a first bounding region, the first waveguide being situated between the first bounding region and the coupling region, the first bounding region having a proximal end adjacent to the proximal end of the first waveguide, the first bounding region having a first bounding region effective index of refraction that decreases adiabatically, in a direction substantially parallel to the waveguides, from a value, at the proximal end of the first bounding region, that is between $\overline{n}_1$ and $\overline{n}_3$, to an intermediate value, in a switching section of the first bounding region, that is less than $\overline{n}_3$; and (e) a second bounding region, the second waveguide being situated between the second bounding region and the coupling region, the second bounding region having a proximal end adjacent to the proximal end of the second waveguide, the second bounding region having a second bounding region effective index of refraction that decreases adiabatically, in the substantially parallel direction, from a value, at the proximal end of the second bounding region, that is between $\overline{n}_2$ and $\overline{n}_3$, to an intermediate value, in a switching section of the second bounding region, that is less than $\overline{n}_3$.

According to the present invention there is provided an optical switch matrix, for switching optical signals from a first number of input waveguides to a second number of output waveguides, a larger of the two numbers being greater than 2, the optical switch matrix including: (a) a plurality of switch waveguides, equal in number to the larger of the two numbers, each switch waveguide being optically coupled to at least one of a respective input waveguide and a respective output waveguide, all the switch waveguides being substantially straight and parallel.

According to the present invention there is provided a directional coupler, including: (a) a first waveguide having a first effective index of refraction; (b) a second waveguide, substantially parallel to the first waveguide and having a second effective index of refraction; (c) a first mechanism for reversibly inducing a first quasiperiodic perturbation in the first effective index of refraction; and (d) a second mechanism for reversibly inducing a second quasiperiodic perturbation in the second effective index of refraction; wherein the first quasiperiodic perturbation has a first envelope function that varies monotonically along the first waveguide, and wherein

the second quasiperiodic perturbation has a second envelope function that varies monotonically along the second waveguide in a sense opposite to the variation of the first envelope function.

According to the present invention there is provided a method for diverting a least a portion of electromagnetic energy, that propagates in a certain direction via a first waveguide, to a second waveguide that is substantially parallel to the first waveguide, including the steps of: (a) inducing a first quasiperiodic perturbation in an effective index of refraction of the first waveguide, the first perturbation having an envelope function that varies monotonically in the propagation direction; and (b) inducing a second quasiperiodic perturbation in an effective index of refraction of the second waveguide, the second perturbation having an envelope function that varies monotonically in the propagation direction in a sense opposite to the variation of the envelope function of the first perturbation.

The devices of the present invention are intended for the manipulation of electromagnetic energy generally, but more particularly infrared light of the frequencies typically used in optical communication. The effective refractive indices defined herein are with respect to a target monochromatic frequency, for example, 193.5 THz, the frequency of the infrared light, commonly used in optical communication, that has a free space wavelength of 1550 nm.

Figure 1 illustrates the effective refractive index structure of a planar waveguide structure **10** of the present invention. Waveguide structure **10** is based on two straight, parallel waveguides **12** and **14**, on either side of a coupling region **16**. Left waveguide **12** has an effective index of refraction $\overline{n}_1$. Right waveguide **14** has an effective index of refraction $\overline{n}_2$. Coupling region **16** has an effective index of refraction $\overline{n}_3$. The only obligatory constraints on $\overline{n}_1$, $\overline{n}_2$ and $\overline{n}_3$ are that $\overline{n}_3 < \overline{n}_1$ and $\overline{n}_3 < \overline{n}_2$; $\overline{n}_2$ may be less than, equal to or greater than $\overline{n}_1$. Proximal ends **18**, **20** and **22** of waveguides **12** and **14** and of coupling region **16** are mutually adjacent. Similarly, distal ends **24**, **26** and **28** of waveguides **12** and **14** and of coupling region **16** are mutually adjacent.

On the other side of left waveguide **12** from coupling region **16** is a left bounding region **30** that has a proximal end **34** adjacent to proximal end **18** of left waveguide **12** and a distal end **40** adjacent to distal end **24** of left waveguide **12**. A

switching section **32** of left bounding region **30** extends from a switching section proximal side **36** to a switching section distal side **38**. Within switching section **32**, left bounding region **30** has an effective index of refraction $\overline{n}_4$. Proximal to switching section **32**, left bounding region **30** has an effective index of refraction that decreases adiabatically from a value of $\overline{n}_{01}$ at proximal end **34** to a value of $\overline{n}_4$ at proximal side **36**. Distal to switching section **32**, left bounding region **30** has an effective index of refraction that increases adiabatically from a value of $\overline{n}_4$ at distal side **38** to a value of $\overline{n}_{01}$ at distal end **40**. $\overline{n}_1$, $\overline{n}_3$, $\overline{n}_4$ and $\overline{n}_{01}$ are related by $\overline{n}_4 < \overline{n}_3 < \overline{n}_{01} < \overline{n}_1$.

Similarly, on the other side of right waveguide **14** from coupling region **16** is a right bounding region **50** that has a proximal end **54** adjacent to proximal end **20** of right waveguide **14** and a distal end **60** adjacent to distal end **26** of right waveguide **14**. A switching section **52** of right bounding region **50** extends from a switching section proximal side **56** to a switching section distal side **58**. Within switching section **52**, right bounding region **50** has an effective index of refraction $\overline{n}_5$. Proximal to switching section **52**, right bounding region **50** has an effective index of refraction that decreases adiabatically from a value of $\overline{n}_{02}$ at proximal end **54** to a value of $\overline{n}_5$ at proximal side **56**. Distal to switching section **52**, right bounding region **50** has an effective index of refraction that increases adiabatically from a value of $\overline{n}_5$ at distal side **58** to a value of $\overline{n}_{02}$ at distal end **60**. $\overline{n}_2$, $\overline{n}_3$, $\overline{n}_5$ and $\overline{n}_{02}$ are related by $\overline{n}_5 < \overline{n}_3 < \overline{n}_{02} < \overline{n}_2$.

Waveguide **12** is shown optically coupled, at proximal end **18**, to an input optical fiber **70**. Similarly, waveguide **12** is shown optically coupled, at distal end **24**, to an output optical fiber **72**, and waveguide **14** is shown optically coupled, at distal end **26**, to an output optical fiber **74**.

Also shown in Figure 1 are the x and z axes of a coordinate system that is defined below in Figure 2.

A physical embodiment of waveguide structure **10** is described below.

Preferably, $\overline{n}_4 = \overline{n}_5$.

As noted above, optical modes confined to waveguides **12** and **14** are coupled via one or optical modes that span waveguides **12** and **14** and coupling region **16**, by periodic perturbations of the effective indices of refraction. One way of achieving

these perturbations is to configure waveguides **12** and **14** to meander transversely, either in the plane of waveguides **12** and **14** or perpendicular to that plane. A second way of achieving these perturbations is to configure waveguides **12** and **14** with thicknesses that vary periodically in the *z* direction, again either in the plane of waveguides **12** and **14** or perpendicular to that plane. A third way of achieving these perturbations is by providing a mechanism for reversibly perturbing the effective indices of refraction. This reversible perturbation may be uniform in the *z* direction when applied in combination with the first or the second perturbation. Alternatively, this reversible perturbation may be periodic in the *z* direction, either alone or in combination with the first or the second perturbation. The mechanism may be thermo-optic, piezo-electric, acousto-optic or electro-optic. Alternatively, the mechanism may rely on the reversible injection of charge carriers into the relevant portions of waveguide structure **10**.

The perturbations of the present invention are defined to be not so large as to change the inequality relationships of the effective indices of refraction.

One application of waveguide structure **10** is as part of a directional coupler, which in turn is a component of a power divider, a wavelength filter, an optical modulator or an attenuator.

Another application of waveguide structure **10** is as part of an optical switch. Multiple such optical switches constitute an optical switch matrix. An important feature of such an optical switch matrix, for switching optical signals from a first number of input optical waveguides such as input optical fiber **70** to a second number of output optical waveguides such as output optical fibers **72** and **74**, is that the waveguides of the switch all are substantially straight and parallel. Such an optical switch matrix includes several instances of waveguide structure **10**, such that each adjacent pair of switching waveguides, such as waveguides **12** and **14**, is coupled as described above.

The directional coupler of the second aspect of the present invention is similar to waveguide structure **10**, insofar as this directional coupler includes two parallel waveguides, such as waveguides **12** and **14**, on either side of a coupling region such as coupling region **16**, with the respective effective refractive indices of both waveguides being greater than the effective refractive index of the coupling region. However, the physical embodiment of this directional coupler need not be a planar

waveguide structure, but may be based, for example, on optical fibers as the waveguides. This directional coupler also includes mechanisms for reversibly inducing quasiperiodic perturbations in the refractive indices of the waveguides. These quasiperiodic perturbations have envelope functions that vary monotonically in opposite senses along the waveguides. The mechanisms may be thermo-optic, piezo-electric, acousto-optic or electro-optic. Alternatively, the mechanisms may rely on the reversible injection of charge carriers into the waveguides.

Preferably, the waveguides of the directional coupler of the second aspect of the present invention are single-mode waveguides.

Applications of the directional coupler of the second aspect of the present invention include using this directional coupler as a component of a power divider, a wavelength filter, an optical switch, an optical modulator or an attenuator.

The scope of the present invention includes using the directional coupler of the second aspect of the present invention to divert at least a portion of electromagnetic energy, propagating in one of the waveguides, to the other waveguide. Preferably, the envelope function of the waveguide, in which the electromagnetic energy initially propagates, increases monotonically in the direction of propagation, and the envelope function of the waveguide, into which the electromagnetic energy is diverted, decreases monotonically in the propagation direction.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIG. 1 illustrates the effective refractive index structure of a planar waveguide structure of the first aspect of the present invention;

FIG. 2 illustrates the physical structure of the planar waveguide structure of FIG. 1;

FIG. 3 is a cross section of the fourth layer of the planar waveguide structure of FIG. 2, parallel to the *xz* plane;

FIGs. 4A and 4B are schematic representations of the effective indices of refraction of the planar waveguide structure of FIGs. 1 and 2, proximal and distal to the switching sections (FIG. 4A) vs. within and between the switching sections (FIG. 4B);

FIG. 5 is FIG. 3 including periodic static perturbations, parallel to the *xz* plane, of the waveguide regions, and also including mechanisms for inducing uniform dynamic perturbations of the effective indices of refraction;

FIG. 6 illustrates a periodic static perturbation, parallel to the *yz* plane, of one of the waveguide regions of FIG. 2;

FIG. 7 is FIG. 3 with mechanisms for inducing periodic dynamic perturbations of the effective indices of refraction;

FIG. 8 is FIG. 7 without the static perturbations;

FIG. 9 is FIG. 5 with alternative periodic static perturbations, in the *xz* plane, of the waveguide regions;

FIG. 10 is FIG. 6 with an alternative periodic static perturbation, in the *yz* plane, of the waveguide region;

FIG. 11 is a schematic illustration of a 4x4 non-blocking optical switch matrix of the first aspect of the present invention;

FIG. 12 is a schematic longitudinal cross section of a directional coupler of the second aspect of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

A first aspect of the present invention is a waveguide structure for implementing the intermediate-state-assisted optical coupler of Vorobeichik et al. A second aspect of the present invention is yet another directional coupler that couples optical modes that propagate separately in two parallel waveguides via a third optical mode common to the two waveguides. The present invention can be used in optical devices such as power dividers, wavelength filters, optical modulators, attenuators and optical switch matrices.

The principles and operation of optical couplers according to the present invention may be better understood with reference to the drawings and the accompanying description.

Referring again to the drawings, Figure 2 illustrates the physical structure of planar waveguide structure **10**. A substrate layer **80** has an index of refraction n_1. A second layer **82** has an index of refraction n_2 which may be smaller than, larger than or equal to n_1. A third layer **84** has an index of refraction n_3 which may be smaller than, larger than or equal to n_2. A fourth layer **86** includes five regions **88**, **90**, **92**, **94**

and **96**. Region **92** has an index of refraction n_4 that is larger than n_3. Regions **90** and **94** have respective indices of refraction n_5 and n_5' which may be smaller than, larger than or equal to n_4, but which must be larger than n_3. n_5 and n_5' may be equal (symmetric configuration) or unequal (asymmetric configuration). A fifth layer **98** has an index of refraction n_6 that is smaller than n_4, n_5 and n_5'. The indices of refraction of regions **88** and **96** vary spatially, as described below.

Also shown in Figure 2 is the (x,y,z) coordinate system that is used to describe planar waveguide structure **10**. The various layers are parallel to the xz plane. Light propagates in the $+z$ direction, from the proximal end of planar waveguide structure **10**, which is the end of planar waveguide structure **10** that is shown in Figure 2, to the distal end of planar waveguide structure **10**.

Figure 3 is a cross section of layer **86** parallel to the xz plane, showing the refractive index structure of layer **86**. As noted above, regions **90** and **94** have refractive index n_5 and region **92** has refractive index n_4. Dashed lines **36**, **38**, **56** and **58** correspond to proximal side **36**, distal side **38**, proximal side **56** and distal side **58** of Figure 1, respectively. Between dashed lines **36** and **38**, the index of refraction of region **88** is n_6. The portion of region **88** in which the index of refraction is n_6 extends past dashed lines **36** and **38**, to interfaces **100** and **102**. Proximal of interface **100** and distal of interface **102**, the index of refraction of region **88** is n_5. Similarly, between dashed lines **56** and **58**, the index of refraction of region **96** is n_6. The portion of region **96** in which the index of refraction is n_6 extends past dashed lines **56** and **58**, to interfaces **104** and **106**. Proximal of interface **104** and distal of interface **106**, the index of refraction of region **96** is n_5'.

