US00RE45249E

(19) **United States**
(12) **Reissued Patent**
Figueroa et al.
(10) **Patent Number: US RE45,249 E**
(45) **Date of Reissued Patent: Nov. 18, 2014**

(54) **SYSTEM METHOD AND APPARATUS FOR SELECTING AND CONTROLLING LIGHT SOURCE BANDWIDTH**

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(21) Appl. No.: **13/778,006**

(22) Filed: **Feb. 26, 2013**

Related U.S. Patent Documents

Reissue of:
(64) Patent No.: **8,144,739**
Issued: **Mar. 27, 2012**
Appl. No.: **12/605,306**
Filed: **Oct. 23, 2009**

U.S. Applications:
(60) Provisional application No. 61/197,246, filed on Oct. 24, 2008.

(51) **Int. Cl.**
H01S 3/10 (2006.01)

(52) **U.S. Cl.**
USPC **372/25**; 372/102

(58) **Field of Classification Search**
USPC 372/25, 102; 359/566, 572, 615
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,095,492	A	*	3/1992	Sandstrom	372/102
5,970,082	A	*	10/1999	Ershov	372/102
6,094,448	A	*	7/2000	Fomenkov et al.	372/102
6,163,559	A	*	12/2000	Watson	372/102
6,212,217	B1	*	4/2001	Erie et al.	372/102
6,493,374	B1		12/2002	Fomenkov et al.	
7,006,538	B2	*	2/2006	Bushida et al.	372/14
7,154,928	B2		12/2006	Sandstrom et al.	
7,471,455	B2	*	12/2008	Das et al.	359/618
7,659,529	B2		2/2010	Figueroa	
7,894,494	B2		2/2011	Ishihara	
7,899,095	B2		3/2011	Partlo	
8,259,764	B2		9/2012	Fomenkove et al.	
2006/0114956	A1		6/2006	Sandstrom et al.	
2006/0114958	A1		6/2006	Trintchouk et al.	
2007/0297467	A1		12/2007	Fomenkov et al.	
2008/0159692	A1		7/2008	Yao	
2008/0232408	A1	*	9/2008	O'Brien et al.	372/19
2011/0122901	A1		5/2011	Sandstrom et al.	
2011/0194580	A1	*	8/2011	Algots et al.	372/55

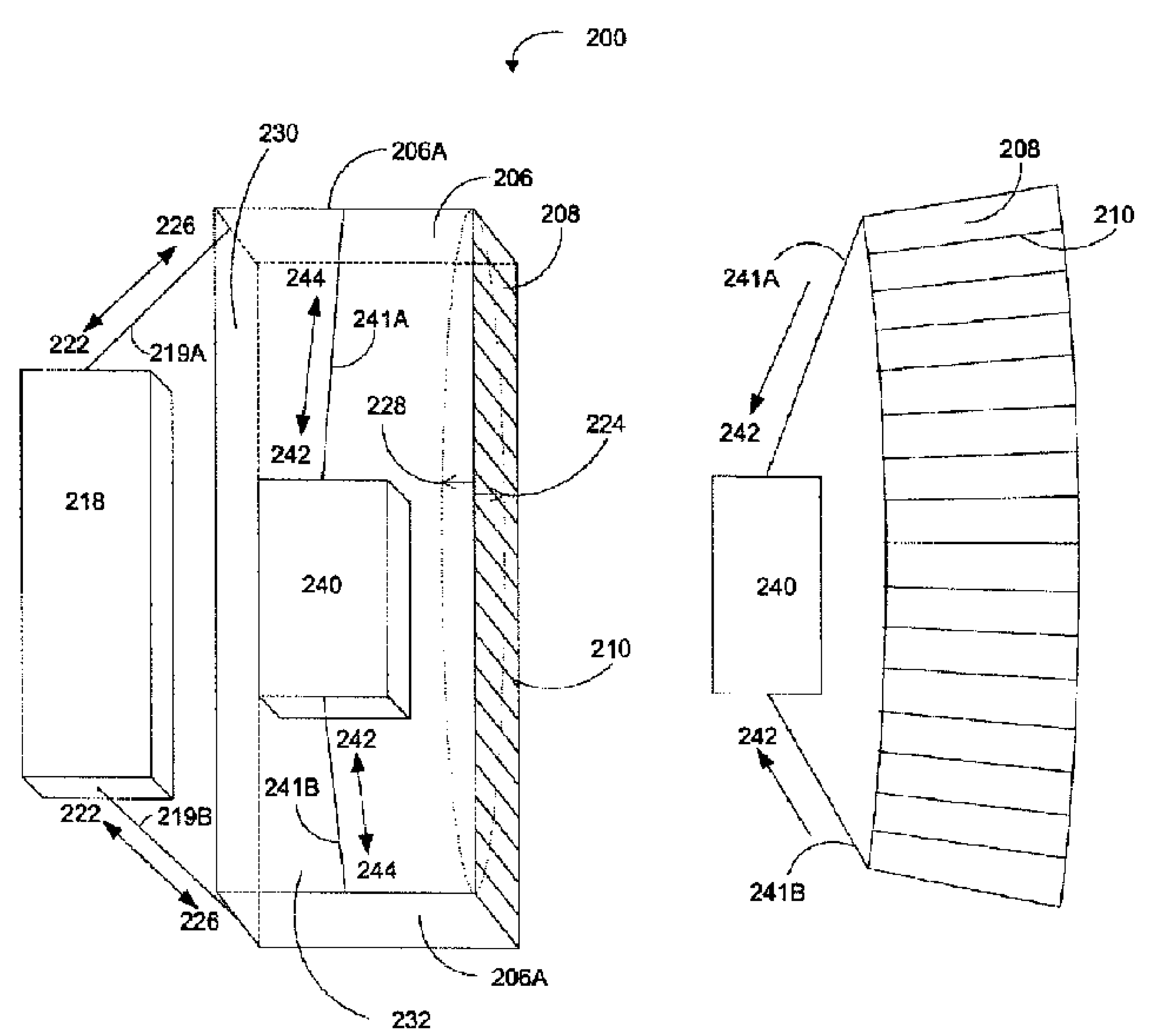
* cited by examiner

Primary Examiner — Arnel C Lavarias
(74) *Attorney, Agent, or Firm* — Martine Penilla Group, LLP

(57) **ABSTRACT**

The bandwidth selection mechanism includes a first actuator mounted on a second face of a dispersive optical element, the second face being opposite from a reflective face, the first actuator having a first end coupled to a first end block and a second end coupled to a second end block, the first actuator being operative to apply equal and opposite forces to the first end block and the second end block to bend the body of the dispersive optical element along the longitudinal axis of the body and in a first direction normal to the reflective face of the dispersive optical element. The bandwidth selection mechanism also includes a second actuator being operative to apply equal and opposite forces to bend the body along the longitudinal axis of the body, in a second direction perpendicular to the reflective face of the dispersive optical element.

33 Claims, 17 Drawing Sheets



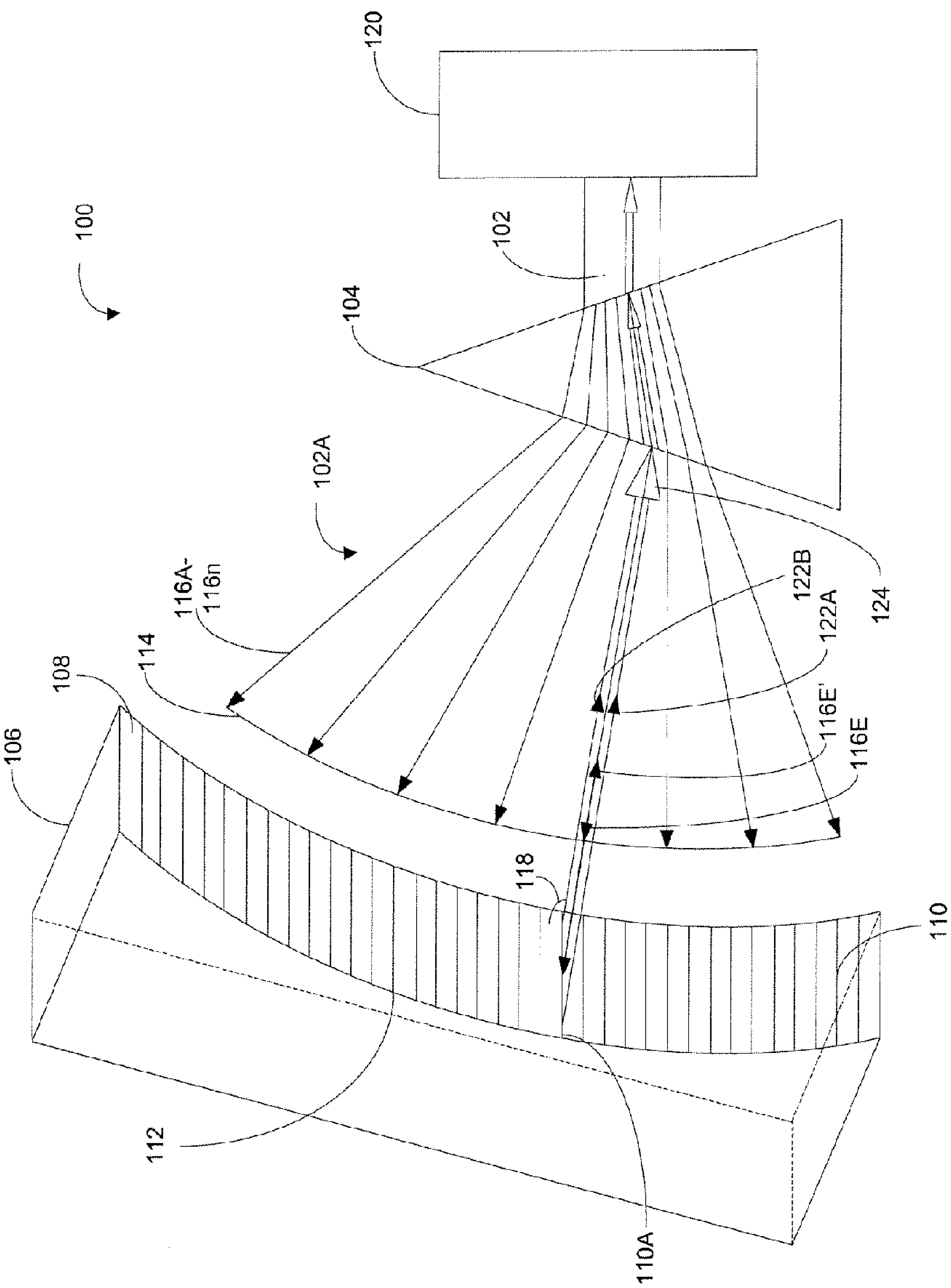


FIG. 1
Prior Art

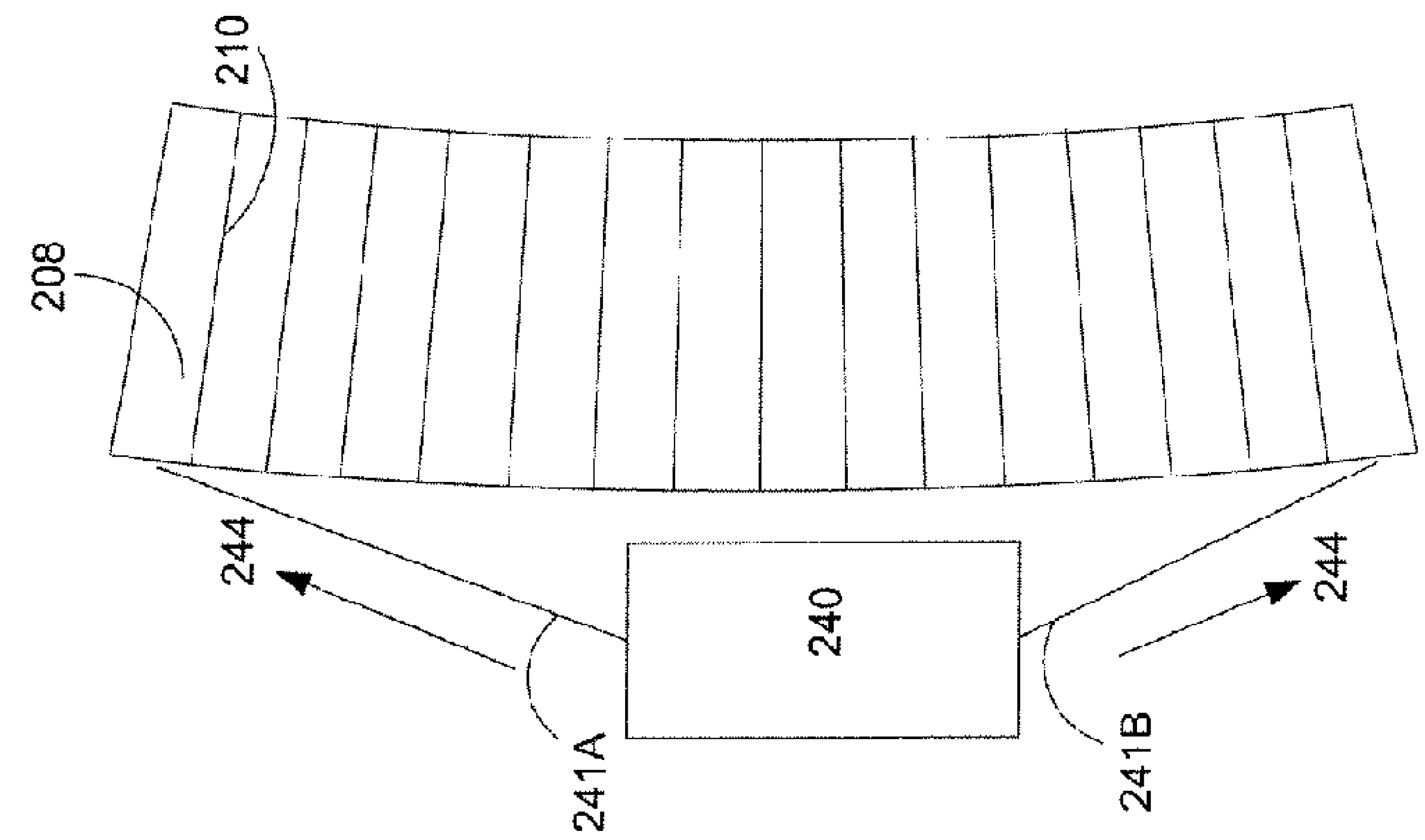


FIG. 2C

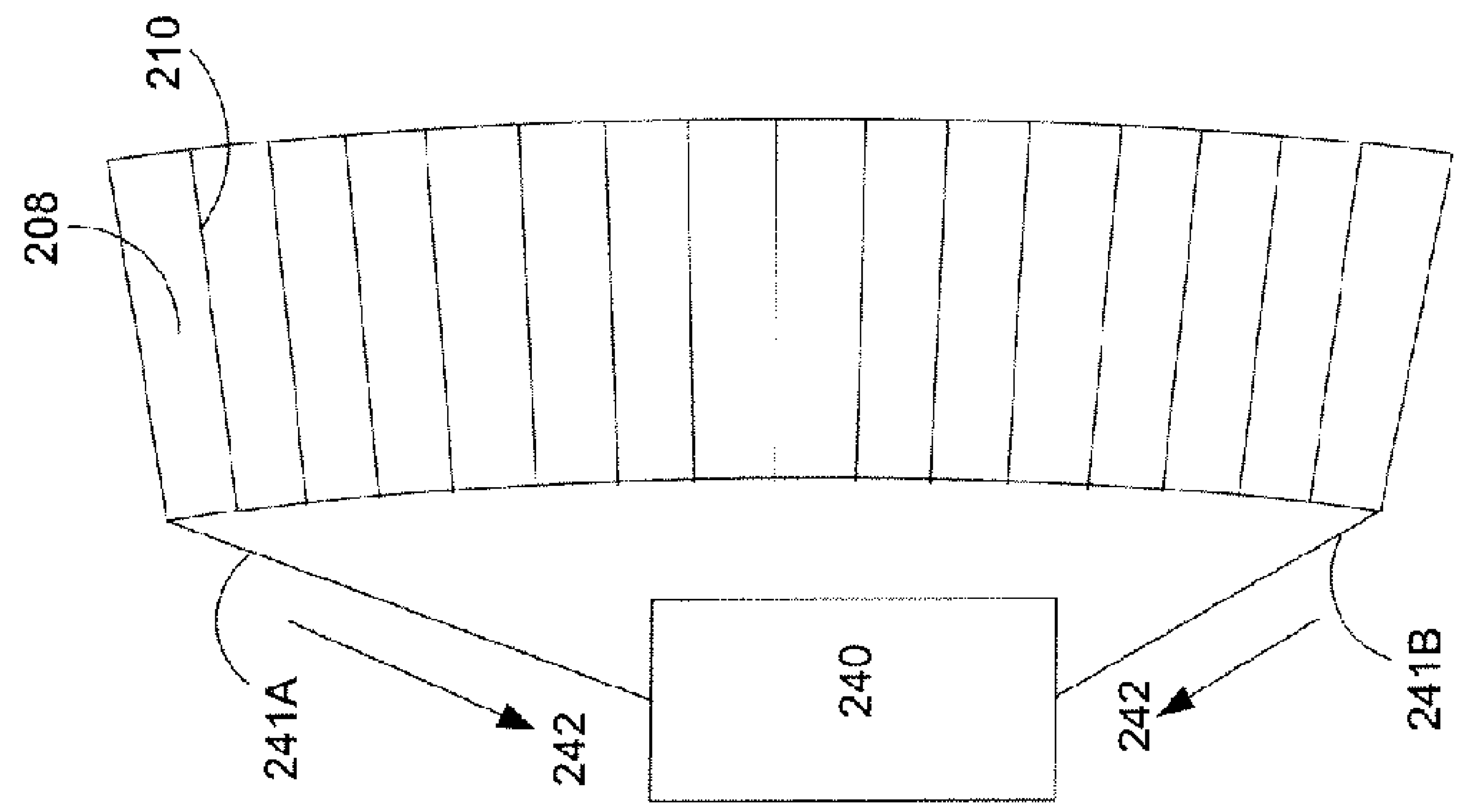


FIG. 2B

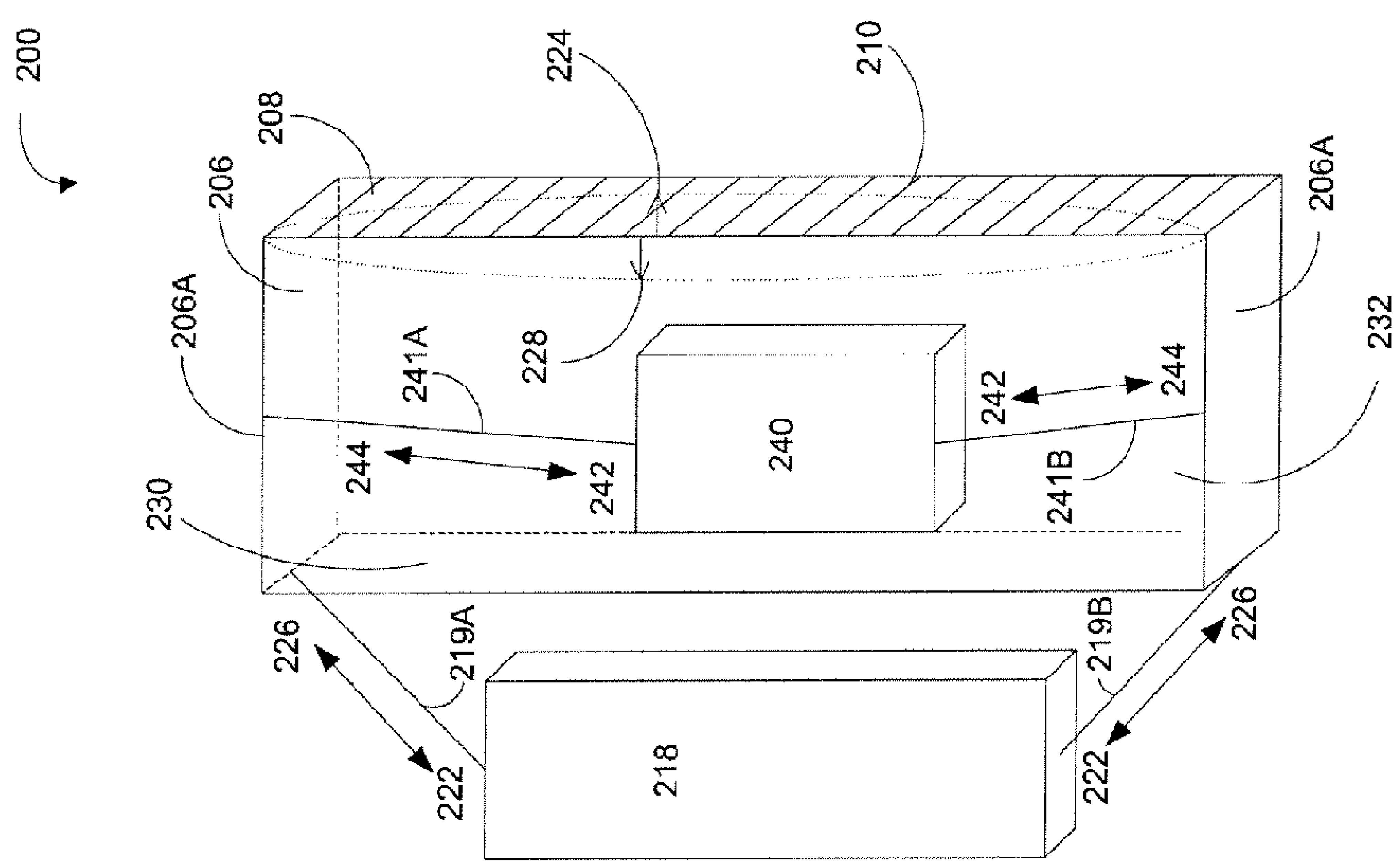


FIG. 2A

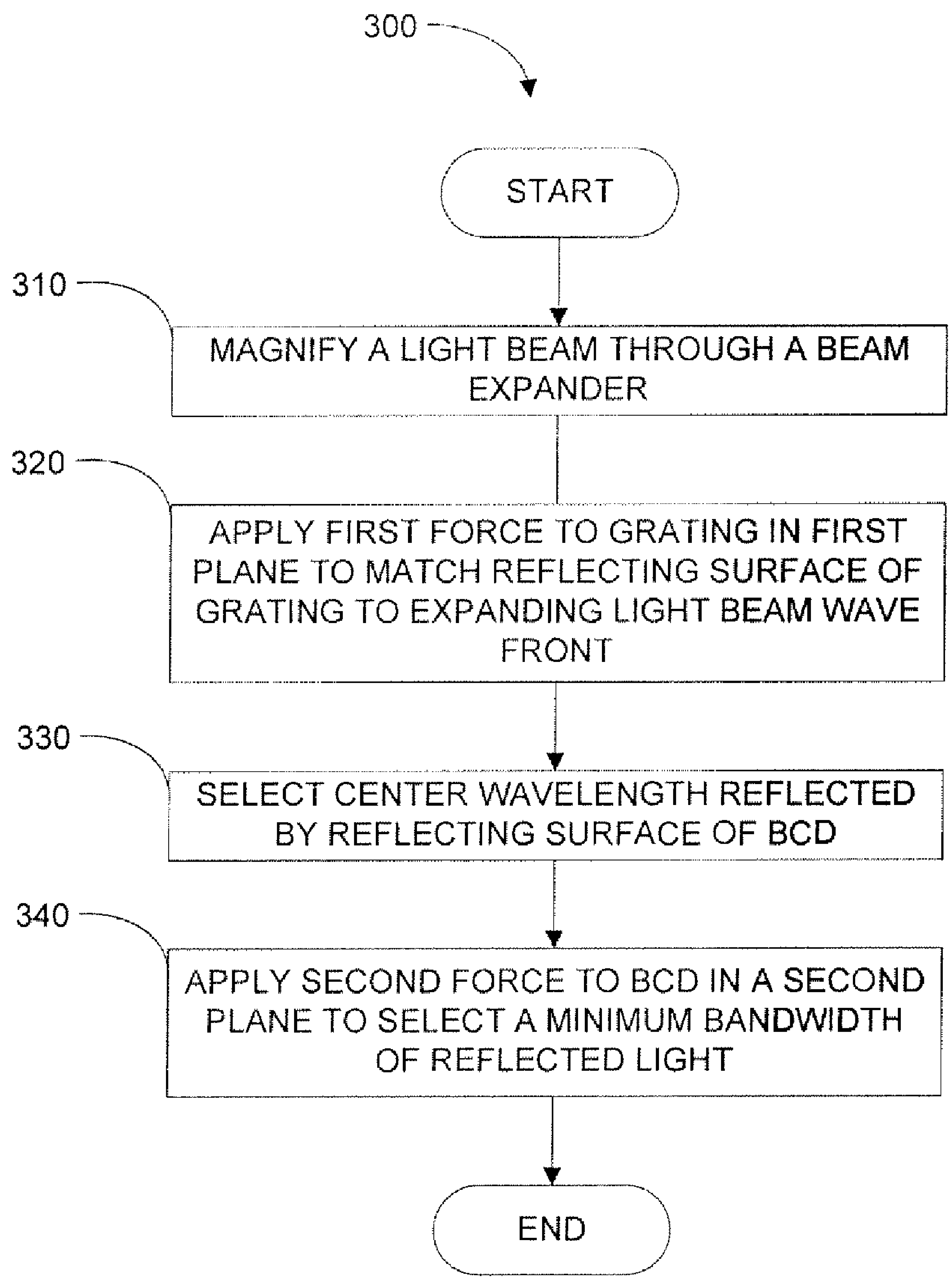

300
START
310
MAGNIFY A LIGHT BEAM THROUGH A BEAM EXPANDER
320
APPLY FIRST FORCE TO GRATING IN FIRST PLANE TO MATCH REFLECTING SURFACE OF GRATING TO EXPANDING LIGHT BEAM WAVE FRONT
330
SELECT CENTER WAVELENGTH REFLECTED BY REFLECTING SURFACE OF BCD
340
APPLY SECOND FORCE TO BCD IN A SECOND PLANE TO SELECT A MINIMUM BANDWIDTH OF REFLECTED LIGHT
END

FIG. 3

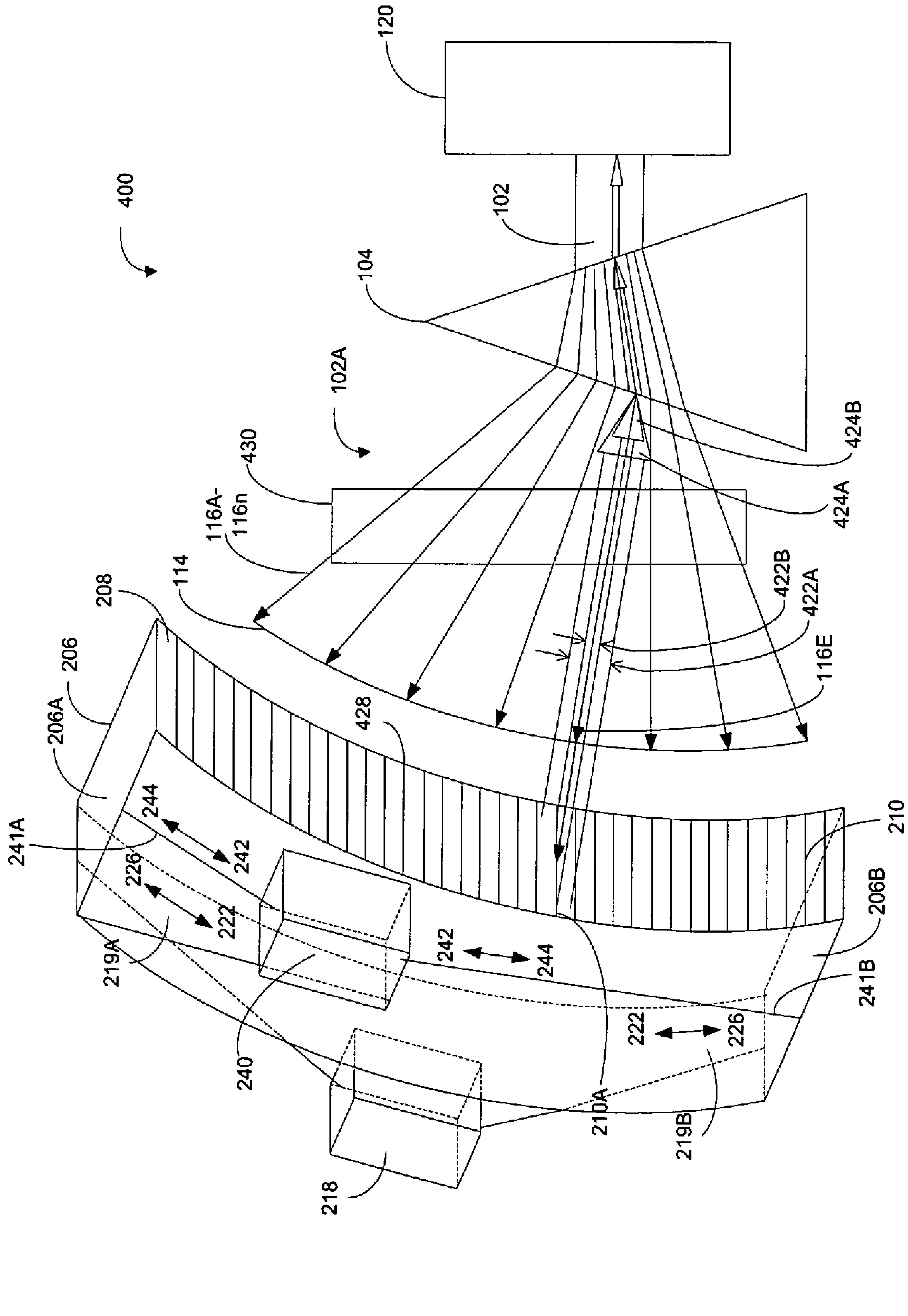


FIG. 4
(Amended)