The following table lists the thicknesses of the regions of layer **86**:

Region	Thickness
88	D_1
90	A
92	C
94	B
96	D_2

These thicknesses are related as follows: A and B may be equal or different, $C<D_1<A$, and $C<D_2<B$.

With input waveguide **70** optically coupled to region **90** at the proximal side of region **90**, with output waveguide **72** optically coupled to region **90** at the distal side of region **90**, and with output waveguide **74** optically coupled to region **94** at the distal side of region **94**, this index-of-refraction and thickness structure gives planar waveguide structure **10** the effective indices of refraction, with respect to light introduced to planar waveguide structure **10** via input waveguide **70**, that are illustrated in Figure 1. Interface **100** is positioned so that the effective index of refraction of left bounding region **30** decreases adiabatically from $\overline{n}_{01}$ at proximal end **34** to $\overline{n}_4$ at proximal side **36**. Interface **102** is positioned so that the effective index of refraction of left bounding region **30** increases adiabatically from $\overline{n}_4$ at distal side **38** to $\overline{n}_{01}$ at distal end **40**. Interface **104** is positioned so that the effective index of refraction of right bounding region **50** decreases adiabatically from $\overline{n}_{02}$ at proximal end **54** to $\overline{n}_5$ at proximal side **56**. Interface **106** is positioned so that the effective index of refraction of right bounding region **50** increases adiabatically from $\overline{n}_5$ at distal side **58** to $\overline{n}_{02}$ at distal end **60**.

One class of materials from which planar waveguide structure **10** may be fabricated is silica with germanium doping (SiO_2/Ge). Silica has an index of refraction, with respect to light having a free space wavelength of 1550 nm, of 1.44. Doping with germanium can increase this index of refraction by as much as 1.5%. Another class of materials from which planar waveguide structure **10** may be fabricated is silica with nitrogen doping (SiON). Doping silica with nitrogen can increase the index of refraction, with respect to light having a free space wavelength of 1550 nm, to as much as 1.6.

Figure 4A is a schematic representation of the effective index of refraction $\overline{n}$, as a function of x, proximal and distal to switching sections **32** and **52**. Figure 4B is a similar schematic representation of the effective index of refraction $\overline{n}$, as a function of x, within and between switching sections **32** and **52**. Note that Figures 4A and 4B illustrate the asymmetric configuration ($n_5 \neq n_5'$). Proximal and distal to switching sections **52**, planar waveguide structure **10** supports only optical modes, represented symbolically by dashed lines **108** and **110**, that are localized to waveguides **12** and **14**. Between switching sections **32** and **52**, planar waveguide structure **10** also supports

optical modes, represented symbolically by a dashed line **112**, that span both waveguides **12** and **14** and also coupling region **16**. The presence of common optical modes **112** enables efficient directional coupling between waveguides **12** and **14** using selective optical mode coupling between (typically zero–order) optical modes **108** and **110** and at least one of high order common optical modes **112**. This coupling is achieved by any method of transferring the optical power carried by optical mode **108** to optical mode **110** and/or vice versa, for example, periodic or almost periodic perturbation of the refractive indices of planar waveguide structure **10**, and periodic or almost periodic changes in the geometry of regions **90** and **94**.

One such geometric perturbation is illustrated in Figure 5, which is a cross section of planar waveguide structure **10** parallel to the *xz* plane, similar to the cross section of Figure 3, but showing regions **90** and **94** meandering periodically, parallel to the *xz* plane. Another such geometric perturbation is illustrated in Figure 6, which is a partial cross section of planar waveguide structure **10**, parallel to the *yz* plane, through a variant of region **90** that meanders periodically, parallel to the *yz* plane.

To achieve efficient and selective optical mode coupling, the periods of the meanders should correspond to the propagation constants of the optical modes:

$$\beta_1 - \beta_3 \approx \frac{2\pi}{\Lambda_1} \tag{1}$$

$$\beta_2 - \beta_3 \approx \frac{2\pi}{\Lambda_2} \tag{2}$$

where β_1 and β_2 are the propagation constants of the zero-order optical modes of waveguides **12** and **14**, respectively; where β_3 is the propagation constant of the third, common optical mode; where Λ_1 is the meander wavelength of region **90**; and where Λ_2 is the meander wavelength of region **94** (see Figures 5 and 6). If equations (1) and (2) are satisfied, then the optical power initially located in the zero-order optical mode of waveguide **12** is transferred to the common high-order optical mode by the periodic perturbation due to the meanders of region **90**, and is simultaneously transferred from the common optical mode to the zero-order optical mode of waveguide **14** by the periodic perturbation due to the meanders of region **94**. In this manner, a complete directional coupling is achieved despite the fact that the direct coupling between the two zero-order optical modes is negligible.

A directional coupler built in this manner also can be used as an optical switch. Two regimes of switching operation are possible.

In a normally "on" switch, the meander parameters are chosen so that the optical mode coupling is efficient and a complete power transfer between waveguides **12** and **14** is achieved. A dynamic perturbation of refractive indices is used to alter the propagation constants of the optical modes and to deactivate the optical mode coupling. In this regime, the optical switch normally is "on". The change of the propagation constants of the optical modes can be achieved in a variety of ways, such as via the thermo-optic, piezo-electric or acousto-optic or electro-optic effects. In Figure 5, shaded portions **114**, **116** and **118** represent mechanisms for the application of such perturbations to switching section **32**, coupling region **16** and switching section **52**, respectively, to modify effective indices of refraction $\overline{n}_4$, $\overline{n}_3$ and $\overline{n}_5$, respectively. For example, perturbative mechanisms **114**, **116** and **118** may be resistive heating elements on the top or bottom surfaces of planar waveguide structure **10**. The spatial extent of the perturbations induced by mechanisms **114**, **116** and **118** extend beyond their respective regions **30**, **16** and **50**: mechanism **114** also perturbs effective index of refraction $\overline{n}_1$; mechanism **116** also perturbs effective indices of refraction $\overline{n}_1$ and $\overline{n}_2$; and mechanism **118** also perturbs effective index of refraction $\overline{n}_2$. Each of the three resistive heating elements can be heated to different (or equal) temperatures to induce the desired changes in the refractive indices in the regions therebelow (or thereabove). The change of the refractive indices in turn modifies the optical properties (*i.e.*, the propagation constants) of the zero-order optical modes of waveguides **12** and **14** as well as the high-order common optical modes, thus activating the switch. It should be noted that the perturbations should not be so large as to change the inequality relationships among the effective indices of refraction.

Alternatively, perturbative mechanisms **114**, **116** and **118** could be electrodes for reversible injection of charge carriers to switching section **32**, coupling region **16** and switching section **52**, respectively.

In a normally "off" switch, the meander parameters are chosen so that the optical mode coupling is inefficient, *i.e.*, equations (1) and (2) are not satisfied. The dynamic change of refractive indices is used to alter the propagation constants of the

optical modes and to activate the optical mode coupling. In this regime, the optical switch normally is "off", and the dynamic perturbation activates the switch.

Figure 5 illustrates the combination of a *z*-dependent (specifically, periodic) static perturbation of indices of refraction with a *z*-independent dynamic perturbation of indices of refraction. Figure 7 illustrates *z*-dependent static and dynamic perturbations of indices of refraction. Specifically, Figure 7 is a cross section of planar waveguide structure **10** parallel to the xz plane, similar to the cross section of Figure 5, but with segmented perturbative mechanisms **124**, **126** and **128** that apply dynamic perturbations that vary periodically (or almost periodically) in the *z* direction. The average change of the refractive indices induced by the perturbation is used to tune (in a normally "off" switch) or detune (in a normally "on" switch) the propagation constants of the optical modes with respect to the parameters of the static perturbations. The difference between the refractive index changes induced in adjacent segments **124**, in adjacent segments **126** or in adjacent segments **128** is used to adjust the strength of the refractive index perturbation that couples the optical modes. This ability to vary the total optical mode coupling strength allows maximization of the power transfer efficiency obtained using the two (static and dynamic) optical mode couplings.

For example, perturbative segments **124**, **126** and **128** could be resistive heating elements placed above or below their respective regions of planar waveguide structure **10**, in three arrays as shown, for the purpose of inducing thermo-optic perturbations of the indices of refraction. In each of the three arrays, the resistive heating elements can be heated to different (or equal) temperatures to induce changes in the refractive indices of the regions of planar waveguide structure **10** therebelow or thereabove. The average change of the refractive indices modifies the optical properties (*i.e.*, the propagation constants) of the zero-order optical modes of waveguides **12** and **14** as well as the high-order common optical modes, thus activating (in the normally "off" switch) or deactivating (in the normally "on" switch) the static perturbations. The alternate heating of adjacent resistive heating elements in each array produces a periodic (or almost periodic) perturbation of the refractive indices which couples (along with the static perturbation) the zero-order optical modes of waveguides **12** and **14** with the high-order optical mode common to both waveguides **12** and **14**.

Alternatively, perturbative segments **124**, **126** and **128** could be electrodes for reversible injection of charge carriers into their respective regions of planar waveguide structure **10**.

Figure 8 illustrates z-dependent dynamic perturbation in the absence of a static perturbation. Specifically, Figure 8 is a cross section of planar waveguide structure **10** parallel to the *xz* plane, similar to the cross section of Figure 3, insofar as regions **90** and **94** are straight rather than meandering, but with segmented perturbative mechanisms **124**, **126** and **128** that apply dynamic perturbations that vary periodically (or almost periodically) in the *z* direction, as in Figure 7. In this case, directional coupling is achieved by applying two dynamic perturbations of the refractive indices. These perturbations selectively couple the zero-order optical modes of each of waveguides **12** and **14** to the high-order optical mode common to both waveguides **12** and **14**. Thus, the optical power initially carried by the zero-order optical mode of waveguide **12** is transferred to the zero-order optical mode of waveguide **14** via the third, common high-order optical mode.

In the case illustrated in Figure 8, the perturbation of the indices of refraction is induced dynamically and there is no static perturbation. Thus, in the absence of any perturbation, waveguides **12** and **14** are sufficiently far apart that the directional coupling between the zero-order optical modes of waveguides **12** and **14** is negligible. When the dynamic perturbation is induced, the optical mode coupling is activated and directional coupling is achieved. Therefore, this configuration can be used as a normally "off" switch. The dynamic perturbation can be achieved in the same way as before, for example, thermo-optically, piezo-electrically or acousto-optically.

For example, perturbative segments **124**, **126** and **128** could be resistive heating elements placed above or below their respective regions of planar waveguide structure **10**, in three arrays as shown, for the purpose of inducing thermo-optic perturbations of the indices of refraction. In this case, resistive heating elements **124** are used to couple the zero-order optical mode of waveguide **12** to the higher-order common optical mode, resistive heating elements **128** are used to couple the zero-order optical mode of waveguide **14** to the higher-order common optical mode, and resistive heating elements **126** are used to couple both zero-order optical modes to the higher-order common optical mode simultaneously. Array **124**, array **126** and array **128** can produce either periodically alternating or constant (*z*-independent)

heating. The alternating heating is used to induce optical mode coupling, and the constant heating is used to change the refractive indices. The *z*-independent change of the indices of refraction produces a corresponding change of the propagation constants of the optical modes, with the differences between these propagation constants being adjusted in accordance with the wavelengths of the periodic perturbations, in accordance with equations (1) and (2).

Alternatively, perturbative segments **124**, **126** and **128** could be electrodes for reversible injection of charge carriers into their respective regions of planar waveguide structure **10**.

Figure 9 is a variant of Figure 5 that shows an alternative periodic geometric perturbation of regions **90** and **94**: periodic variations of the thicknesses of regions **90** and **94** parallel to the *xz* plane. Figure 10 is a variant of Figure 6 that shows another alternative periodic geometric perturbation of region **90**: periodic variations of the thickness of region **90** parallel to the *yz* plane.

In all configurations of the 2x2 optical switch described above, the optical waveguides are straight and parallel to each other. There is no need to change the separation distance between the optical waveguides along the propagation direction, because the separation distance is kept constant and large to preclude direct coupling between the zero-order optical modes of the waveguides. Directional coupling is achieved via mode coupling between the zero-order optical modes of the waveguides and the common high-order optical modes. In fact, this optical mode coupling is almost totally insensitive to the distance between the waveguides: optical switching is possible between waveguides which are many zero-order optical mode diameters apart. Because the waveguides are straight and parallel, larger switching matrices based on the 2x2 switch of the present invention are particularly compact and efficient.