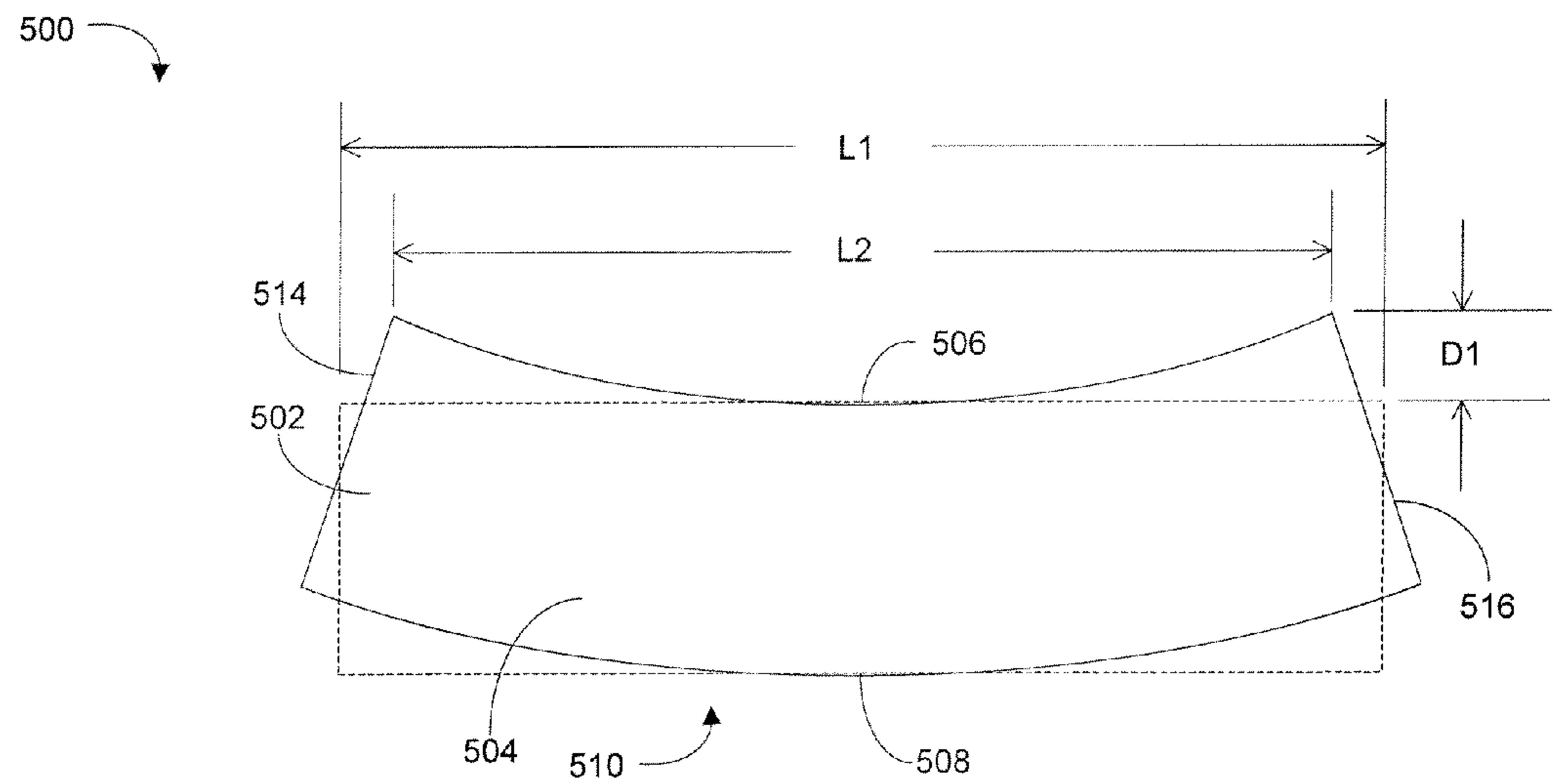


FIG. 5

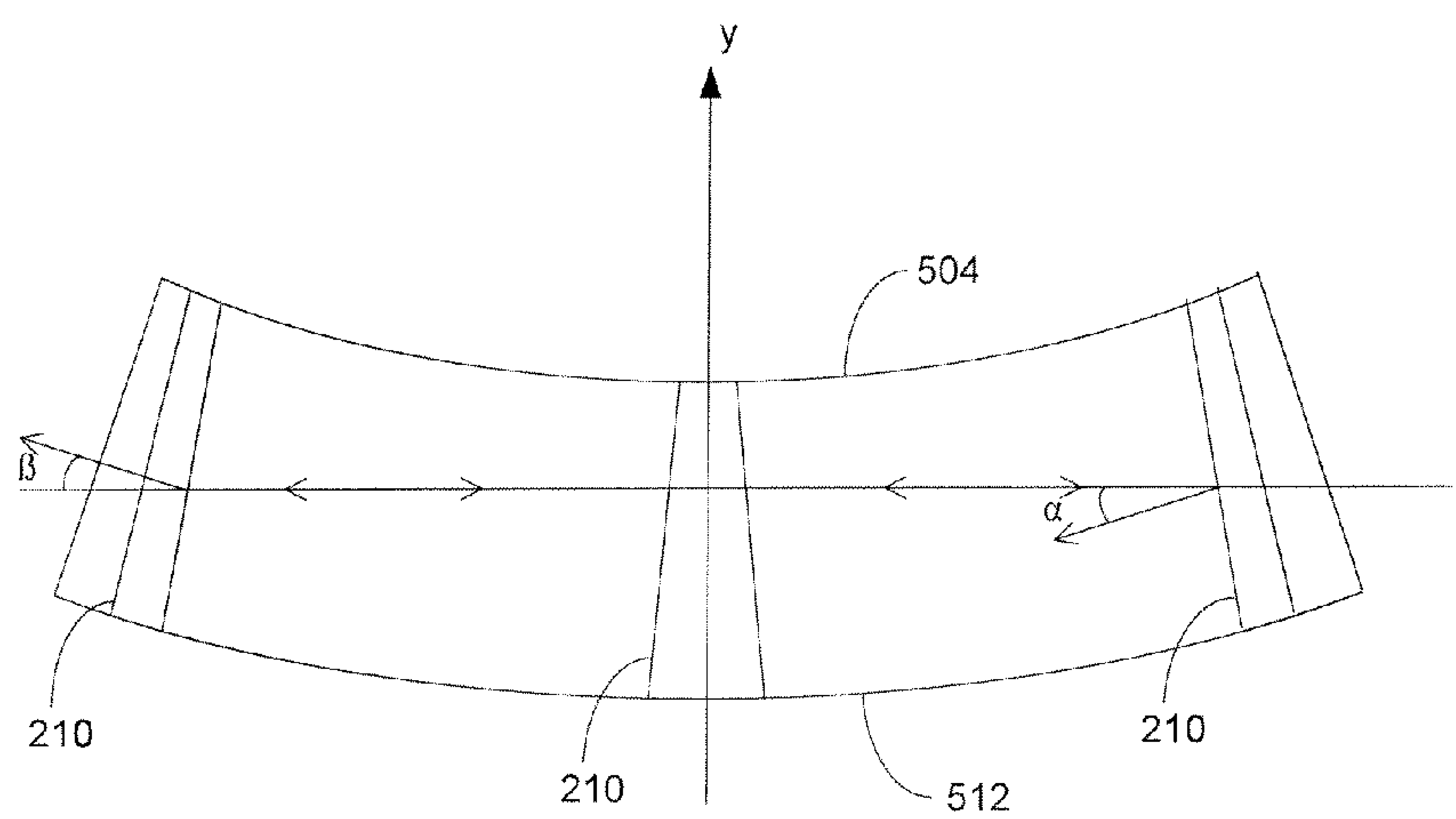


FIG. 6

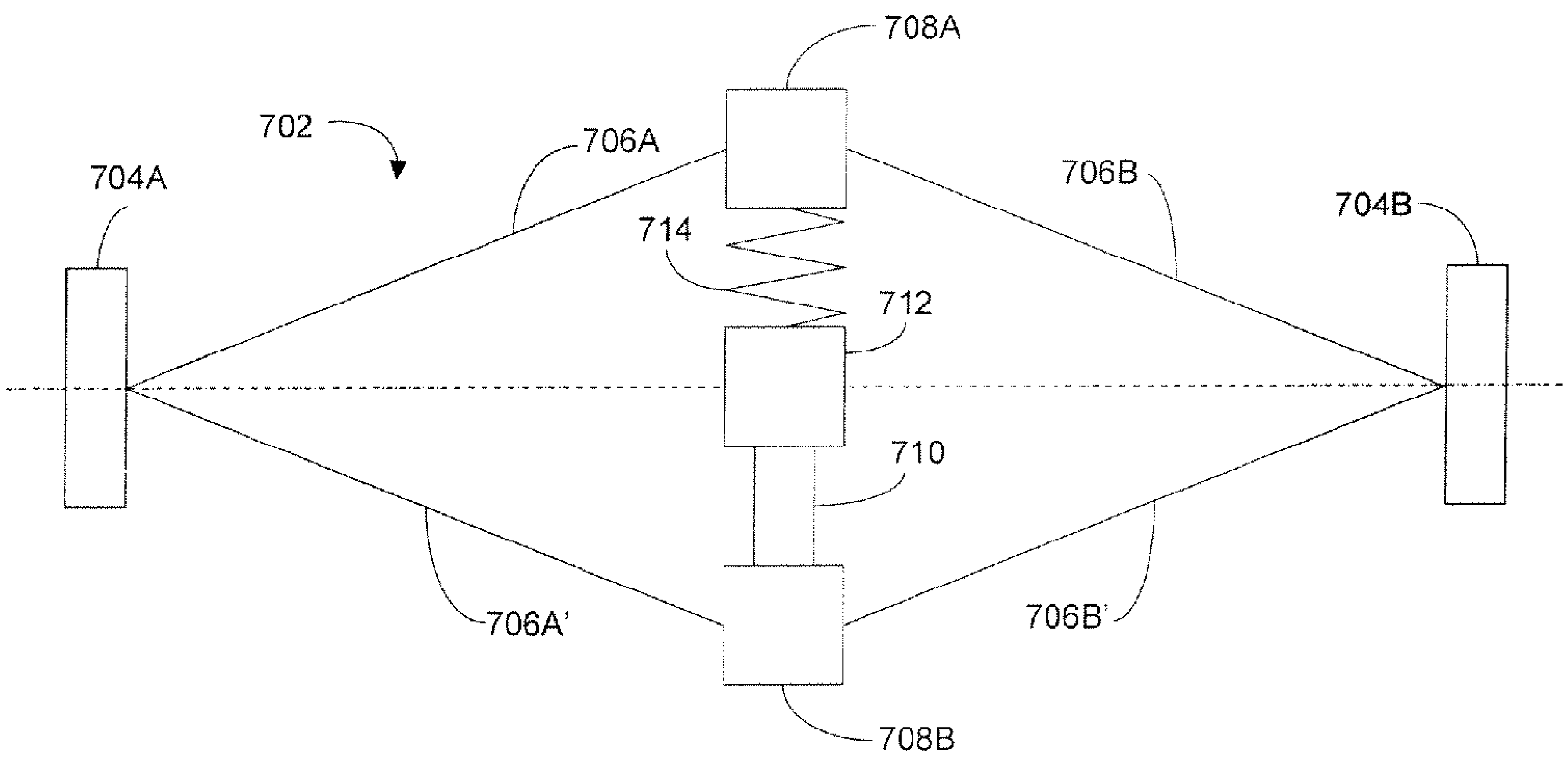


FIG. 7A

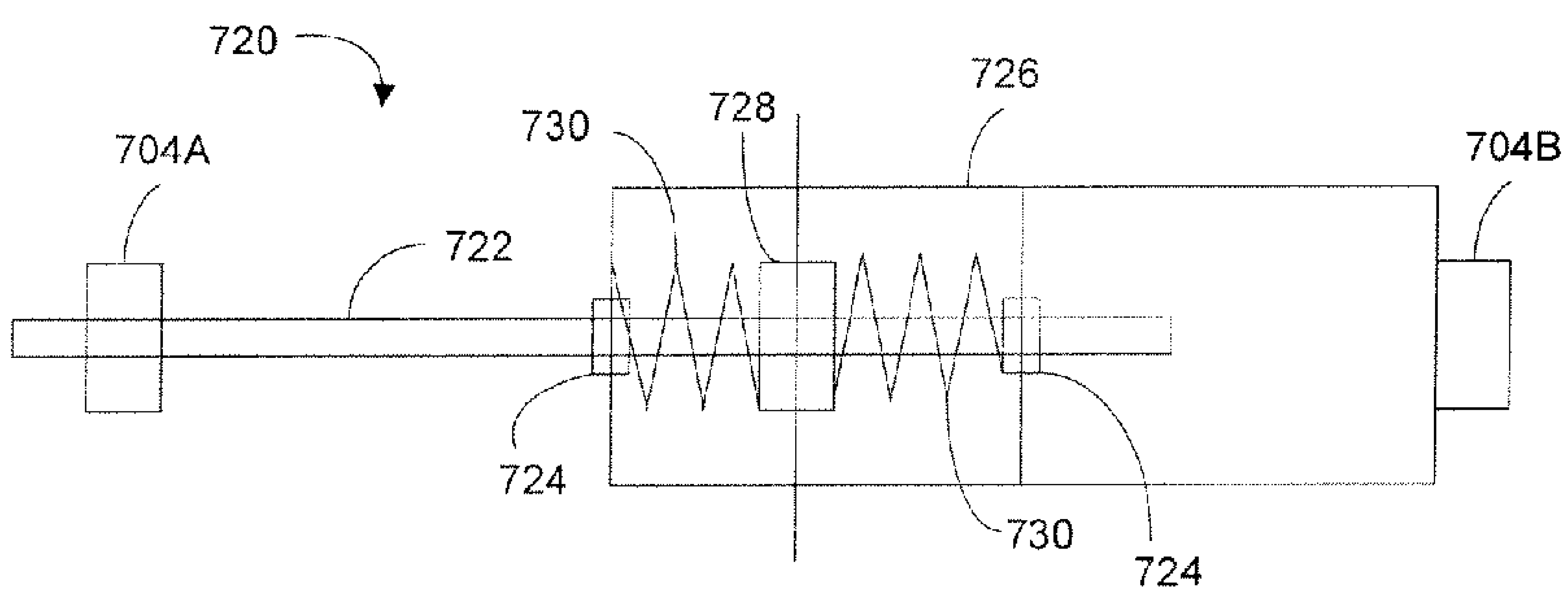