Figure 11 is a schematic illustration of a 4x4 non-blocking optical switch matrix **150** that is based on six 2x2 optical switches **160**, **162**, **164**, **166**, **168** and **170** of the present invention that couple four straight, parallel waveguides **152**, **154**, **156** and **158** as shown. Each 2x2 optical switch of Figure 11 is essentially identical to planar waveguide structure **10** of Figure 1, and couples two adjacent waveguides: waveguides **152** and **154**, waveguides **154** and **156**, or waveguides **156** and **158**. For example, the portion of waveguide **152** internal to switch **160** is waveguide **12** of

switch **160**, and is optically coupled by switch **160** to the portion of waveguide **154** internal to switch **160**, which is waveguide **14** of switch **160**; the portion of waveguide **152** internal to switch **166** is waveguide **12** of switch **166**, and is optically coupled by switch **166** to the portion of waveguide **154** internal to switch **166**, which is waveguide **14** of switch **166**; and the portion of waveguide **154** internal to switch **164** is waveguide **12** of switch **164**, and is optically coupled by switch **164** to the portion of waveguide **156** internal to switch **164**, which is waveguide **14** of switch **164**, etc. There is no need to connect the 2x2 switches of Figure 11 by S-bends. Therefore, the total length of 4x4 switch matrix **150** is significantly smaller than the length of comparable prior art switch matrices that require long S-bends. Moreover, because the waveguides are kept parallel in each separate 2x2 switch, there is no need to introduce S-bends or other slow variations of the inter-waveguide distances within the 2x2 switches. Each 2x2 switch can be as short as about one millimeter. Thus, large switching matrices can be produced on a scale that is much smaller than in the cases where S-bends or other slow variations of inter-waveguide distances are needed. Similarly, larger non-blocking switching matrices can be designed. Existing architectures can be used as well as novel architectures which are suitable for connecting large numbers of switches built around straight, parallel waveguides.

For switching purposes, each of switches **160**, **162**, **164**, **166**, **168** and **170** is placed in one of two states: a straight-through state, in which no power is exchanged between the respective waveguides, and a crossover state, in which power is exchanged totally between the two respective waveguides. The following table shows the states that switches **160**, **162**, **164**, **166**, **168** and **170** are set to in order to achieve the twenty-four possible switching combinations, for a signal "a" that enters switch matrix **150** via waveguide **152**, a signal "b" that enters switch matrix **150** via waveguide **154**, a signal "c" that enters switch matrix **150** via waveguide **156** and a signal "d" that enters switch matrix **150** via waveguide **158**. The first four columns show which signal exits switch matrix **150** via each of waveguides **152**, **154**, **156** and **158**. The last six columns show the corresponding settings of switches **160**, **162**, **164**, **166**, **168** and **170**. A straight-through state is represented by "=". A crossover state is represented by "X".

OUTPUT				SWITCH SETTINGS					
152	**154**	**156**	**158**	**160**	**162**	**164**	**166**	**168**	**170**
a	b	c	d	=	=	=	=	=	=
a	b	d	c	=	=	=	=	X	=
a	c	b	d	=	=	=	=	=	X
a	c	d	b	=	=	X	=	X	=
a	d	b	c	=	=	=	=	X	X
a	d	c	b	=	=	X	=	X	X
b	a	c	d	=	=	=	X	=	=
b	a	d	c	=	=	=	X	X	=
b	c	a	d	=	=	=	X	=	X
b	c	d	a	X	=	X	=	X	=
b	d	a	c	=	=	=	X	X	X
b	d	c	a	X	=	X	=	X	X
c	a	b	d	=	=	X	X	=	=
c	a	d	b	=	=	X	X	X	=
c	b	a	d	=	=	X	X	=	X
c	b	d	a	X	=	X	X	X	=
c	d	a	b	=	=	X	X	X	X
c	d	b	a	X	=	X	X	X	X
d	a	b	c	=	X	X	X	=	=
d	a	c	b	=	X	X	X	X	=
d	b	a	c	=	X	X	X	=	X
d	b	c	a	X	X	X	X	X	=
d	c	a	b	=	X	X	X	X	X
d	c	b	a	X	X	X	X	X	X

The directional coupler of the second aspect of the present invention is based on non-evanescent adiabatic optical mode coupling. A special form of refraction index perturbation is used, such that optical mode coupling is achieved by varying the coupling strength along the propagation direction. Similar principles were used by E. Peral and A. Yariv, as described in "Supermodes of grating-coupled multi-mode waveguides and applications to mode conversion between copropagating modes mediated by backward Bragg scattering". *J. Lightwave Tech.*, vol. 17 pp. 942-947 (1999), for mode conversion between optical modes of a multi-mode waveguide. Specifically, mode conversion between co-propagating optical modes within the same waveguide was mediated by a backward-propagating optical mode. By contrast, in the directional coupler of the second aspect of the present invention, optical power is transferred from one waveguide to another; and the waveguides may be, and indeed usually are, single-mode waveguides.

To understand adiabatic optical power transfer between two waveguides, consider a system in which the optical field $\boldsymbol{E}$ is assumed to be given by a linear combination of three optical modes, such that

$$\boldsymbol{E}(x,y,z) = C_1(z)\exp(i\beta_1 z)\Phi_1^{(0)}(x,y) + C_2(z)\exp(i\beta_2 z)\Phi_2^{(0)}(x,y) + C_3(z)\exp(i\beta_3 z)\Phi_3^{(0)}(x,y) \quad (3)$$

where $C_j(z)$ are the z-dependent coefficients of the ideal optical modes $\Phi_j^{(0)}(x,y)$ and z is the direction of propagation. These ideal optical modes and their propagation constants β_j describe an optical wave propagating in a medium with a z-independent refractive index $n(x,y)$.

In the directional coupling problem, $\Phi_1^{(0)}(x,y)$ and $\Phi_2^{(0)}(x,y)$ represent optical fields localized in the first and second waveguides, respectively. The waveguides are sufficiently far apart that direct evanescent coupling between $\Phi_1^{(0)}(x,y)$ and $\Phi_2^{(0)}(x,y)$ is negligible.

Directional coupling and optical switching via adiabatic optical mode coupling can be achieved for either equivalent waveguides or for differing waveguides. The difference between the waveguides may be in their refractive indices, in their geometries, or in both. If the two waveguides are different (asynchronous directional coupler), $\Phi_1^{(0)}(x,y)$ is approximately the zero-order optical mode of the first waveguide and $\Phi_2^{(0)}(x,y)$ is approximately the zero-order optical mode of the second waveguide. If the two waveguides are equivalent (synchronous directional coupler), then the optical modes of the entire structure can be classified into optical modes of even and odd parity. Because the waveguides are far apart, the odd and even optical modes are almost degenerate. In this case, $\Phi_1^{(0)}(x,y)$ is the sum of the first even optical mode and the first odd optical mode, and is localized in one of the waveguides; and $\Phi_2^{(0)}(x,y)$ is the difference between the first even optical mode and the first odd optical mode, and is localized in the other waveguide. $\Phi_3^{(0)}(x,y)$ is a high-order optical mode of the entire two-waveguide structure, and is different from the high-order optical modes of the waveguides considered individually.

The three optical modes $\Phi_j^{(0)}(x,y)$, j=1,2,3, are coupled by modulating the refractive index in the direction of propagation:

$$V(x,y,z) = \frac{\omega^2}{c^2}[n^2(x,y,z) - \hat{n}^2(x,y)] \quad (4)$$

In equation (4), the modulation of the refractive index is expressed in terms of V, the product of the (coordinate-dependent) perturbation of the electric permeability (the square of the index of refraction) and the square of the free space wavenumber (ω/c). $\hat{n}(x,y)$ is the refractive index distribution of the unperturbed waveguide. ω is the angular frequency of the (monochromatic) optical wave, and c is the speed of light in a vacuum. The refractive index perturbation is assumed to be of the form

$$V(x,y,z)=\frac{\omega^2}{c^2}\left[\Delta\varepsilon_1(x,y)g_1(z)\cos\left(\frac{2\pi}{\Lambda_1}\right)z+\Delta\varepsilon_2(x,y)g_2(z)\cos\left(\frac{2\pi}{\Lambda_2}\right)z\right] \qquad (5)$$

such that

$$\frac{2\pi}{\Lambda_1}\approx\beta_1-\beta_3 \qquad (6)$$

$$\frac{2\pi}{\Lambda_{12}}\approx\beta_2-\beta_3 \qquad (7)$$

where the β_j are the propagation constants of the optical modes. $\Delta\varepsilon_1(x,y)$ and $\Delta\varepsilon_2(x,y)$ represent local amplitudes of the perturbation of the refractive index that couples $\Phi_3^{(0)}(x,y)$ with $\Phi_1^{(0)}(x,y)$ and $\Phi_2^{(0)}(x,y)$. $g_1(z)$ and $g_2(z)$ are z-dependent envelope functions that represent the change in optical mode coupling strength in the propagation direction.

Optical mode coupling is achieved by periodic or quasi-periodic perturbation of the refractive index. In the limiting case of infinitely long period, $g_1(z) = g_2(z) = 1$.

It is assumed that the refractive index modulation is such that $\Phi_1^{(0)}(x,y)$ and $\Phi_2^{(0)}(x,y)$ are not directly coupled. In addition, the perturbation of the refractive index with wavelength Λ_1 couples only $\Phi_1^{(0)}(x,y)$ and $\Phi_3^{(0)}(x,y)$, whereas the perturbation of the refractive index with wavelength Λ_2 couples only $\Phi_2^{(0)}(x,y)$ and $\Phi_3^{(0)}(x,y)$. It can be shown in such a case that the z-dependent coefficients of the optical modes (equation (3)) satisfy the following equation:

$$2ik_0\frac{d}{dz}\begin{pmatrix}C_1\\C_2\\C_3\end{pmatrix}=\begin{pmatrix}0&0&\kappa_1\\0&0&\kappa_2\\\kappa_1&\kappa_2&0\end{pmatrix}\begin{pmatrix}C_1\\C_2\\C_3\end{pmatrix} \qquad (8)$$

where k_0 is the wavenumber in the cladding and $\kappa_1(z)$ and $\kappa_2(z)$ are z-dependent coupling coefficients obtained by multiplying z-independent constant coupling coefficients

$$\kappa_1^{(0)} = \frac{\omega^2}{c^2} \int_{-\infty}^{\infty} \Delta\varepsilon_1(x,y)\Phi_1^{(0)}(x,y)\Phi_3^{(0)}(x,y)dxdy \quad (9)$$

and

$$\kappa_2^{(0)} = \frac{\omega^2}{c^2} \int_{-\infty}^{\infty} \Delta\varepsilon_2(x,y)\Phi_2^{(0)}(x,y)\Phi_3^{(0)}(x,y)dxdy \quad (10)$$

by the z-dependent envelope functions $g_1(z)$ and $g_2(z)$, respectively:

$$\kappa_1(z) = g_1(z)\kappa_1^{(0)} \quad (11)$$

$$\kappa_2(z) = g_2(z)\kappa_2^{(0)} \quad (12)$$

Equation (8) can be solved analytically. It can be shown that if $\kappa_1(z)$ and $\kappa_2(z)$ are such that

$$\frac{k_0 \left| d\vartheta / dz \right|}{\sqrt{\kappa_1^2(z)+\kappa_2^2(z)}} << 1 \quad (13)$$

where

$$\vartheta(z) = \arctan\left(\frac{\kappa_1(z)}{\kappa_2(z)}\right) \quad (14)$$

then adiabatic power transfer between the optical modes is obtained. Moreover, if initially $C_1(z=0)=1$, $C_2(z=0)=0$ and $C_3(z=0)=0$, and $\kappa_1(z)$ and $\kappa_2(z)$ are such that $\kappa_1(z=0)<<\kappa_2(z=0)$, then the coefficients of the optical modes are given by

$$C_1(z) = \frac{\kappa_2(z)}{\sqrt{\kappa_1^2(z)+\kappa_2^2(z)}} \quad (15)$$

$$C_2(z) = \frac{\kappa_1(z)}{\sqrt{\kappa_1^2(z)+\kappa_2^2(z)}} \quad (16)$$

$$C_3(z) = 0 \quad (17)$$

Finally, if $\kappa_1(z)$ and $\kappa_2(z)$ are such that $\kappa_1(z=L)>>\kappa_2(z=L)$, where L is the length of the waveguide section in which the refractive index is modulated, then

$$|C_2(z=L)|^2 = 1 \quad (18)$$

Thus, the optical power initially carried by the optical mode $\Phi_1^{(0)}(x,y)$ is transferred completely to the optical mode $\Phi_2^{(0)}(x,y)$. Note that $\Phi_1^{(0)}(x,y)$ and $\Phi_2^{(0)}(x,y)$ are not coupled directly to each other and that each of them is coupled to the third optical mode $\Phi_3^{(0)}(x,y)$ by $\kappa_1(z)$ and $\kappa_2(z)$, respectively. However, the third optical mode does not contribute to the optical field propagation, provided that the adiabatic condition is satisfied. Moreover, the adiabatic power transfer is obtained by

a counterintuitive sequence of couplings $\kappa_1(z)$ and $\kappa_2(z)$. That is, in order to transfer optical power from the first optical mode to the second optical mode, the perturbation of the refractive index that couples the second and the third initially unpopulated optical modes (κ_2) must be introduced *upstream* of the perturbation that couples the initially populated first optical mode and the initially unpopulated third optical mode (κ_1). Both the adiabaticity of the optical mode coupling and the efficiency of the optical power transfer depend on the form of the optical mode coupling coefficients $\kappa_1(z)$ and $\kappa_2(z)$. From equation (13) and the boundary conditions $\kappa_1(z=0)<<\kappa_2(z=0)$ and $\kappa_1(z=L)>>\kappa_2(z=L)$ it follows that the z-dependent envelopes of the coupling coefficients must overlap, because the optical mode coupling strength between $\Phi_1^{(0)}(x,y)$ and $\Phi_3^{(0)}(x,y)$ increases with z, whereas the optical mode coupling strength between $\Phi_2^{(0)}(x,y)$ and $\Phi_3^{(0)}(x,y)$ decreases with z. The precise z-dependence of the coupling strengths is not important, provided that $\kappa_1(z)$ and $\kappa_2(z)$ vary sufficiently slowly with z to preserve adiabaticity.