FIG. 7B

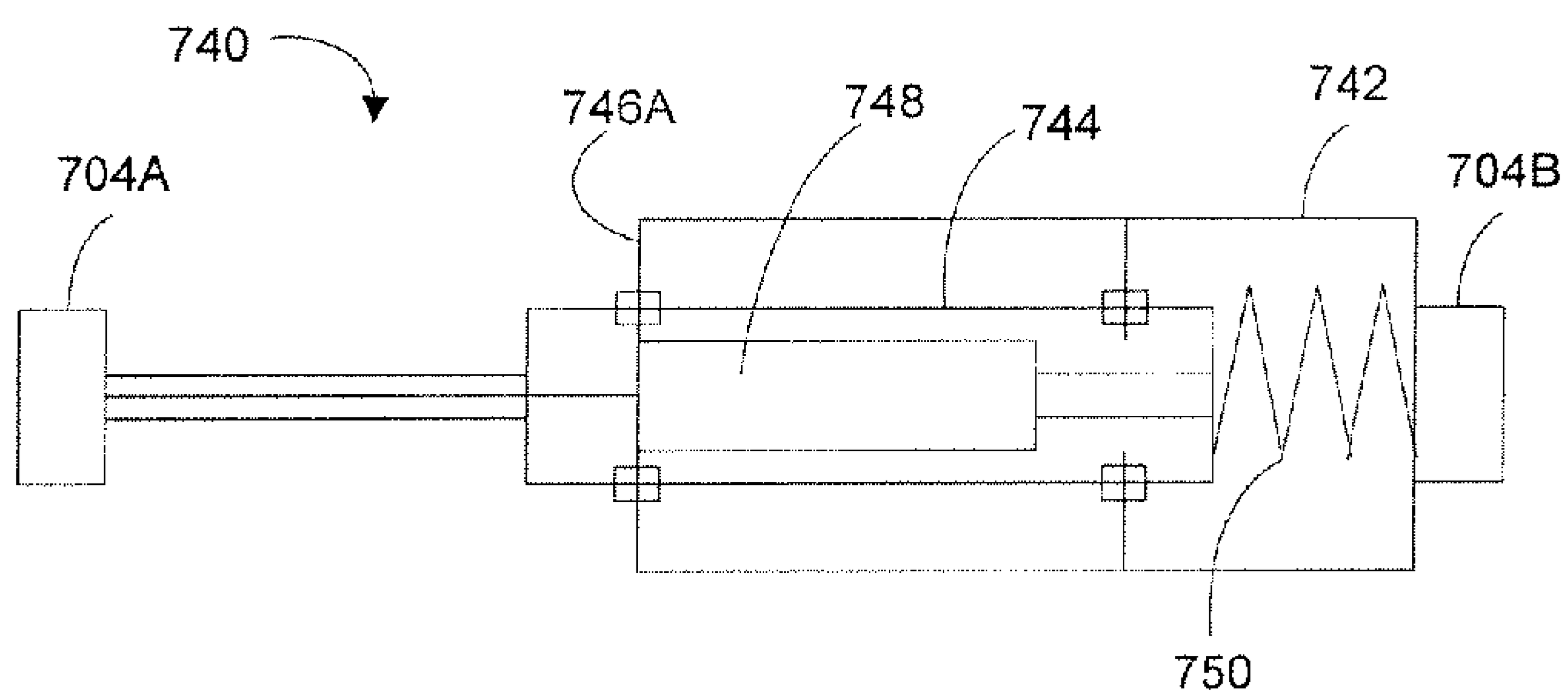


FIG. 7C

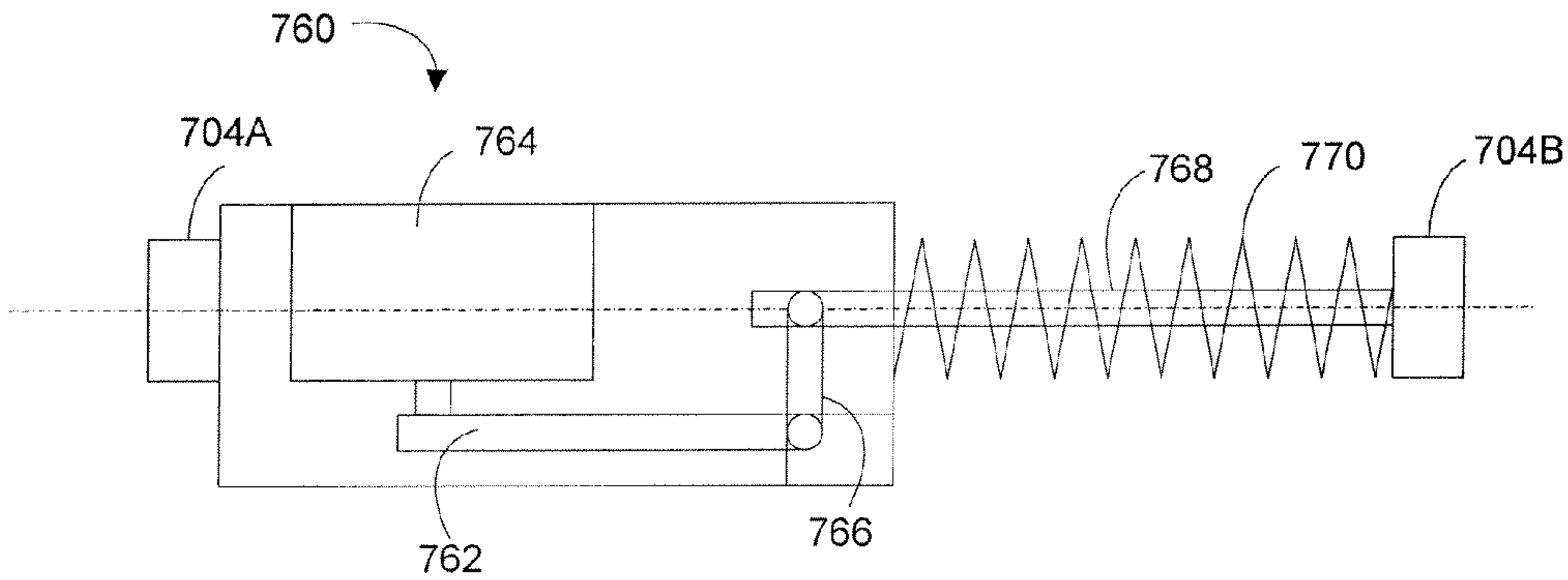


FIG. 7D

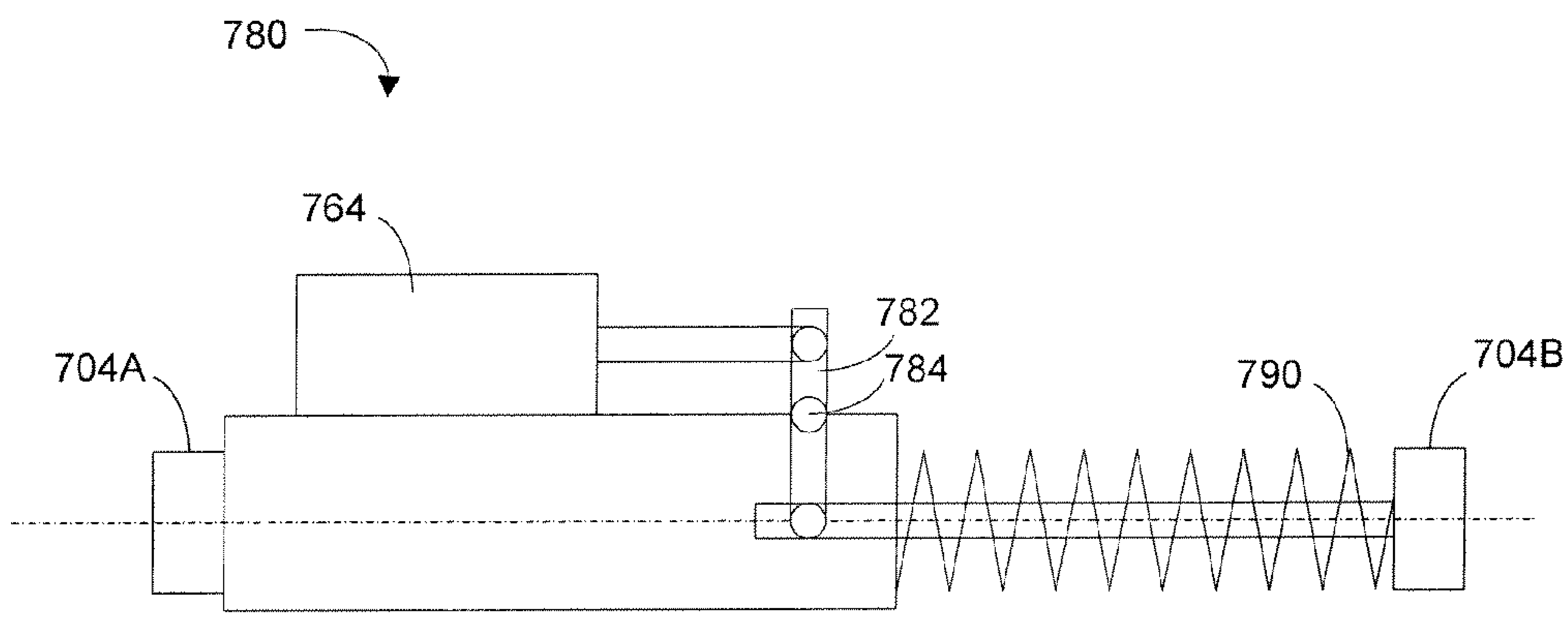
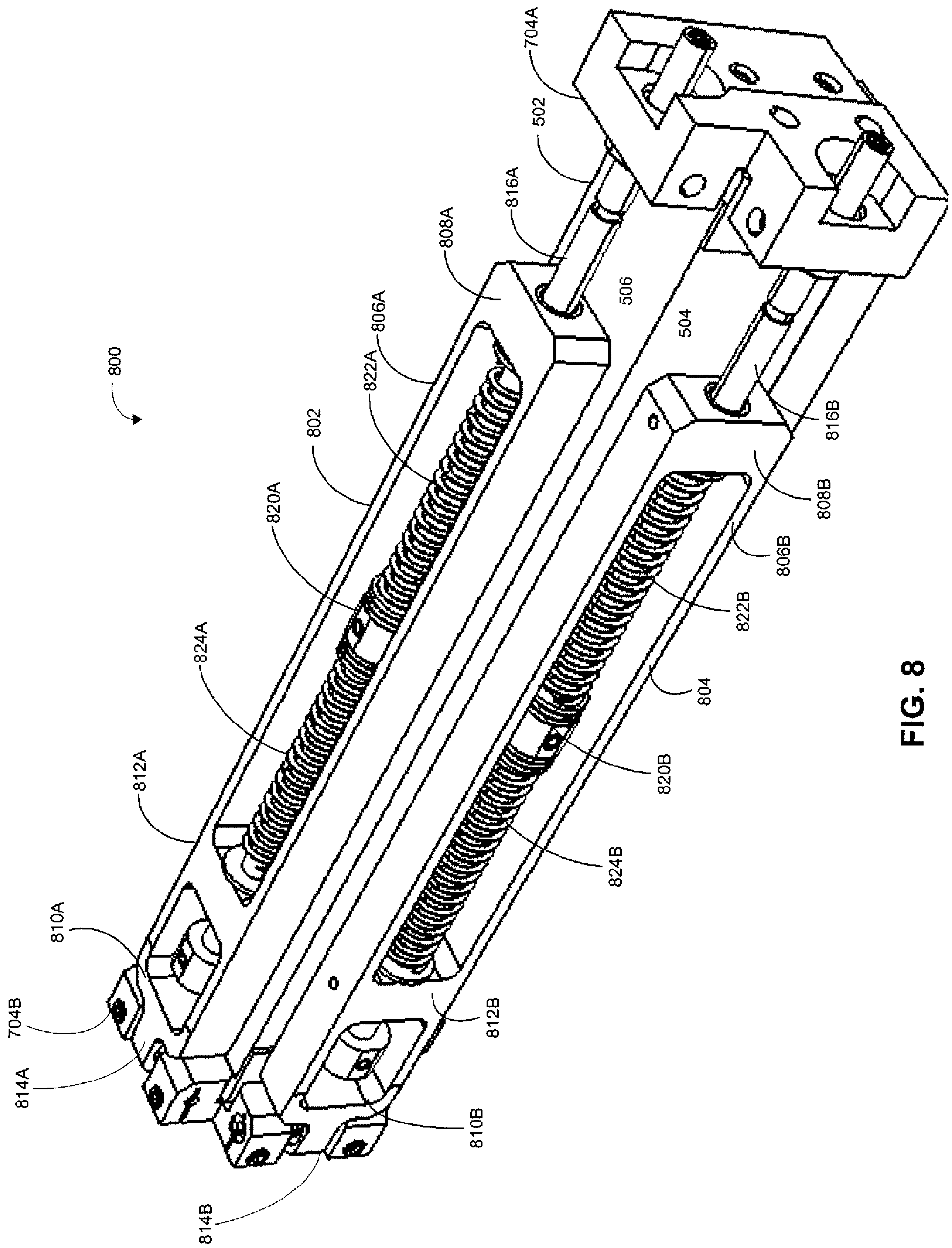