Figure 12, which is adapted from Figure 3 of Vorobeichik et al., is a schematic longitudinal cross-section of a directional coupler **200** of the second aspect of the present invention, for reversibly coupling two optical fibers **210** and **220**. Optical fiber **210** includes a core **214** encased in a cladding **212**. Similarly, optical fiber **220** includes a core **224** encased in a cladding **222**. Claddings **212** and **222** are in contact along a boundary **208**. The parallel portions of cores **214** and **224** adjacent to boundary **208** constitute coupling sections **216** and **226**. Cores **214** and **224** have indices of refraction that are larger than the indices of refraction of claddings **212** and **222**, so that cores **214** and **224** and the immediately adjacent portions of claddings **212** and **222** constitute waveguides, analogous to waveguides **12** and **14** of planar waveguide structure **10**, with respective effective indices of refraction; and the portions of claddings **212**and **222** between coupling sections **216** and **226** constitute a coupling region, analogous to coupling region **16** of planar waveguide structure **10**, with a respective effective index of refraction that is lower than the effective indices of refraction of the waveguides. Also shown in Figure 12 are coordinate axes x (transverse) and z (longitudinal).

On opposite sides of optical fibers **210** and **220**, parallel to coupling sections **216** and **226**, are planar gratings **230** and **240**, and cams **232** and **242** that, when

rotated, cause their respective planar gratings **230** and **240** to pivot on respective hinges **234** and **244**. In the illustrated positions of cams **232** and **242**, optical fibers **210** and **220** are unstressed, and the indices of refraction of coupling sections **216** and **226** are longitudinally homogeneous, as are the effective indices of refraction of the corresponding waveguides. By rotating cams **232** and **242**, longitudinal periodic stress fields are imposed on optical fibers **210** and **220**, thereby perturbing the indices of refraction of coupling sections **216** and **218**, and hence the effective indices of refraction of the equivalent waveguides, in a quasiperiodic manner. By a "quasiperiodic" perturbation is meant a periodic perturbation with a laterally non-uniform envelope function, so that the peak (maximum and minimum) amplitudes of the perturbation have different values in different cycles or periods of the perturbation. In particular, the envelope function of the stress field imposed on optical fiber **210** by planar grating **230**, and hence the envelope function of the perturbation induced in the indices of refraction of optical fiber **210** and in the effective index of refraction of the equivalent waveguide by planar grating **230**, increases monotonically in the $+z$ direction; whereas the envelope function of the stress field imposed on optical fiber **220** by planar grating **240**, and hence the envelope function of the perturbation induced in the indices of refraction of optical fiber **220** and in the effective index of refraction of the equivalent waveguide by planar grating **240**, decreases monotonically in the +z direction. As a result, by the principles of the second aspect of the present invention, light that propagates in the $+z$ direction in optical fiber **210** is coupled by these perturbations into optical fiber **220**. Directional coupler **200** thus functions as a normally "off" optical switch. When cams **232** and **242** are in the positions shown in Figure 12, so that no stress fields are imposed on optical fibers **210** and **220**, light propagating in the $+z$ direction via optical fiber **210** remains in optical fiber **210**. When cams **232** and **242** are rotated to urge planar gratings **230** and **240** towards optical fibers **210** and **220**, thereby imposing their respective stress fields on optical fibers **210** and **220**, at least part of the light that propagates in the $+z$ direction via optical fiber **210** is coupled into optical fiber **220**, to propagate in the $+z$ direction via optical fiber **220**.

Planar gratings **230** and **240**, and their associated cams **232** and **242** and pivots **234** and **244**, constitute mechanical mechanisms for reversibly inducing quasiperiodic perturbations in the indices of refraction of optical fibers **210** and **220**, and so in the

effective indices of refraction of the equivalent waveguides, according to the principles of the second aspect of the present invention. It will be apparent to those skilled in the art that other types of mechanisms, for example thermo-optic mechanisms, piezo-electric mechanisms, acousto-optic mechanisms, electro-optic mechanisms and mechanisms that reversibly inject charge carriers into optical fibers **210** and **220**, also may be used.

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.

WHAT IS CLAIMED IS:

1. A waveguide structure comprising:

(a) a first waveguide, having a proximal end, and having a first waveguide effective index of refraction $\overline{n}_1$;

(b) a second waveguide, substantially parallel to said first waveguide, having a proximal end, and having a second waveguide effective index of refraction $\overline{n}_2$;

(c) a coupling region, situated between said waveguides, having a coupling region effective index of refraction $\overline{n}_3$ that is less than $\overline{n}_1$ and that also is less than $\overline{n}_2$;

(d) a first bounding region, said first waveguide being situated between said first bounding region and said coupling region, said first bounding region having a proximal end adjacent to said proximal end of said first waveguide, said first bounding region having a first bounding region effective index of refraction that decreases adiabatically, in a direction substantially parallel to said waveguides, from a value, at said proximal end of said first bounding region, that is between $\overline{n}_1$ and $\overline{n}_3$, to an intermediate value, in a switching section of said first bounding region, that is less than $\overline{n}_3$; and

(e) a second bounding region, said second waveguide being situated between said second bounding region and said coupling region, said second bounding region having a proximal end adjacent to said proximal end of said second waveguide, said second bounding region having a second bounding region effective index of refraction that decreases adiabatically, in said substantially parallel direction, from a value, at said proximal end of said second bounding region, that is between $\overline{n}_2$ and $\overline{n}_3$, to an intermediate value, in a switching section of said second bounding region, that is less than $\overline{n}_3$.

2. The waveguide structure of claim 1, wherein said first and second waveguides have respective distal ends, wherein said first bounding region has a distal end adjacent to said distal end of said first waveguide, wherein said second bounding region has a distal end adjacent to said distal end of said second waveguide, wherein said first bounding region effective index of refraction increases adiabatically, in said substantially parallel direction, from said intermediate value thereof, in said switching section of said first bounding region, to a value, at said distal end of said first bounding region, that is between $\overline{n}_1$ and $\overline{n}_3$, and wherein said second bounding region effective index of refraction increases adiabatically, in said substantially parallel direction, from said intermediate value thereof, in said switching section of said second bounding region, to a value, at said distal end of said second bounding region, that is between $\overline{n}_2$ and $\overline{n}_3$.

3. The waveguide structure of claim 1, wherein said intermediate values are substantially equal.

4. The waveguide structure of claim 1, wherein said waveguides meander transversely to said parallel direction between said switching sections of said bounding regions.

5. The waveguide structure of claim 4, wherein said meandering is substantially in a plane defined by said waveguides.

6. The waveguide structure of claim 4, wherein said meandering is substantially perpendicular to a plane defined by said waveguides.

7. The waveguide structure of claim 4, wherein said meandering couples respective optical modes of said waveguides, that are substantially confined to said waveguides, to a high-order optical mode common to both said waveguides.

8. The waveguide structure of claim 7, wherein said respective optical modes of said waveguides are zero-order optical modes of said waveguides.

9. The waveguide structure of claim 1, wherein respective thicknesses of said waveguides vary substantially periodically in said parallel direction between said switching sections of said bounding regions.

10. The waveguide structure of claim 9, wherein said varying of said thicknesses is substantially in a plane defined by said waveguides.

11. The waveguide structure of claim 9, wherein said varying of said thicknesses is substantially perpendicular to a plane defined by said waveguides.

12. The waveguide structure of claim 9, wherein said varying of said thicknesses couples respective optical modes of said waveguides, that are substantially confined to said waveguides, to a high-order optical mode common to both said waveguides.

13. The waveguide structure of claim 12, wherein said respective optical modes of said waveguides are zero-order optical modes of said waveguides.

14. The waveguide structure of claim 1, further comprising:

(f) a mechanism for reversibly perturbing, in and between said switching sections, at least one effective index of refraction selected from the group consisting of said bounding region effective indices of refraction, $\overline{n}_1$, $\overline{n}_2$ and $\overline{n}_3$.

15. The waveguide structure of claim 14, wherein said perturbation is substantially uniform in said substantially parallel direction.

16. The waveguide structure of claim 14, wherein said perturbation is substantially periodic in said substantially parallel direction.

17. The waveguide structure of claim 14, wherein said mechanism is thermo-optic.

18. The waveguide structure of claim 14, wherein said mechanism is piezo-electric.

19. The waveguide structure of claim 14, wherein said mechanism is acousto-optic.

20. The waveguide structure of claim 14, wherein said mechanism is electro-optic.

21. The waveguide structure of claim 14, wherein said mechanism is operative to inject charge carriers reversibly into at least one portion of the waveguide structure selected from the group consisting of said waveguides, said bounding regions and said coupling region.

22. A directional coupler comprising the waveguide structure of claim 14.

23. A power divider comprising the directional coupler of claim 22.

24. A wavelength filter comprising the directional coupler of claim 22.

25. An optical modulator comprising the directional coupler of claim 22.

26. An attenuator comprising the directional coupler of claim 22.

27. An optical switch comprising the waveguide structure of claim 14.

28. An optical switch matrix comprising at least one optical switch of claim 27.

29. An optical switch matrix, for switching optical signals from a first number of input waveguides to a second number of output waveguides, a larger of said two numbers being greater than 2, the optical switch matrix comprising:

(a) a plurality of switch waveguides, equal in number to the larger of said two numbers, each said switch waveguide being optically coupled to at least one of a respective input waveguide and a respective output waveguide, all said switch waveguides being substantially straight and parallel.

30. The optical switch matrix of claim 29, further comprising:

(b) for each adjacent pair of said switch waveguides, at least one coupling mechanism for optically coupling said each adjacent pair of switch waveguides.

31. The optical switch matrix of claim 30, wherein, for each adjacent pair of said switch waveguides, each said coupling mechanism includes:

(i) a coupling region, between at least a portion of a first of said switch waveguides of said each adjacent pair and at least a portion of a second of said switch waveguides of said each adjacent pair, said at least portion of said first switch waveguide having a first waveguide effective index of refraction $\overline{n}_1$, said at least portion of said second switch waveguide having a second waveguide effective index of refraction $\overline{n}_2$, said coupling region having a coupling region effective index of refraction $\overline{n}_3$ that is less than $\overline{n}_1$ and that also is less than $\overline{n}_2$.

32. The optical switch matrix of claim 31, wherein, for each said coupling region, said at least portions of said first and second switch waveguides have respective proximal ends; and wherein each said coupling mechanism further includes:

(d) a first bounding region, said at least portion of said first switch waveguide being situated between said first bounding region and said coupling region, said first bounding region having a proximal end adjacent to said proximal end of said at least portion of said first switch waveguide, said first bounding region having a first bounding region effective index of refraction that decreases adiabatically, in a direction

substantially parallel to said switch waveguides, from a value, at said proximal end of said first bounding region, that is between $\overline{n}_1$ and $\overline{n}_3$, to an intermediate value, in a switching section of said first bounding region, that is less than $\overline{n}_3$; and

(e) a second bounding region, said at least portion of said second switch waveguide being situated between said second bounding region and said coupling region, said second bounding region having a proximal end adjacent to said proximal end of said at least portion of said second switch waveguide, said second bounding region having a second bounding region effective index of refraction that decreases adiabatically, in said substantially parallel direction, from a value, at said proximal end of said second bounding region, that is between $\overline{n}_2$ and $\overline{n}_3$, to an intermediate value, in a switching section of said second bounding region, that is less than $\overline{n}_3$.

33. The optical switch matrix of claim 32, wherein, for each said coupling region: said at least portions of said first and second switch waveguides have respective distal ends, wherein said first bounding region has a distal end adjacent to said distal end of said at least portion of said first switch waveguide, wherein said second bounding region has a distal end adjacent to said distal end of said at least portion of said second switch waveguide, wherein said first bounding region effective index of refraction increases adiabatically, in said substantially parallel direction, from said intermediate value thereof, in said switching section of said first bounding region, to a value, at said distal end of said first bounding region, that is between $\overline{n}_1$ and $\overline{n}_3$, and wherein said second bounding region effective index of refraction increases adiabatically, in said substantially parallel direction, from said intermediate value thereof, in said switching section of said second bounding region, to a value, at said distal end of said second bounding region, that is between $\overline{n}_2$ and $\overline{n}_3$.

34. A directional coupler, comprising:

(a) a first waveguide having a first effective index of refraction;

(b) a second waveguide, substantially parallel to said first waveguide and having a second effective index of refraction;

(c) a first mechanism for reversibly inducing a first quasiperiodic perturbation in said first effective index of refraction; and

(d) a second mechanism for reversibly inducing a second quasiperiodic perturbation in said second effective index of refraction;

wherein said first quasiperiodic perturbation has a first envelope function that varies monotonically along said first waveguide, and wherein said second quasiperiodic perturbation has a second envelope function that varies monotonically along said second waveguide in a sense opposite to said variation of said first envelope function.