FIG. 7E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704A
502
816A
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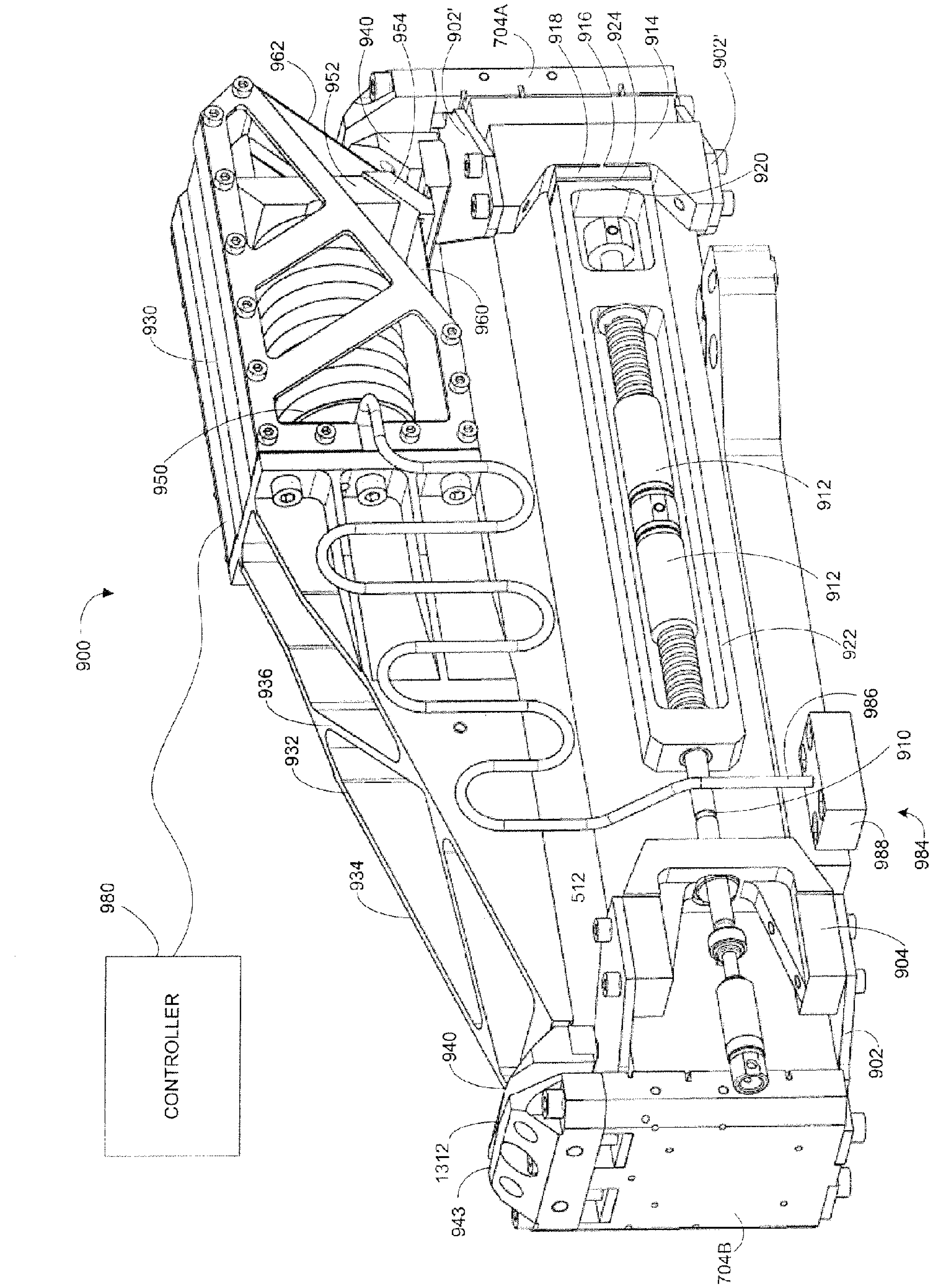
806A
822A
802
820A
824A
812A
810A
704B
814A
814B
810B
812B
824B
820B
804
822B
806B
808B
816B
504
506

FIG. 8


CONTROLLER
980
900
930
950
962
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902'
704A
918
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920
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912
912
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904
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1312
943
704B