35. The directional coupler of claim 34, further comprising:

(e) a coupling region situated between said first and second waveguides and having a third effective index of refraction that is less than both said first effective index of refraction and said second effective index of refraction;

36. The directional coupler of claim 34, wherein said waveguides are single-mode waveguides.

37. The directional coupler of claim 34, wherein said mechanisms are thermo-optic.

38. The directional coupler of claim 34, wherein said mechanisms are piezo-electric.

39. The directional coupler of claim 34, wherein said mechanisms are acousto-optic.

40. The directional coupler of claim 34, wherein said mechanisms are electro-optic.

41. The directional coupler of claim 34, wherein said first and second mechanisms are operative to inject charge carriers reversibly into said first waveguide and into said second waveguide, respectively.

42. A power divider comprising the directional coupler of claim 34.

43. A wavelength filter comprising the directional coupler of claim 34.

44. An optical switch comprising the directional coupler of claim 34.

45. An optical modulator comprising the directional coupler of claim 34.

46. An attenuator comprising the directional coupler of claim 34.

47. A method for diverting a least a portion of electromagnetic energy, that propagates in a certain direction via a first waveguide, to a second waveguide that is substantially parallel to the first waveguide, comprising the steps of:

(a) inducing a first quasiperiodic perturbation in an effective index of refraction of the first waveguide, said first perturbation having an envelope function that varies monotonically in the propagation direction; and

(b) inducing a second quasiperiodic perturbation in an effective index of refraction of the second waveguide, said second perturbation having an envelope function that varies monotonically in the propagation direction in a sense opposite to said variation of said envelope function of said first perturbation.

48. The method of claim 47, wherein said envelope function of said first perturbation increases in the propagation direction and wherein said envelope function of said second perturbation decreases in the propagation direction.