FIG. 9

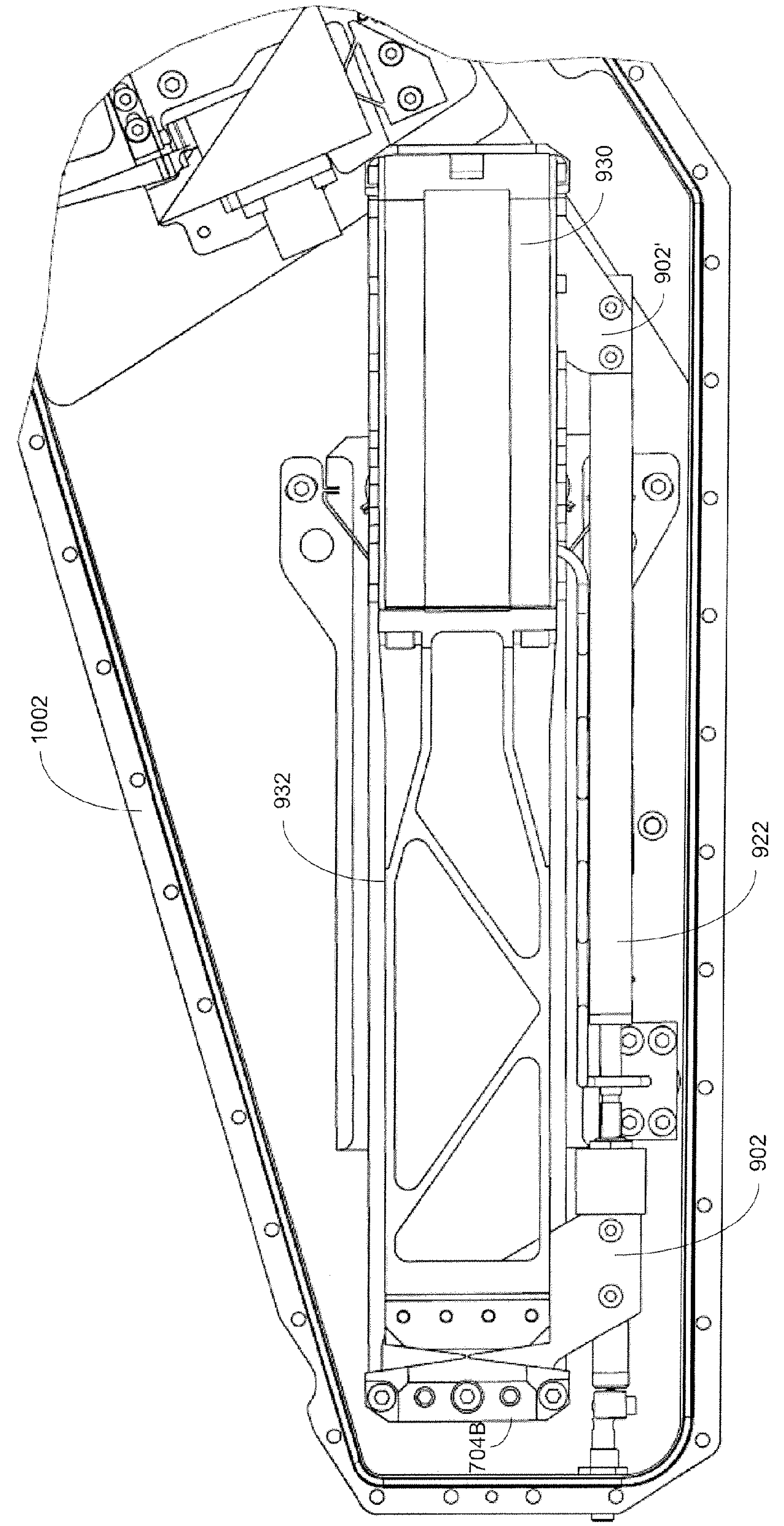

FIG. 10

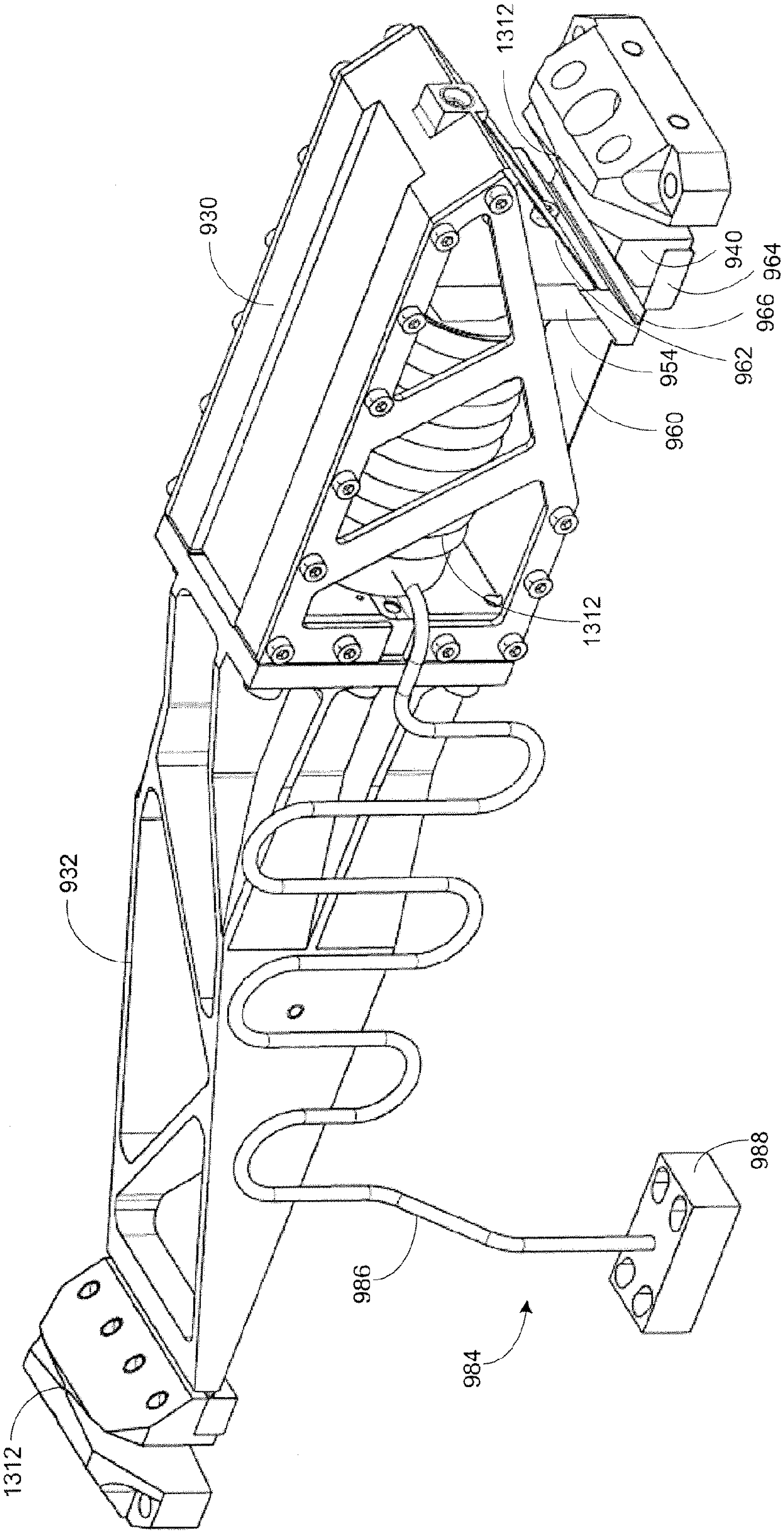

FIG. 11

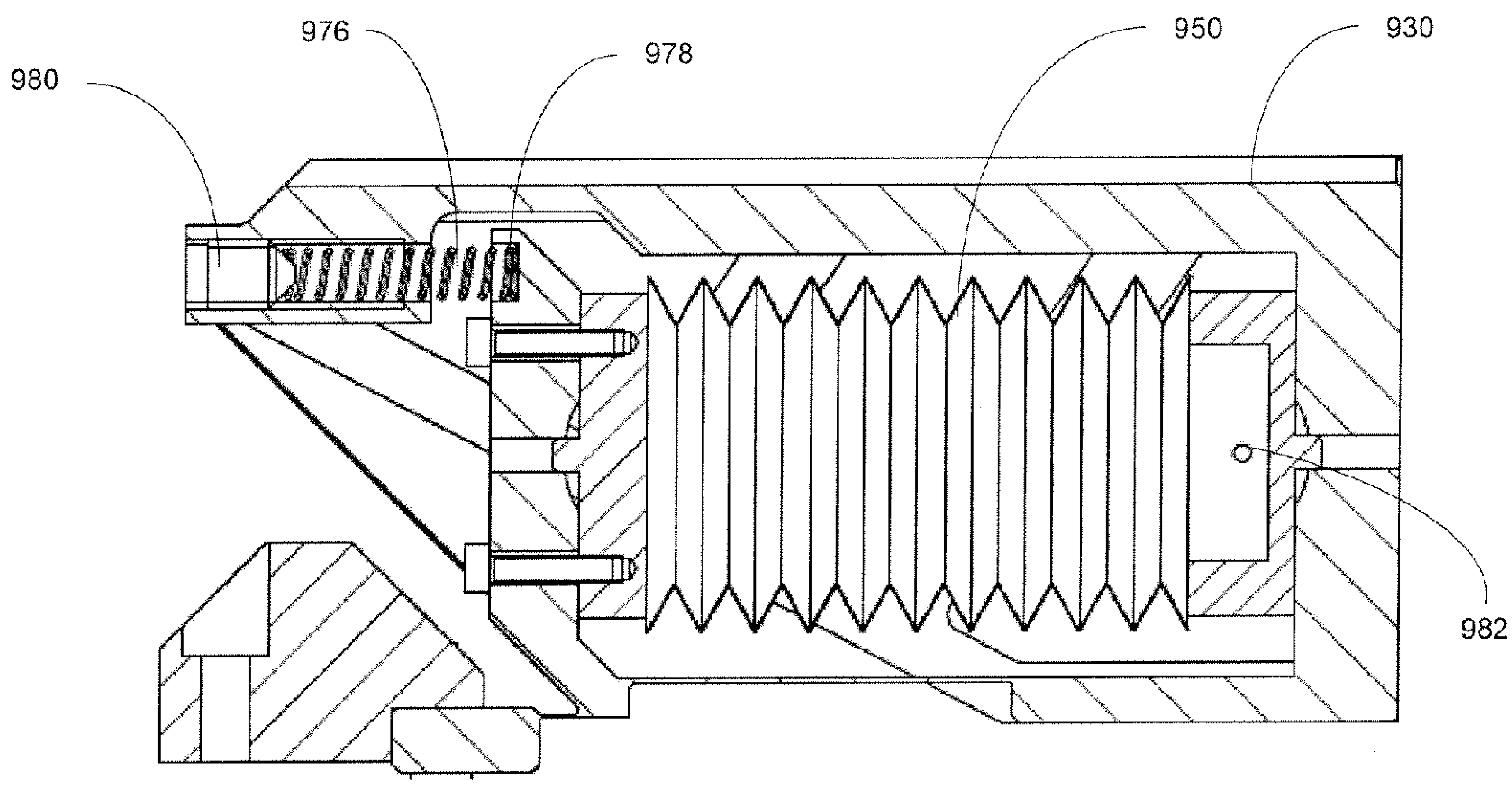

FIG. 12

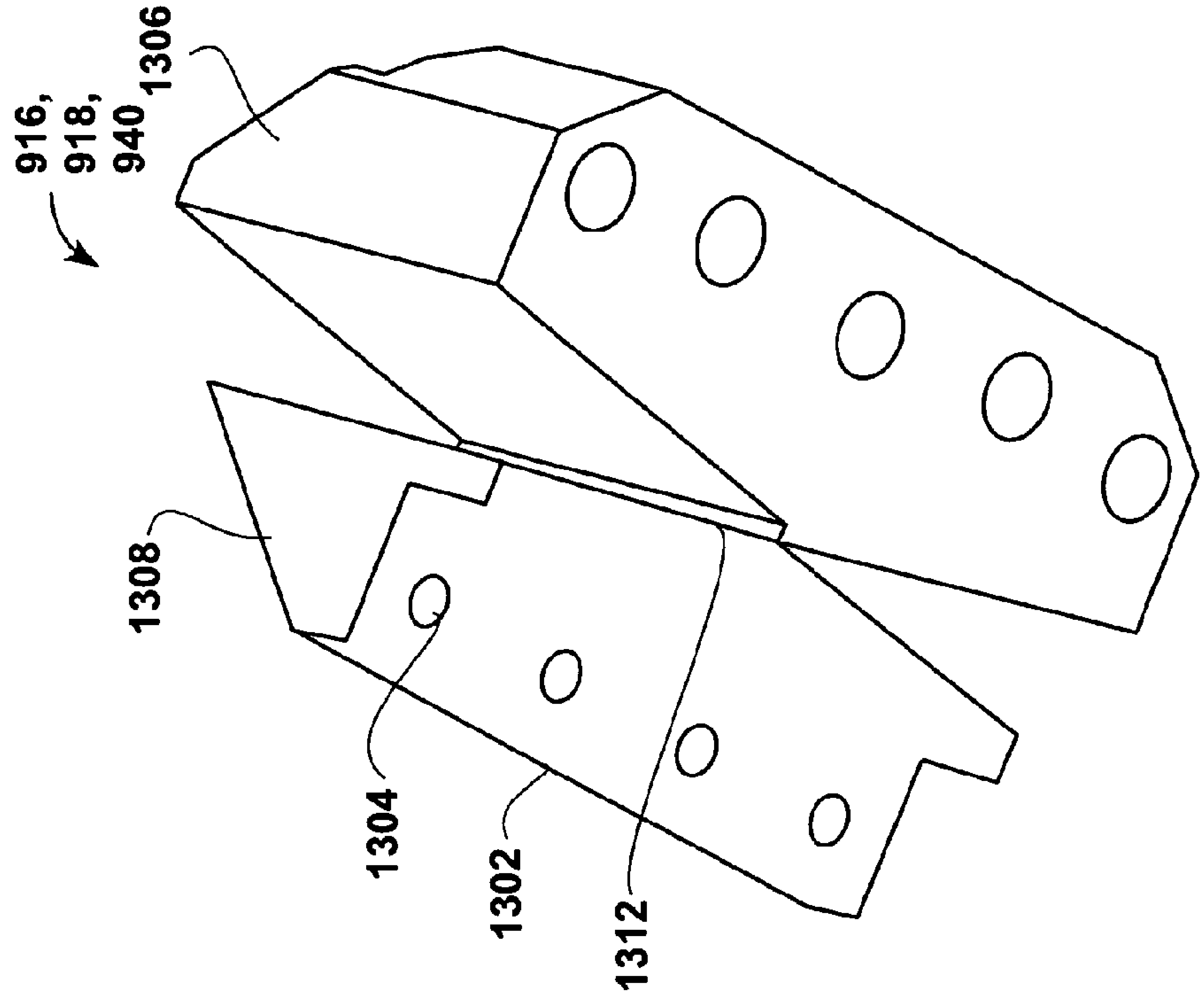

FIG. 13B

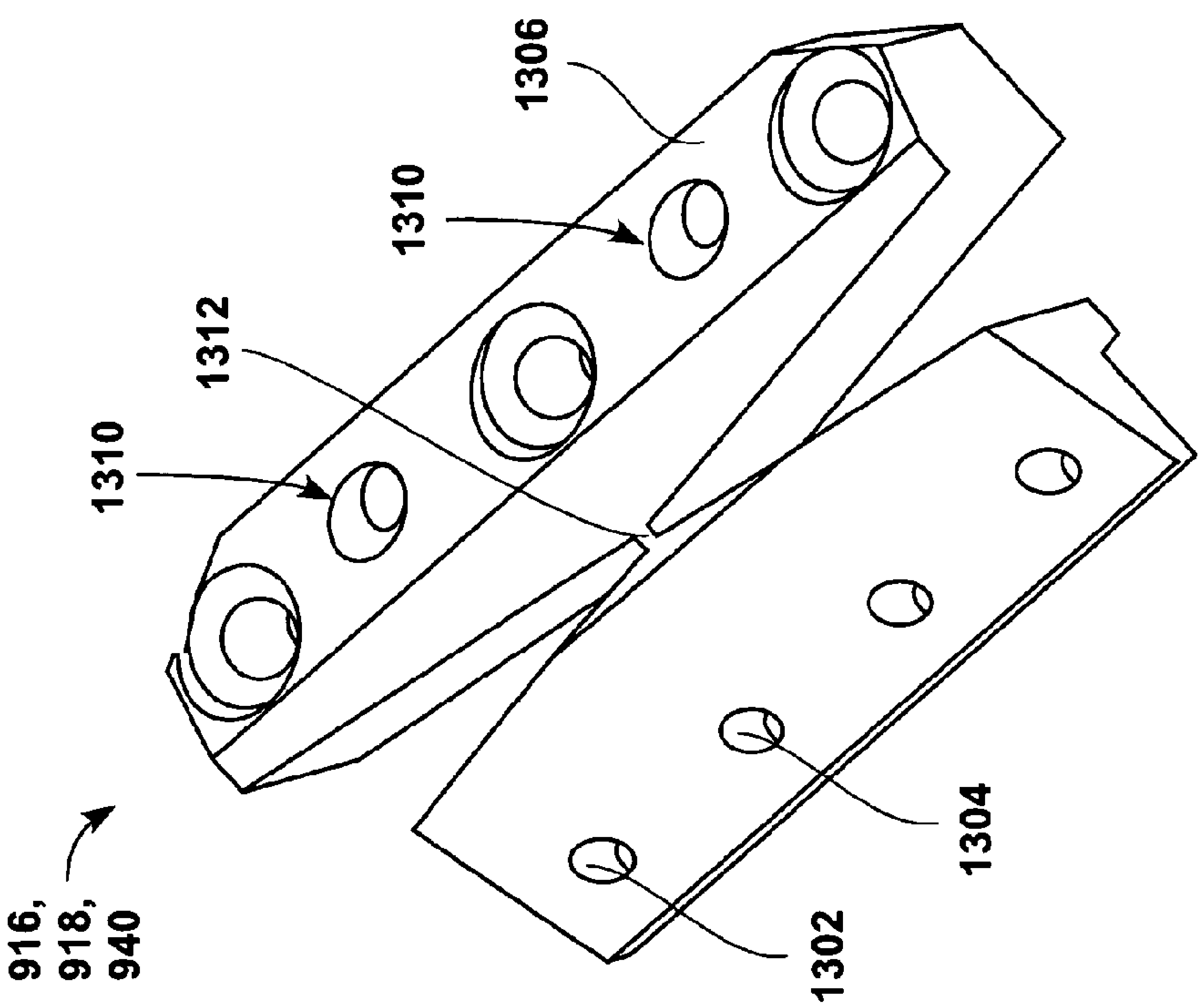

FIG. 13A

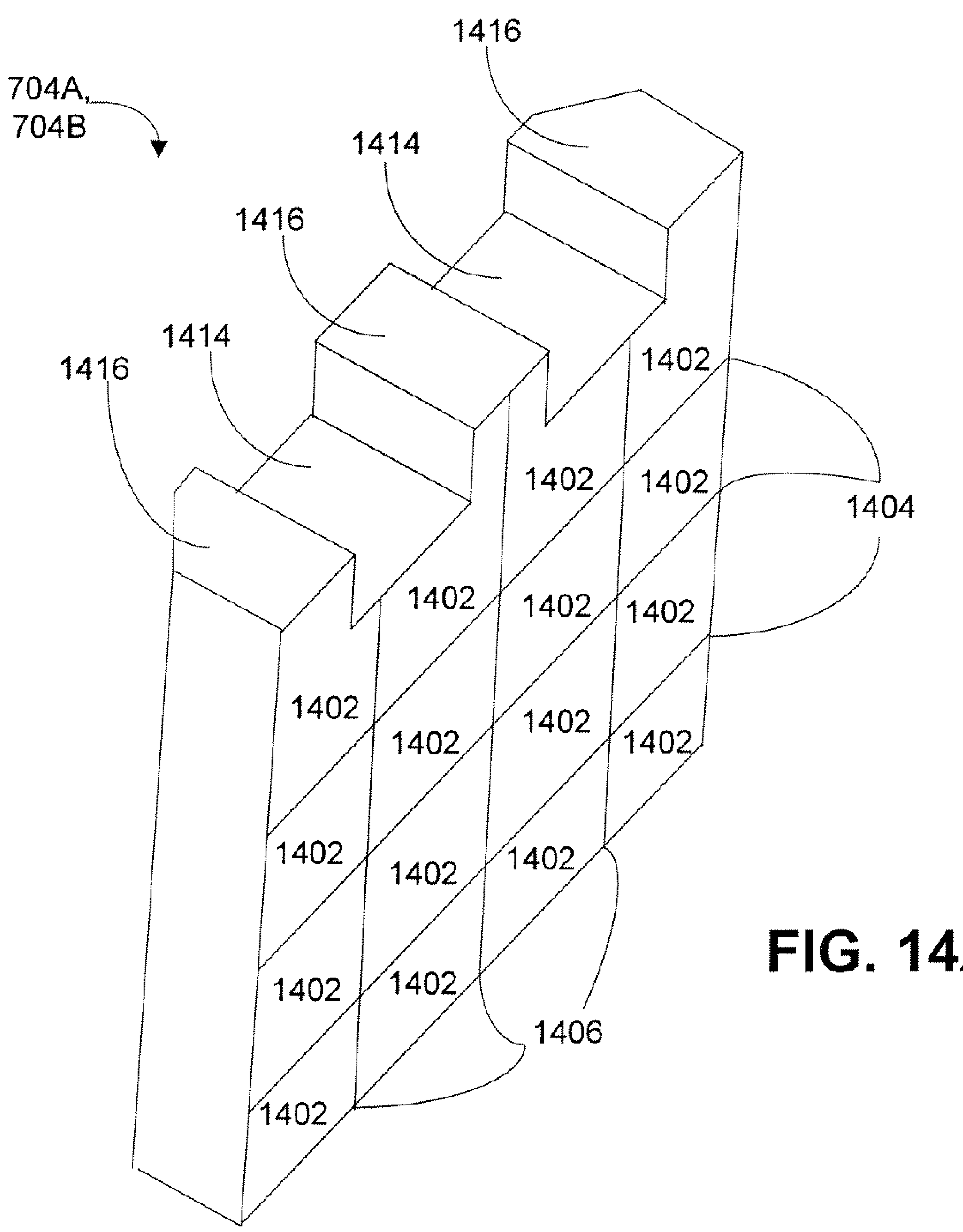

FIG. 14A

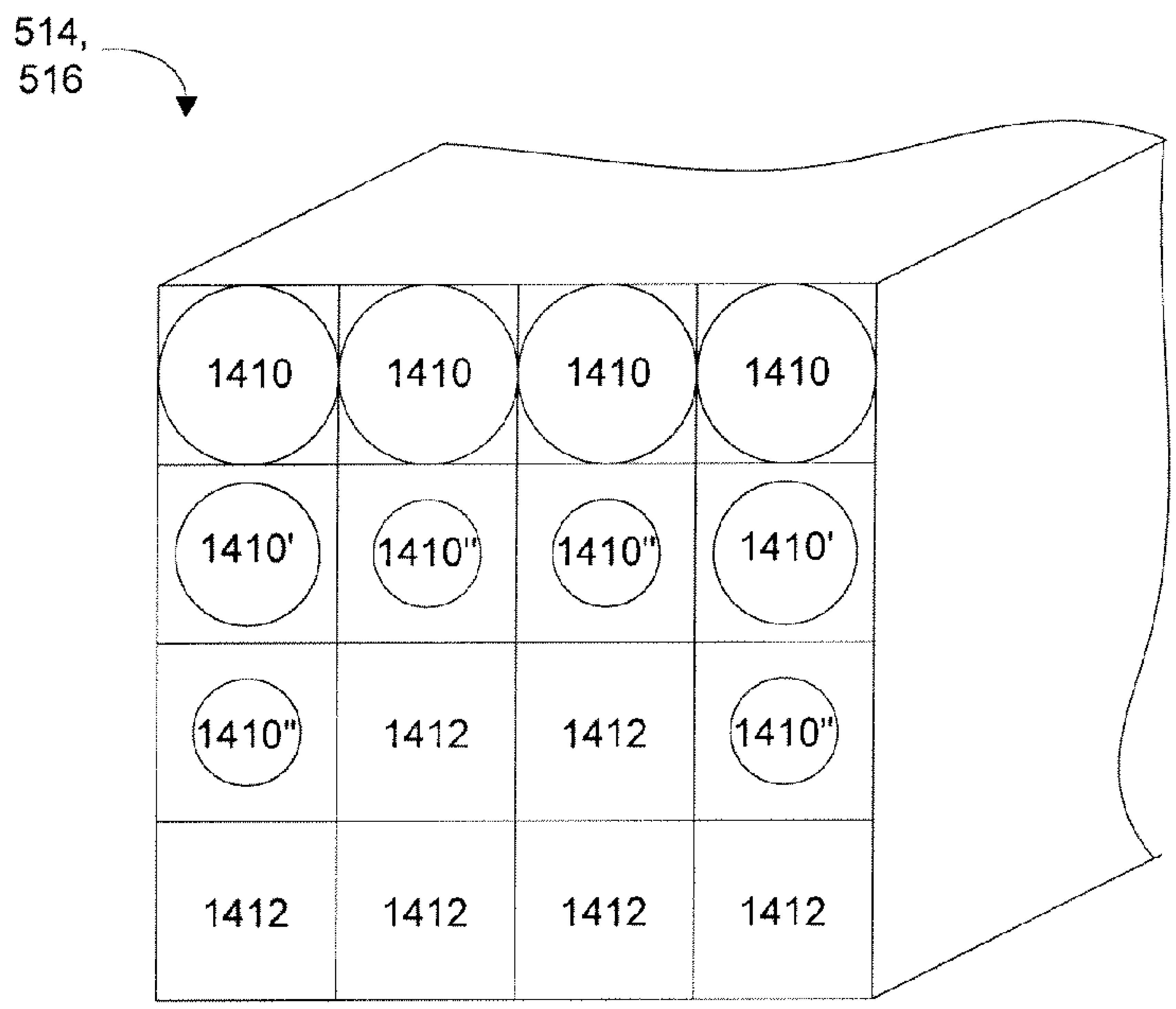

FIG. 14B

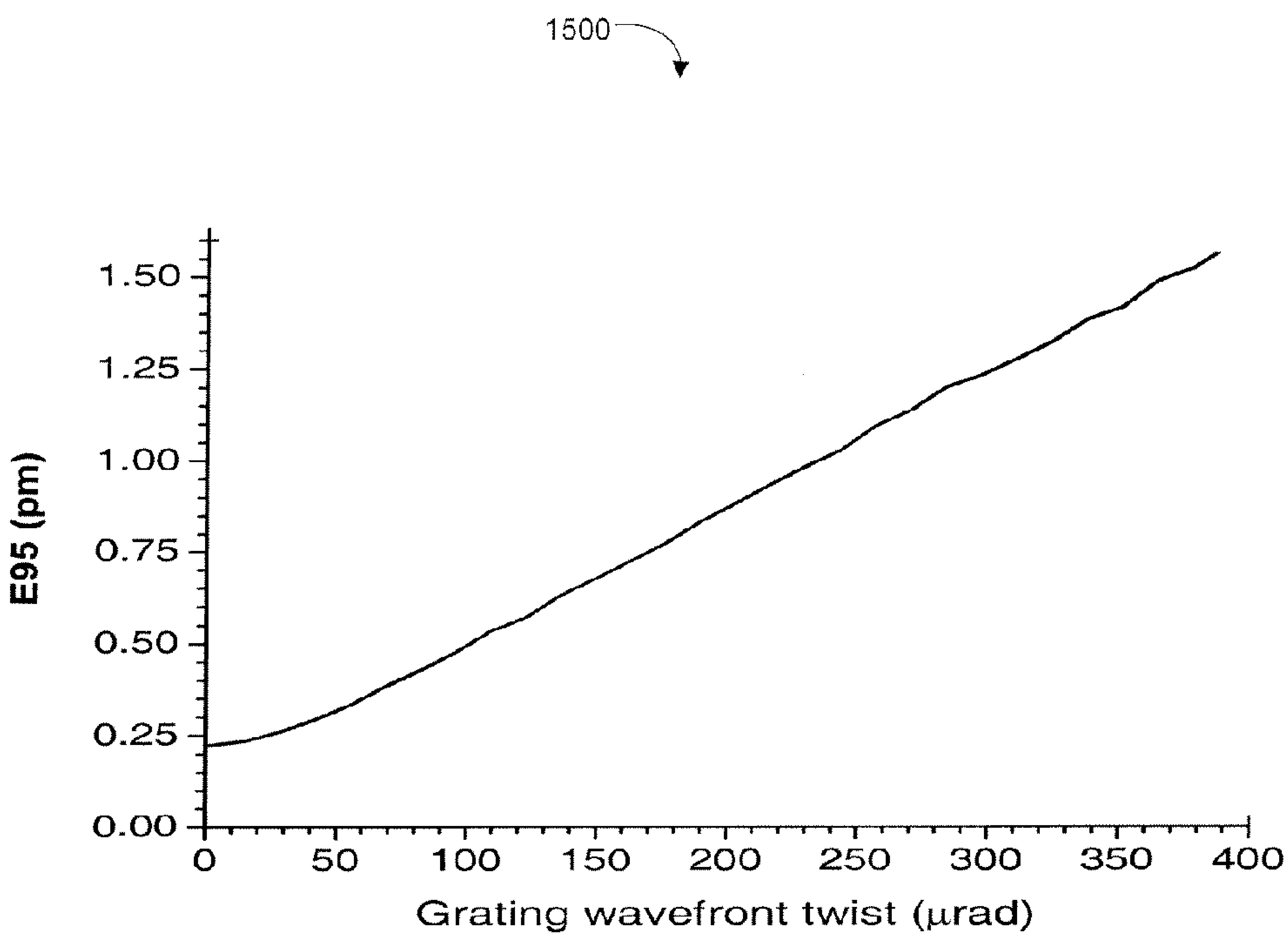
1500
E95 (pm)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
50
100
150
200
250
300
350
400
Grating wavefront twist (μrad)

FIG. 15A

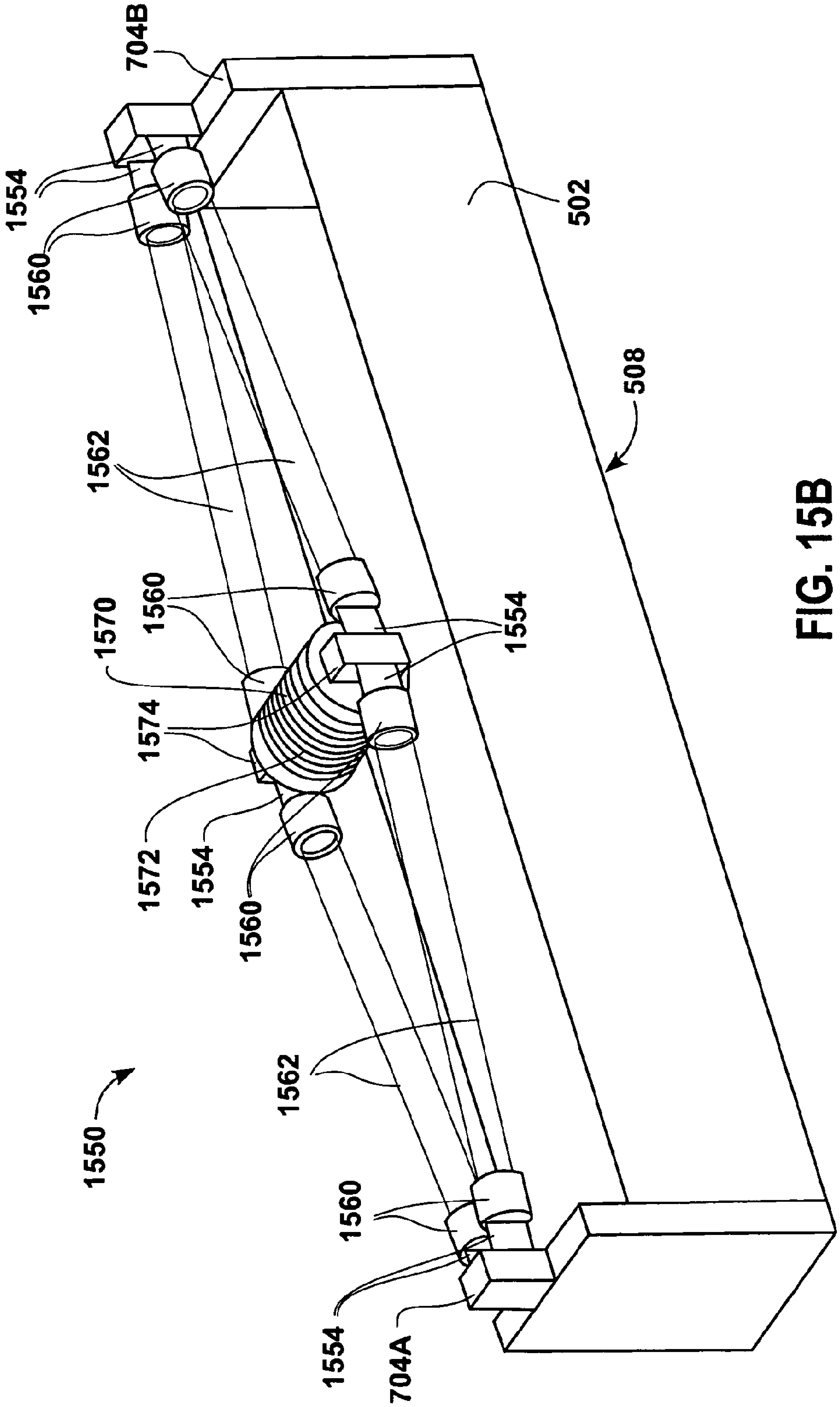
704B
1554
1560
502
508
1562
1570
1560
1554
1574
1572
1554
1560
1562
1550
1560
1554
704A

FIG. 15B

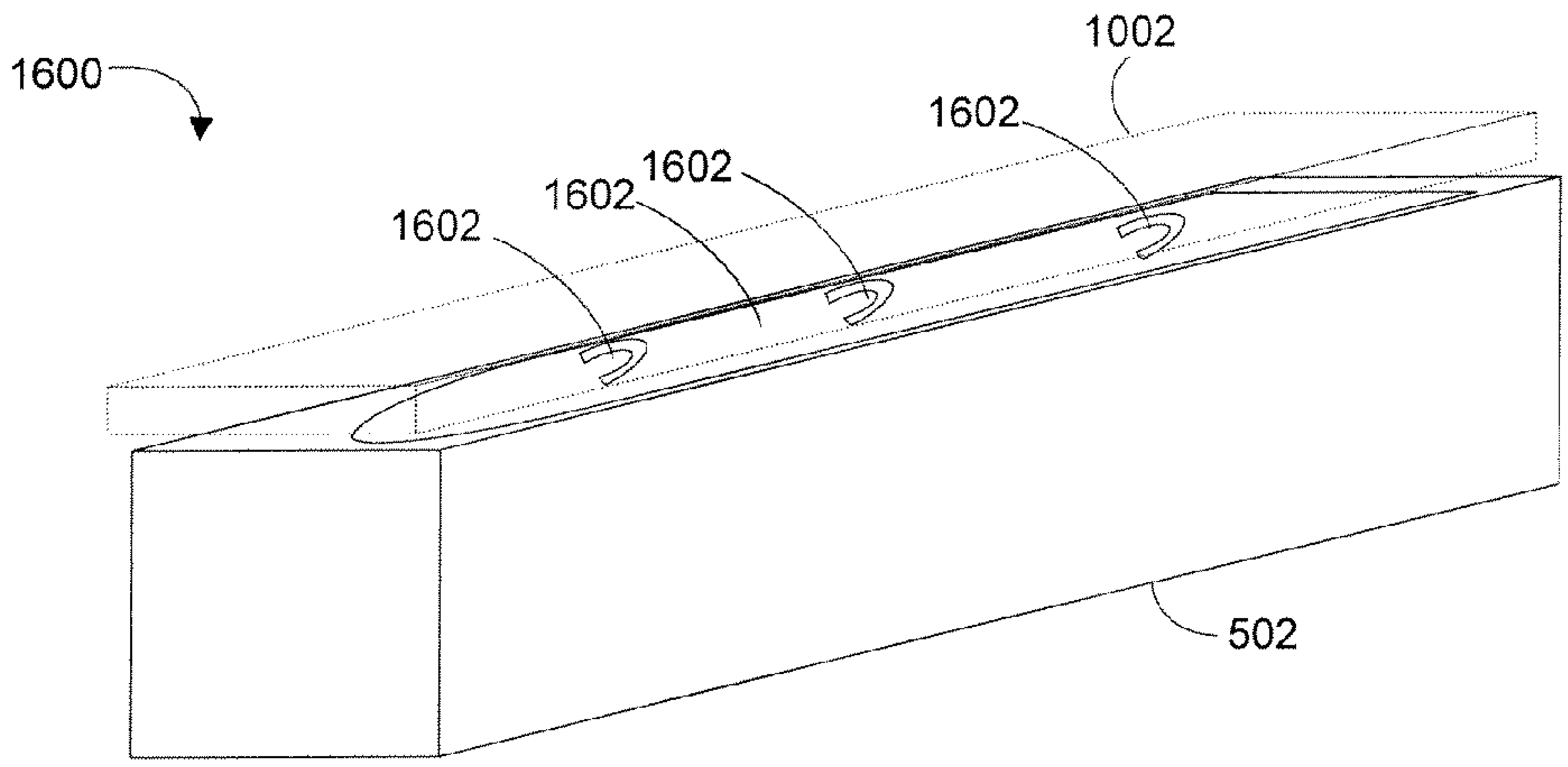

FIG. 16A

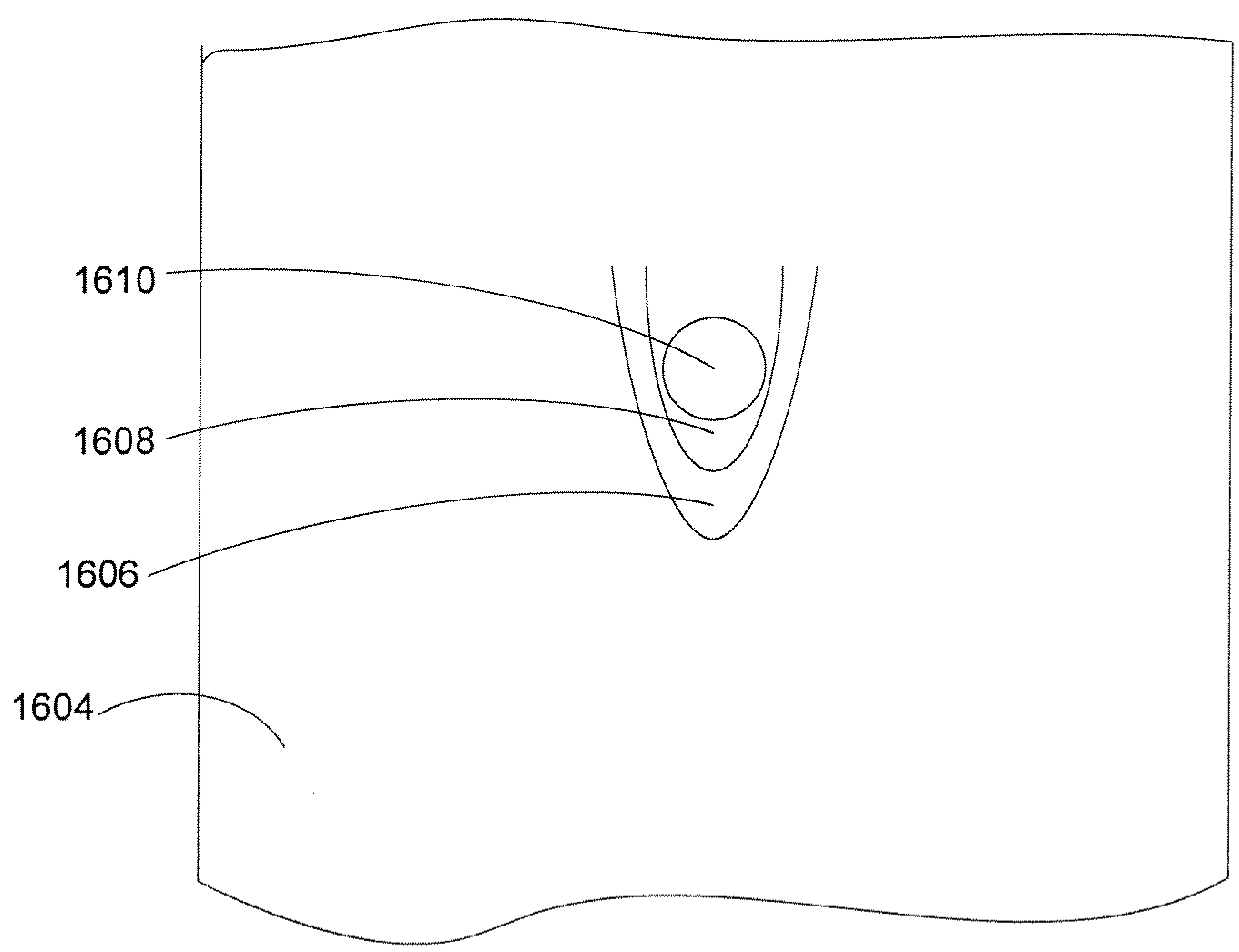

FIG. 16B

SYSTEM METHOD AND APPARATUS FOR SELECTING AND CONTROLLING LIGHT SOURCE BANDWIDTH

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority from U.S. Provisional Patent Application No. 61/197,246, filed Oct. 24, 2008 and entitled "Bandwidth Control Device," which is incorporated herein by reference in its entirety for all purposes.