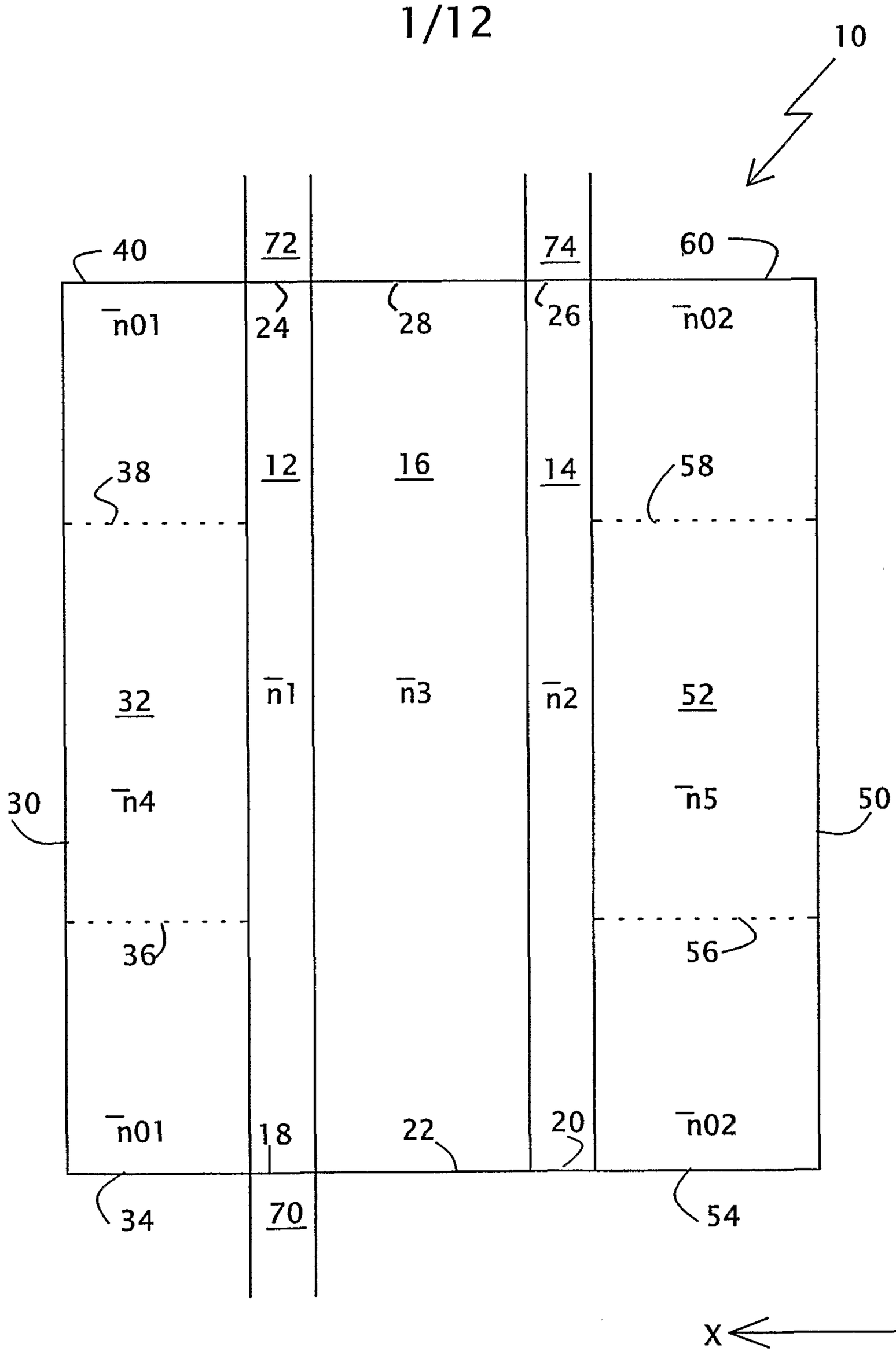

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Fig. 1

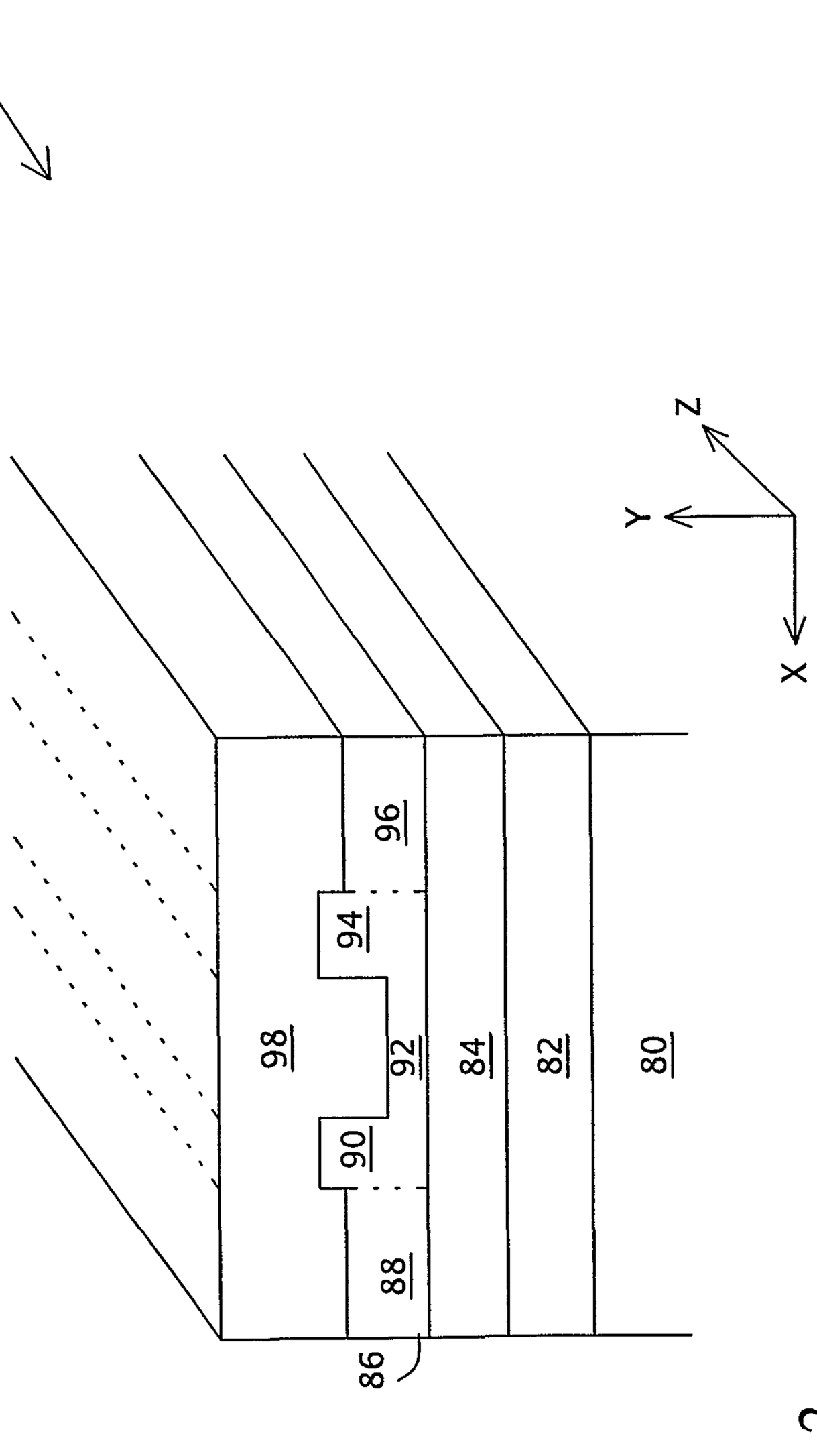


Fig. 2

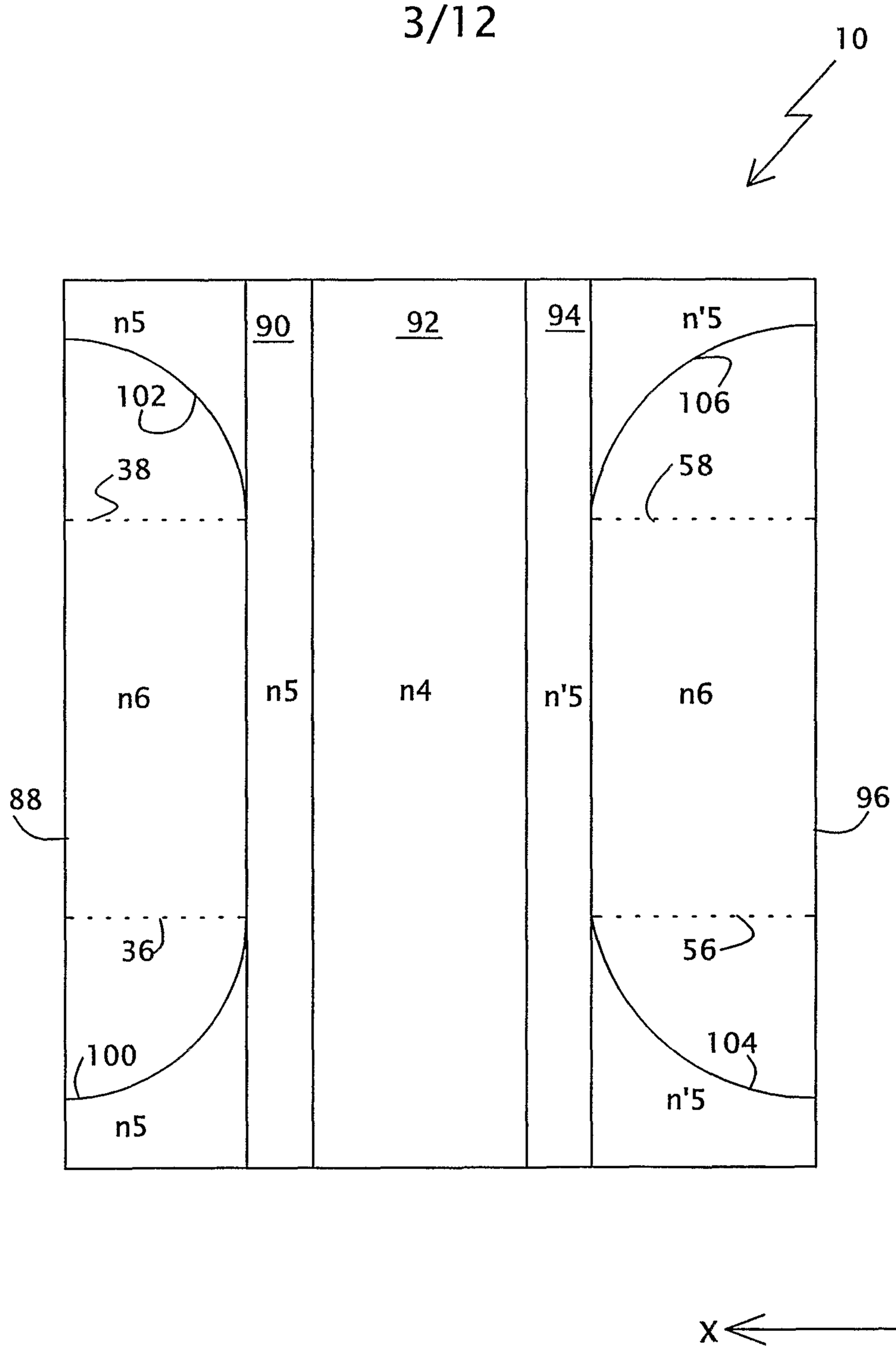

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Fig. 3

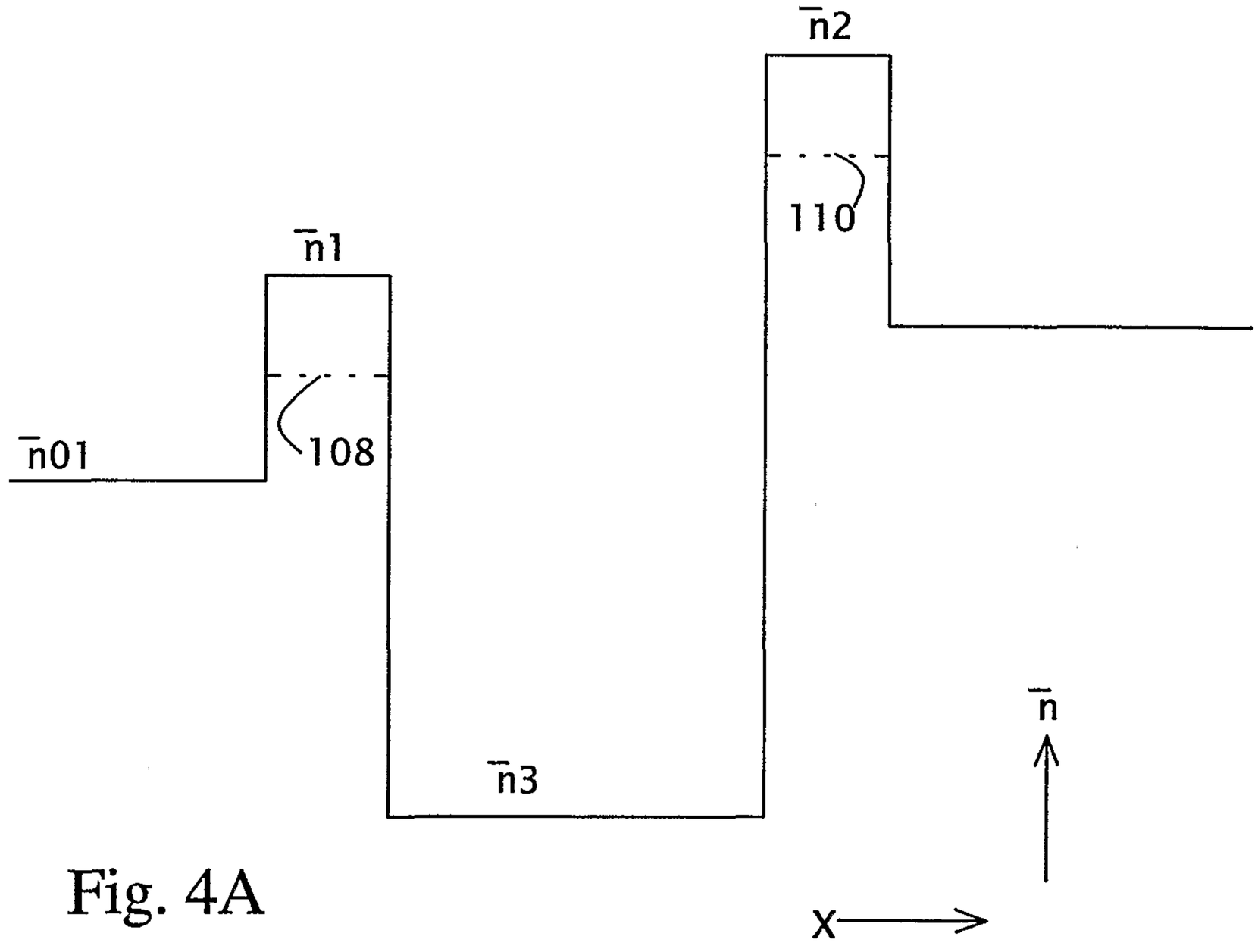


Fig. 4A

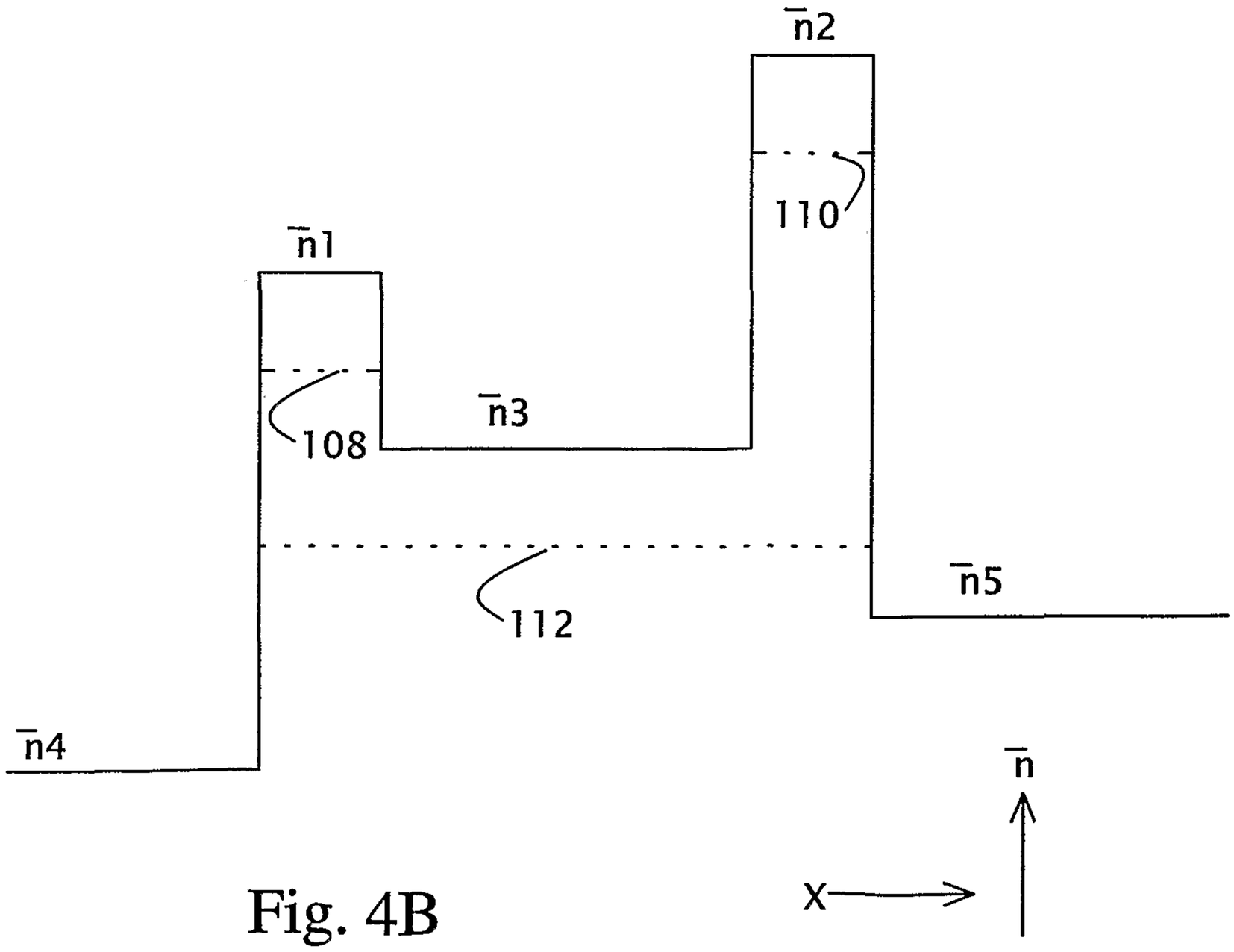


Fig. 4B

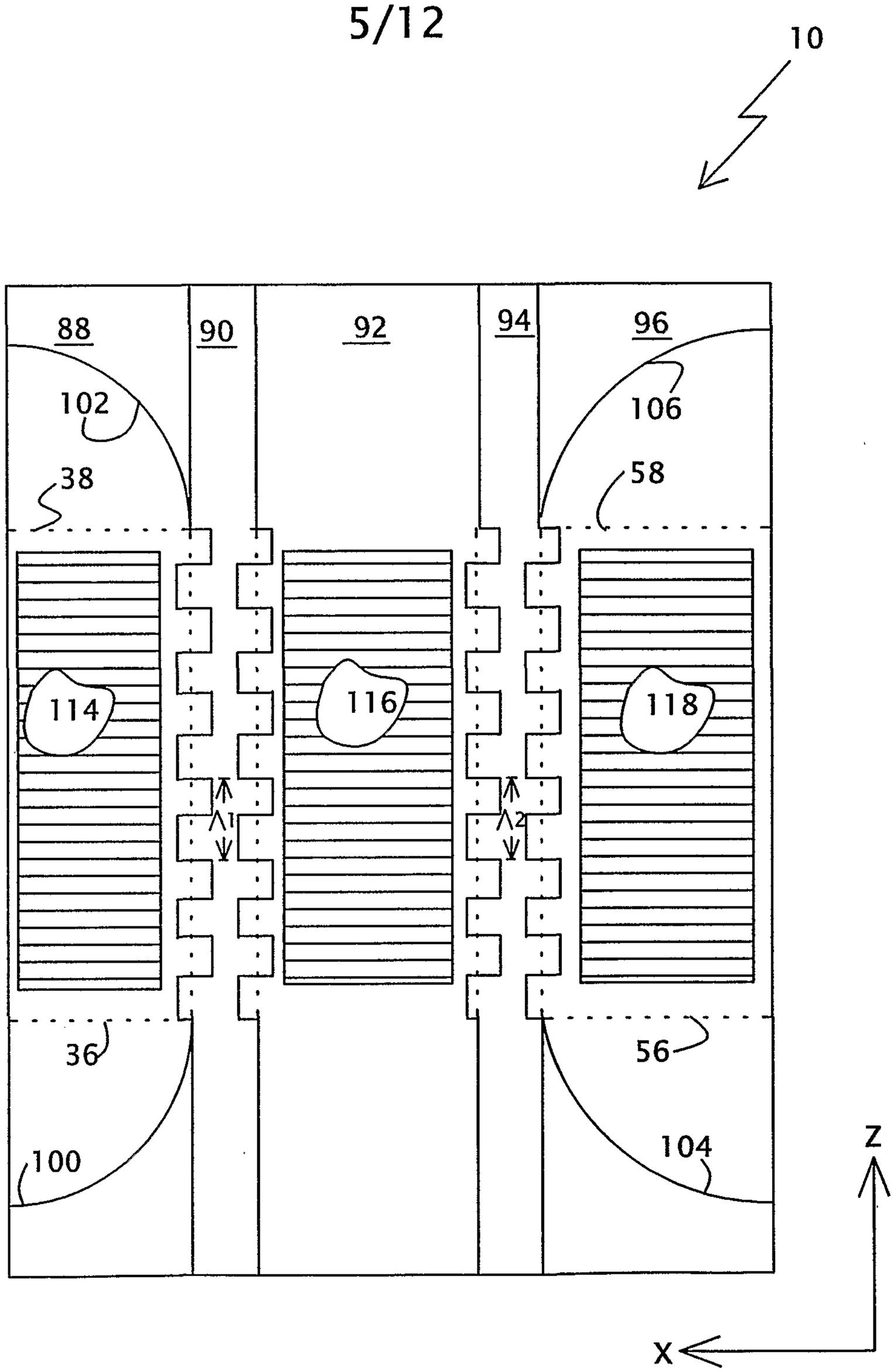


Fig. 5

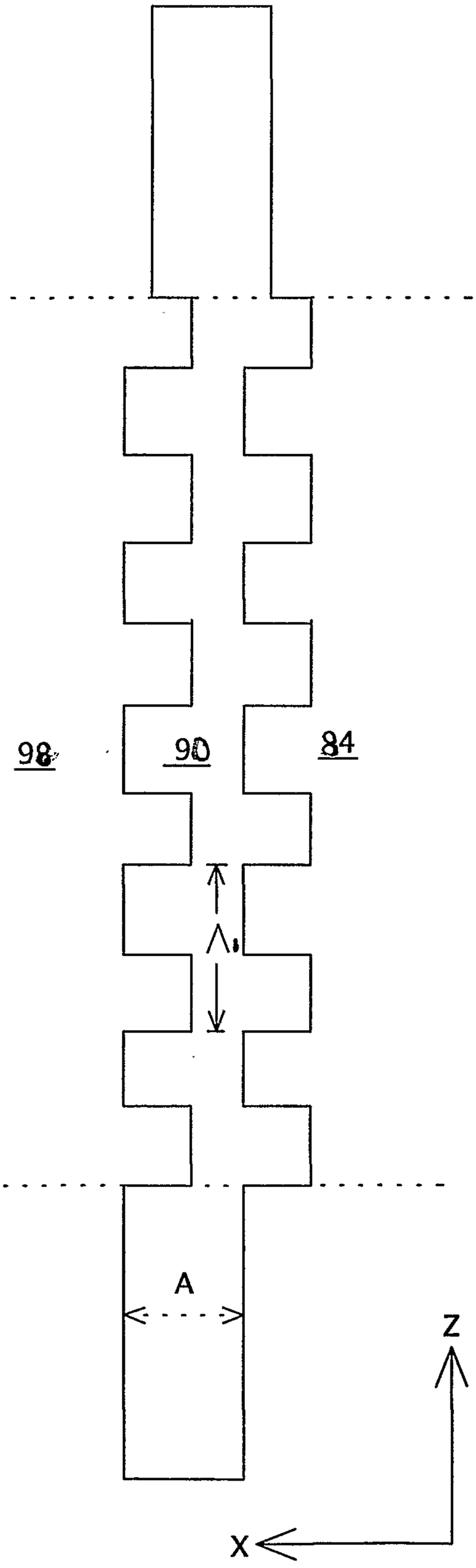


Fig. 6

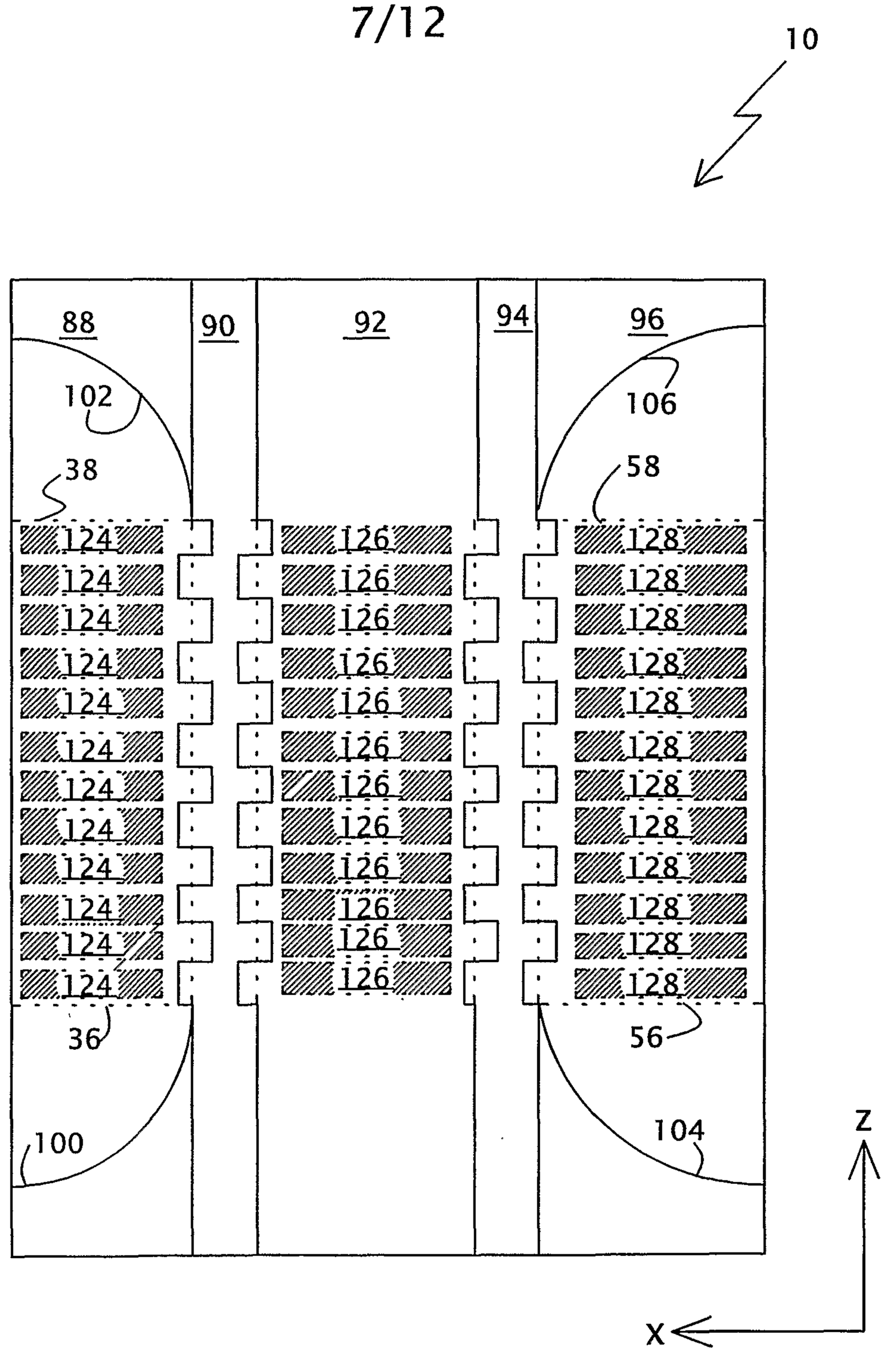


Fig. 7

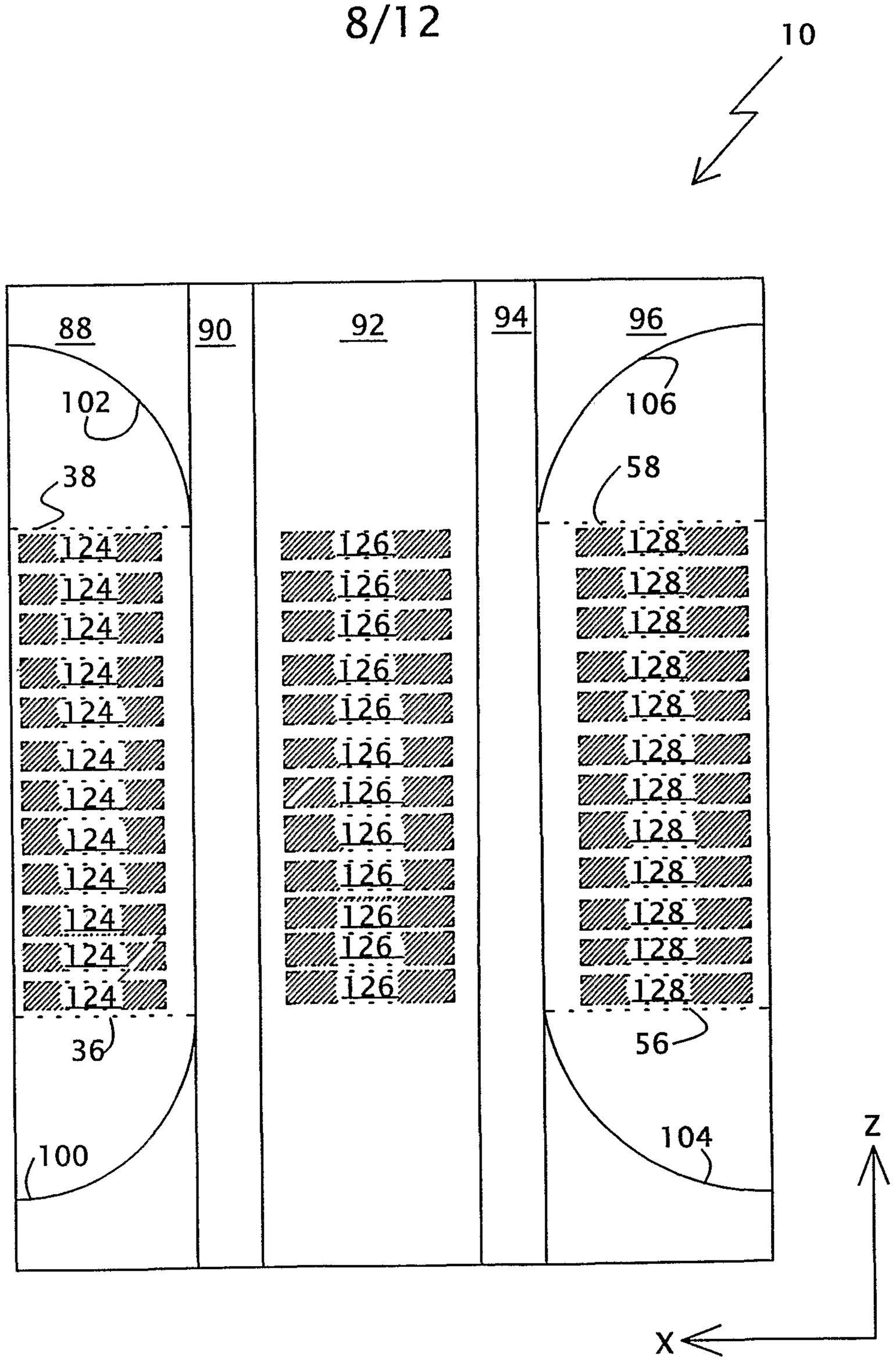


Fig. 8

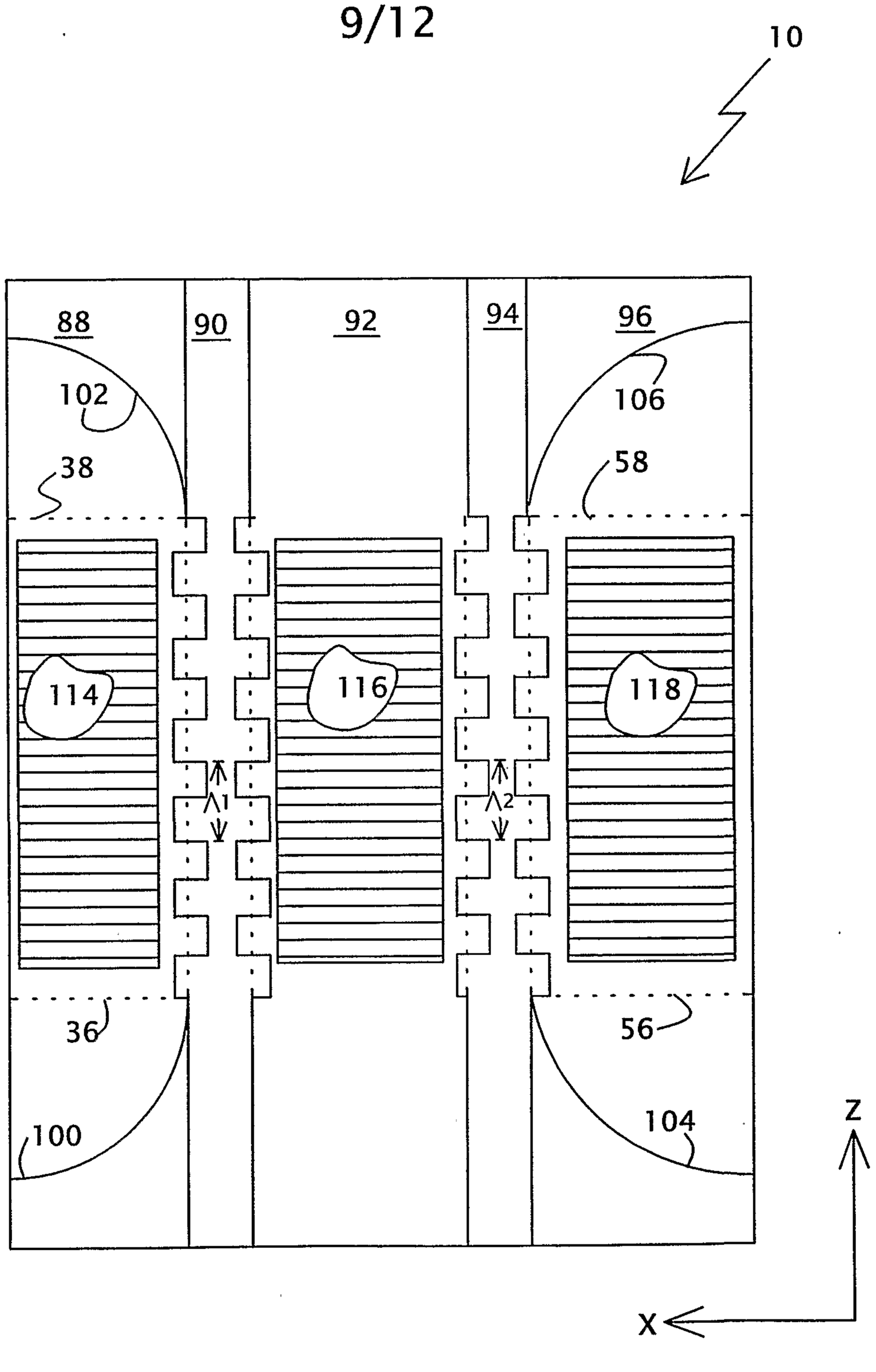

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Fig. 9

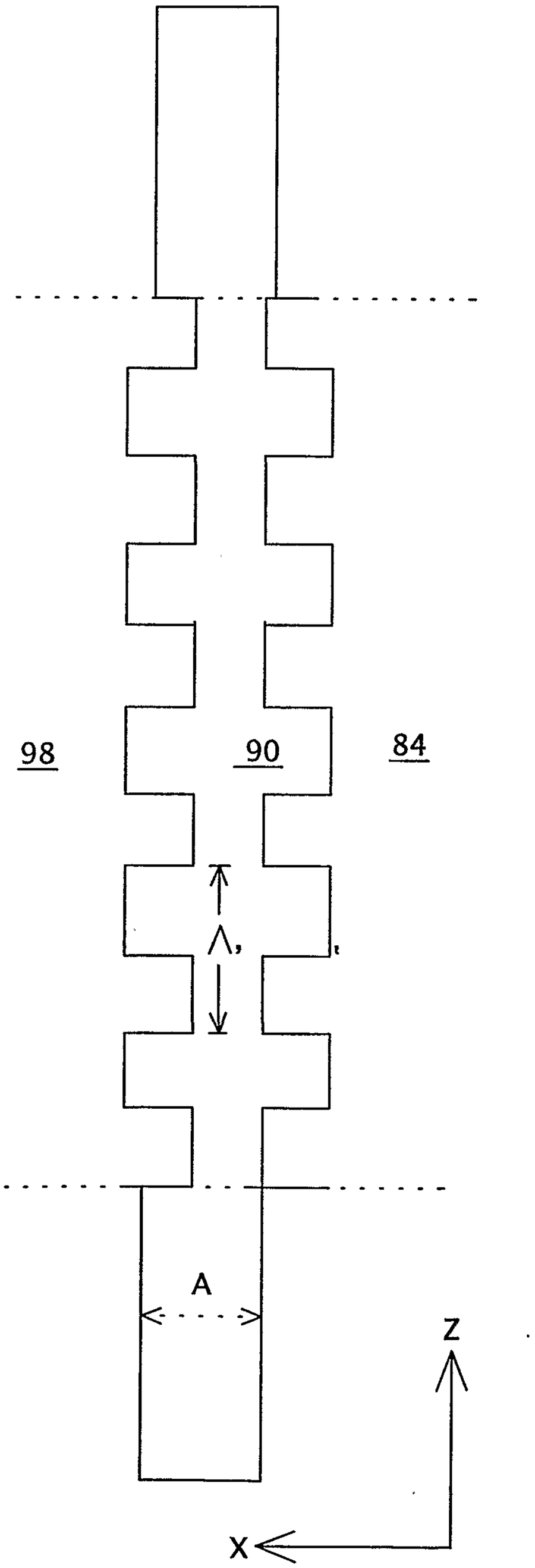


Fig. 10

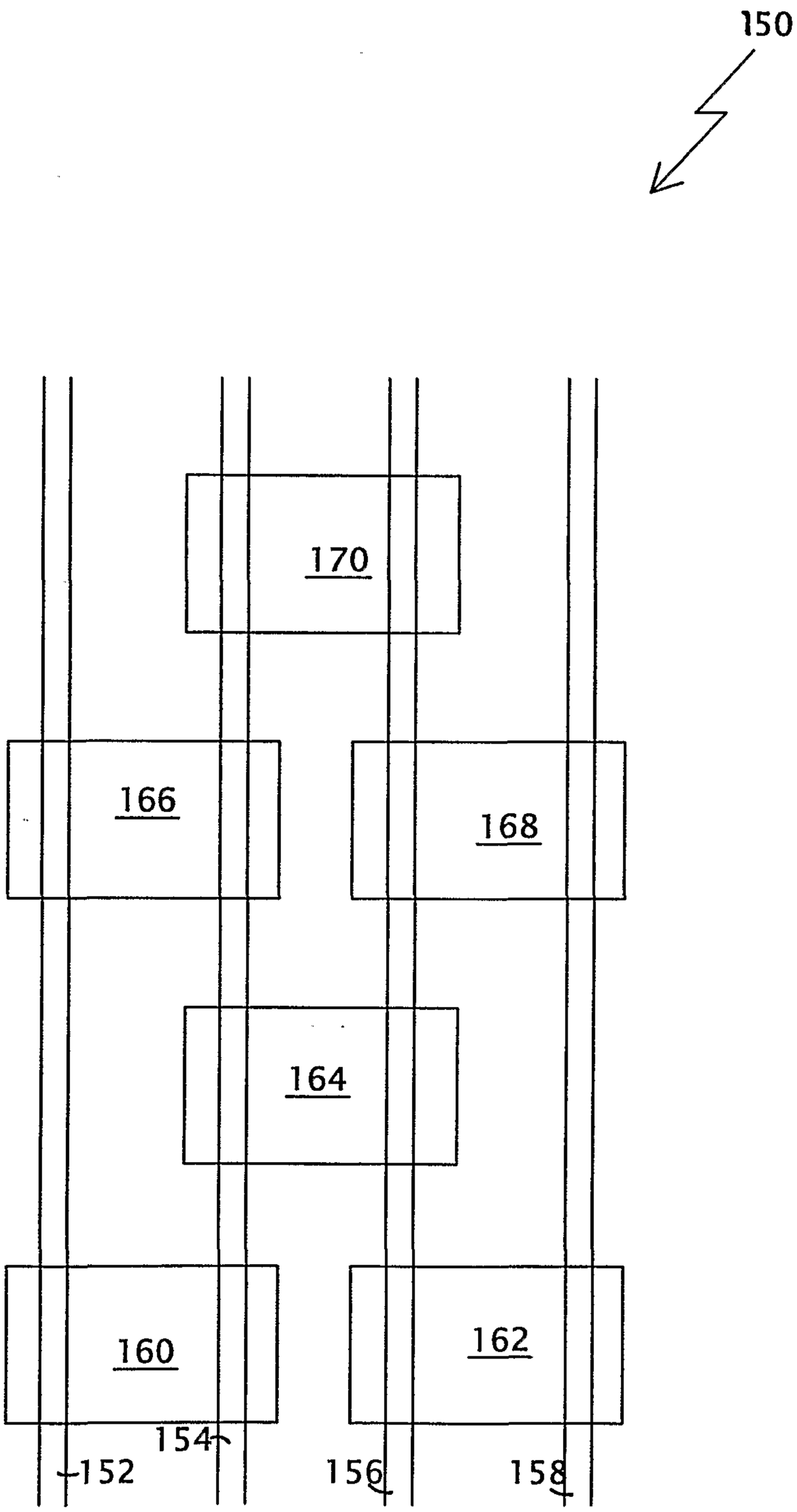


Fig. 11

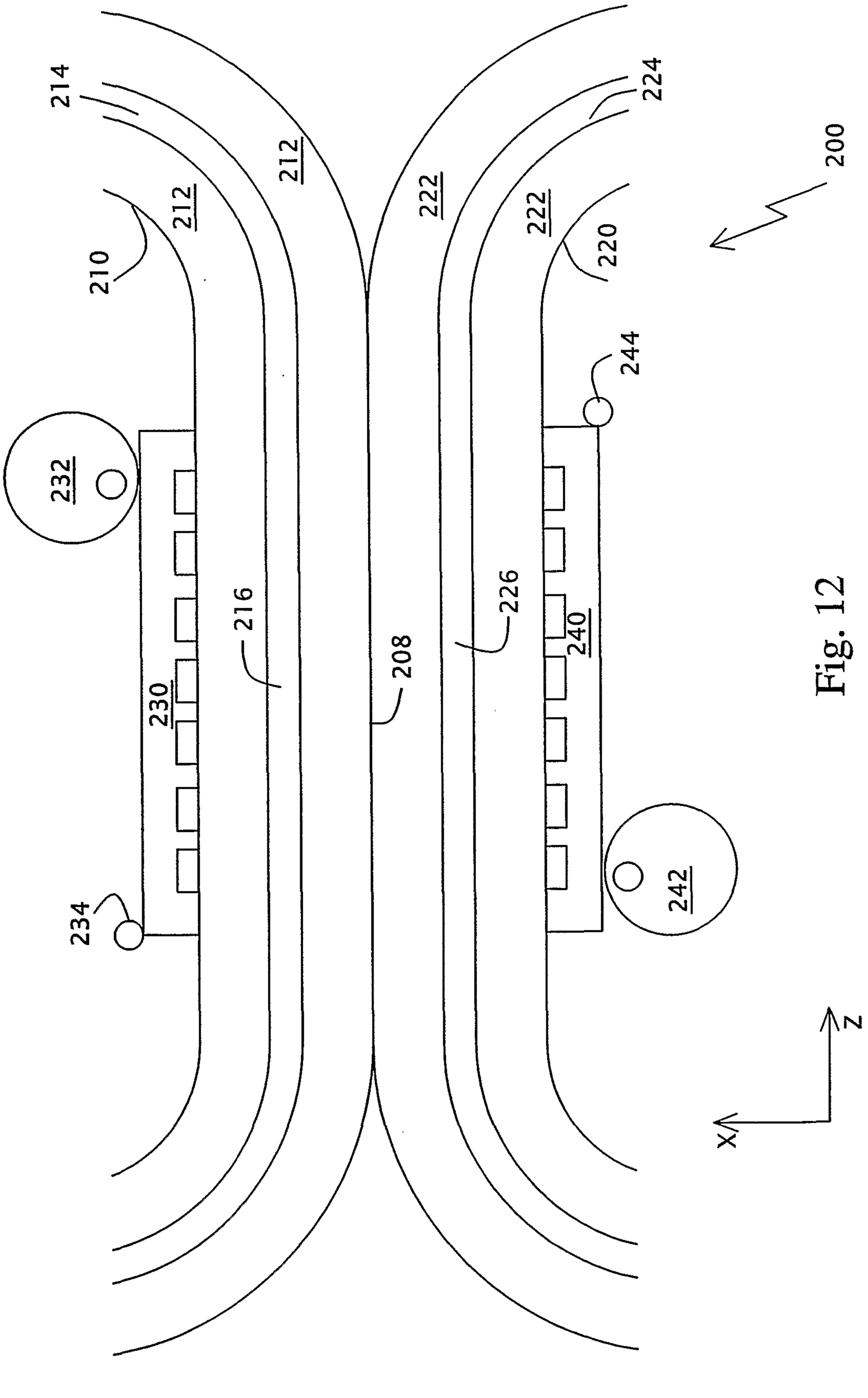
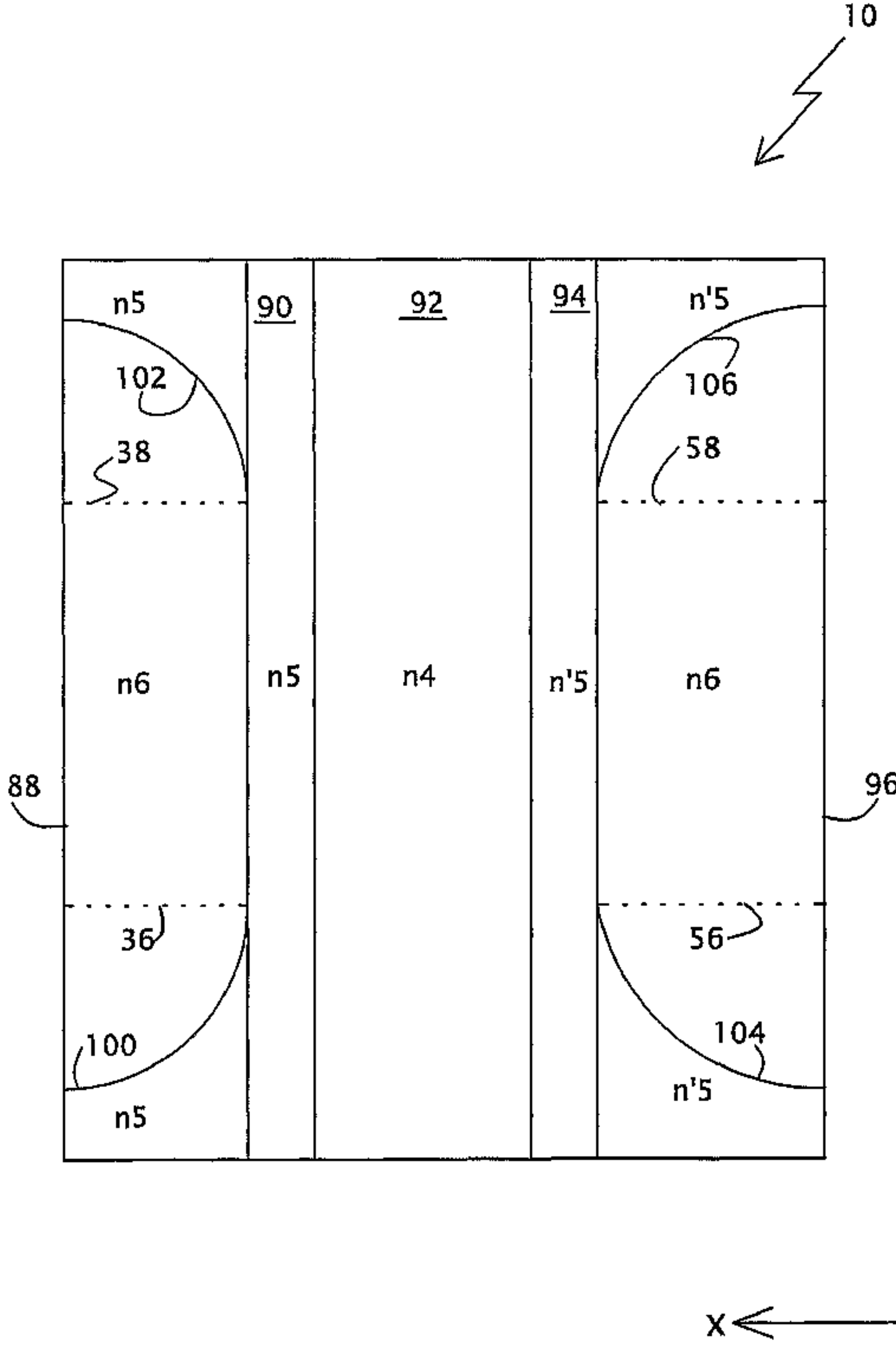

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Fig. 12


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