BACKGROUND

The present invention relates generally to optical gratings, and more particularly, to systems methods and apparatus for tuning and controlling bandwidth by bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength.

Gratings are commonly used to select a narrowed light beam. However, the bandwidth of wavelengths in the narrowed light beam is not as easily selectable with a typical grating. FIG. **1** is a simplified schematic of a typical light beam narrowing system **100**. The typical light beam narrowing system **100** includes a source light beam **102**, directed through a beam expander **104** (typically including one or more prisms), and a grating **106**. The grating **106** has a reflecting surface **108** with many grating lines **110**. The reflecting surface **108** has a curve **112** substantially equaling a wavefront curve **114** of the expanded source light beam **102**A. It should be noted that the components **102-114** of the light beam narrowing system **100** are not drawn to scale and specifically the curve **112**, wavefront **114** and the pitch of the grating are exaggerated for exemplary purposes.

The expanded source light beam **102**A includes multiple wavelengths **116**A-n of light. The multiple wavelengths **116**A-n of light are diverging at different angles relative to the beam expander **104** and impinge on the reflecting surface **108** in corresponding different locations.

Ideally, a selected grating line **110**A reflects a narrowed light beam **124** including only the corresponding reflected wavelength **116**E' toward the beam expander **104** at the appropriate angle **118** such that the narrowed light beam **124** passes back though the beam expander **104** to the optical system **120** beyond the beam expander **104**. Unfortunately, the selected grating line **110**A also reflects a bandwidth of wavelengths including slightly shorter wavelengths **1502**A than the reflected center wavelength **116**E' and slightly longer wavelengths **1502**B than the reflected center wavelength **116**E'. Thus the narrowed light beam **124** includes the reflected center wavelength **116**E' and the bandwidth of wavelengths including slightly shorter wavelengths **1502**A than the reflected center wavelength **116**E' and slightly longer wavelengths **1502**B than the reflected center wavelength **116**E'.

Tuning the beam expander **104** and the amount of curvature in the curve **112** allows for a very precise center wavelength selection and a very narrow maximum bandwidth, e.g., less than 1.0 pm (1.0×10^{-12} meter)+/−either side of the reflected center wavelength **116**E', for the narrowed light beam **124**. However, tuning the beam expander **104** does not allow for accurate control or selection of both a maximum bandwidth and a minimum bandwidth for the narrowed light beam **124**, e.g. a bandwidth between 0.5 to 1.0 pm+/−either side of the reflected center wavelength **116**E'.

The optical system **120** can include many sub-systems that use the narrowed light beam **124**. Some of the subsystems can require both a selected maximum bandwidth and a selected minimum bandwidth. By way of example, the optical system **120** can include a scanner that requires several wavelengths centered on a selected wavelength and distributed across a bandwidth of sufficient breadth that can be used to generate a desired interference pattern.

In order to satisfy continuingly more stringent requirements to control bandwidth, particularly the width of the spectrum containing a selected percentage of the intensity, i.e., 95% ("E95%" or simply "E95") or E95 separately from full width half maximum ("FWHM") the need exists to distort the wavefront interaction surface of a center wavelength selection and bandwidth selection optical element (e.g., a dispersive grating having a plurality of dispersive optical features, e.g., grooves on one face thereof. These requirements can include a need for greater range of control as well as maintaining bandwidth within some small range and/or not to exceed some selected value. This distortion needs to be in two planes and needs to be independent in each of the two planes, with as little interference between the distorting mechanisms as possible and one distorting mechanism, such as the one distorting the separation of the groove forming features across the face of the dispersive optical element (as opposed to along the length of the dispersive optical element) has been found to need to be capable of exerting more distorting force. Applicants propose such modifications to existing laser system bandwidth control mechanisms.

In view of the foregoing, there is a need for a system, method and apparatus for bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength and having a selected minimum bandwidth and a selected maximum bandwidth.

SUMMARY

Broadly speaking, the present invention fills these needs by providing a system, method and apparatus for bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength and having a selected minimum bandwidth and a selected maximum bandwidth. It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, computer readable media, or a device. Several inventive embodiments of the present invention are described below.

Bandwidth selection systems and methods disclosed herein include bending a reflective face of dispersion of dispersive optical element in two different directions: vertically and horizontally while also substantially decoupling the vertical bending forces from the horizontal bending forces. The decoupling minimizes the interaction or interference between the vertical bending forces and the horizontal bending forces. One or more flexures are used to decouple each of the vertical bending forces and the horizontal bending forces.

One embodiment provides a mechanism for bandwidth selection that includes a dispersive optical element having a body including a reflective face of dispersion including an area of incidence extending in a longitudinal axis direction along the reflective face of the dispersive optical element. The body also includes a first end block, disposed at a first longitudinal end of the body and a second end block, disposed at a second longitudinal end of the body, the second longitudinal end being opposite the first longitudinal end. The bandwidth selection mechanism also includes a first actuator mounted on a second face of the dispersive optical element, the second face being opposite from the reflective face, the first actuator having a first end coupled to the first end block and a second end coupled to the second end block, the first actuator being operative to apply equal and opposite forces to the first end block and the second end block to bend the body along the longitudinal axis of the body and in a first direction normal to the reflective face of the dispersive optical element. The bandwidth selection mechanism also includes a second actuator mounted on a third face of the dispersive optical element, the third face being normal to the reflective face, the second actuator having a first end coupled to the first end block with a first flexture and a second end coupled to the second end block with a second flexture, the first actuator being operative to apply equal and opposite forces to the first end block and the second end block to bend the body along the longitudinal axis of the body, in a second direction perpendicular to the reflective face of the dispersive optical element, the second direction also being perpendicular to the first direction the second actuator including a pressurized fluid force application mechanism. A method of selecting bandwidth is also disclosed.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings.

FIG. **1** is a simplified schematic of a typical light beam narrowing system.

FIG. **2**A is a simplified schematic of a beam control device, in accordance with aspects of an embodiment of the disclosed subject matter.

FIGS. **2**B and **2**C are simplified schematics of a reflecting face of a beam control device, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **3** is a flowchart diagram that illustrates the method operations performed in bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength and having a selected minimum bandwidth and a selected maximum bandwidth, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **4** is a simplified schematic of a light beam narrowing system, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **5** is a top view of a dispersive optical element, in accordance with aspects of an embodiment of the disclosed subject matter

FIG. **6** is a side view of a dispersive optical element, in accordance with aspects of an embodiment of the disclosed subject matter.

FIGS. **7**A-**7**E are simplified schematics of various forms of actuators for applying force to a grating body, in accordance with aspects of embodiments of the disclosed subject matter.

FIG. **8** is a perspective view of a dual action bandwidth control device, in accordance with aspects of an embodiment of the disclosed subject matter.

FIGS. **9**-**12** illustrate another dual acting bandwidth control mechanism, in accordance with aspects of an embodiment of the disclosed subject matter.

FIGS. **13**A and **13**B are perspective views of flexured elements, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **14**A is a perspective view of a force plate, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **14**B is a perspective view of a front end or a rear end of a dispersive optical element body, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **15**A is a graph of a E95 bandwidth, in accordance with aspects of an embodiment of the disclosed subject matter.

FIG. **15**B is a perspective view of another apparatus for bending a dispersive optical element, such as a grating, according to aspects of an embodiment of the disclosed subject matter.

FIGS. **16**A and **16**B schematically illustrate a flexured grating mount that may be useful according to aspects of an embodiment of the disclosed subject matter.

DETAILED DESCRIPTION

Several exemplary embodiments for systems, methods and apparatus for bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength and having a selected minimum bandwidth and a selected maximum bandwidth will now be described. It will be apparent to those skilled in the art that the present invention may be practiced without some or all of the specific details set forth herein.

FIG. **2**A is a simplified schematic of a beam control device **200**, in accordance with aspects of an embodiment of the disclosed subject matter. The BCD includes a grating **206** and a first force device **218**. The first force device **218** is coupled to the opposing ends **206**A, **206**B of the grating **206** in a first plane **230**.

The first force device **218** can apply a first force to the opposing ends **206**A, **206**B of the grating **206** though links **219**A, **219**B, respectively, to cause the reflecting surface **208** of the grating to bend in a controlled manner. By way of example the first force device **218** can apply a pulling force **[**5022**]** *222* on the opposing ends **206**A, **206**B of the grating **206** to cause the grating to bend in a controlled, convex direction **[**5024**]** *224*. Similarly, the first force device **218** can apply a pushing force **[**5026**]** *226* on the opposing ends **206**A, **206**B of the grating **206** to cause the grating to bend in a controlled, concave direction **[**5028**]** *228*. In this way the first force device **218** can bend the reflecting face **212** of the grating **206** to substantially match a wavefront curve of a lightbeam and thus select a reflected center wavelength and a maximum bandwidth of the reflected narrowed light beam.

The light beam heats the grating **206** during use. Heating the grating **206** causes the grating to expand according to a thermal expansion coefficient of the material of the grating. Typically, the grating **206** is formed from a material having a low coefficient of expansion.

The first force device **218** and the links **219**A, **219**B have a thermal expansion coefficient substantially similar to the grating **206** so that the first force device will expand at the same rate as the grating. Thus the force **[**5022, 5026**]** *222, 226* exerted by the first force device on the grating will be substantially constant across the expected thermal operational range.

A second force device **240** is coupled to the opposing ends **206**A, **206**B of the grating **206** in a second plane **232** different from the first plane **230**. The second force device **240** is coupled to the opposing ends **206**A, **206**B of the grating **206** though links **241**A, **241**B, respectively. By way of example, the second plane **232** can be substantially perpendicular relative to the first plane **230** as shown. The second force device **240** and the links **241**A, **241**B have a thermal expansion coefficient substantially similar to the grating **206** so that the first force device will expand at the same rate as the grating. Thus the force **[**5022, 5026**]** *222, 226* exerted by the second force device on the grating will be substantially constant across the expected thermal operational range.

FIGS. **2**B and **2**C are simplified schematics of a reflecting face **208** of a beam control device **200**, in accordance with aspects of an embodiment of the disclosed subject matter. The second force device **240** can apply a second force to the opposing ends **206**A, **206**B of the grating **206** to cause the grating to bend in a controlled manner. In this way the second force device **240** can bend the reflecting face **212** of the grating **206** such that the grating lines **210** are in a fan pattern on the reflecting face **208** of the grating. The fan pattern changes the shape of the reflected light beam as the edges of the reflected light beam are reflected in different direction due to the fan pattern.

By way of example, as shown in FIG. **2**B, the second force device **240** can apply a pulling force **242** on the opposing ends **206**A, **206**B of the grating **206** to cause the fan pattern of the grating lines **210** to increase right to left. Similarly and as shown in FIG. **2**C, the second force device **240** can apply a pushing force **246** on the opposing ends **206**A, **206**B of the grating **206** to cause the fan pattern to wider on the left and closer together of the right.

FIG. **3** is a flowchart diagram that illustrates the method operations **300** performed in bending an optical grating to select a bandwidth of wavelengths of light centered on a selected center wavelength and having a selected minimum bandwidth and a selected maximum bandwidth, in accordance with aspects of an embodiment of the disclosed subject matter. The operations illustrated herein are by way of example, as it should be understood that some operations may have sub-operations and in other instances, certain operations described herein may not be included in the illustrated operations. With this in mind, the method and operations **300** will now be described. FIG. **4** is a simplified schematic of a light beam narrowing system **400**, in accordance with aspects of an embodiment of the disclosed subject matter. It should be noted that the components **102**-**424** of the light beam narrowing system **400** are not drawn to scale and specifically the curve **[**5028**]** *428*, wavefront **114** and the pitch of the grating are exaggerated for exemplary purposes.

In an operation **310**, a light beam is passed through a magnifier such as a prism, e.g., beam expander **104**, to magnify and expand or spread the light beam. In an operation **320**, a first force device **218** applies a first force **222** or **226** to the opposing ends **206**A, **206**B of the grating **206** though links **219**A, **219**B, respectively, to cause the reflecting surface **208** of the grating to bend in a controlled manner. The reflecting surface **208** is bent so that the reflecting surface substantially matches a wave front **114** of the expanded light beam **102**A.

In an operation **330**, a center wavelength is selected. The center wavelength **116**E is selected by a gridline **210**A that reflects the center wavelength back toward the beam expander **104** and the optical system **120**. Selecting the center wavelength **116**E and matching the reflecting surface **208** to the wave front **114** of the expanded light beam **102**A also determines a maximum bandwidth **422**A of the narrowed reflected light beam **424**A.

In an operation **340**, the second force device **240** applies a second force **242** or **244** to the opposing ends **206**A, **206**B of the grating **206** though links **241**A, **241**B, respectively, to cause a fanning of the grating lines **210** on the reflecting surface **208** of the grating to increase or decease. Varying the fanning of the grating lines **210** determines a bandwidth **422**B of the line-narrowed reflected light beam **424**B.

The light beam narrowing system **400** can also include a variable aperture **430**. The variable aperture **430** can vary the area of the grating surface that the expanded light beam impinges on. The variable aperture **430** can also increase or decrease the divergence of the expanded light beam. The divergence is the angle at which the various light beams **116A**-**116**n are separating from one another. Increasing the divergence increases the angle between the light beams **116A**-**116**n and also increases the difference in the angles which those light beams **116A**-**116**n reflect off the grating **208**. As a result the variable aperture **430** can increase or decrease the angles of light that are reflected back from the grating surface. In combination with the bending of the grating in horizontal and vertical directions, the variable aperture can increase the range of the reflected bandwidth from between less than about 200 fm to greater than about 1500 fm.

FIG. **5** is a top view of a dispersive optical element **500**, in accordance with aspects of an embodiment of the disclosed subject matter. The dispersive optical element **500** may be used for center wavelength selection, i.e., a grating such as an eschelle grating. The dispersive optical element **500** may also serve at least in part to determine bandwidth. The dispersive optical element **500** includes a dispersive optical element body **502** having dispersive optical element top **504**. It will be understood that the designation top is purely for reference and refers here to the fact that the dispersive optical element **500** when placed in a line narrowing module housing **1002**, such as is shown in FIG. **10**, which is a top view, will face the top of the housing **1002**. The dispersive optical element **500** may also have one face forming a dispersive optical element dispersive surface **508** formed on the front face **510** of the dispersive optical element body **502**. The dispersive optical element body **502** may also have a back face **506**. The dispersive optical element body **502** may also have a dispersive optical element bottom **512** shown in FIGS. **6** and **9**.

The dispersive optical element **500** may also have a dispersive optical element forward end **514** and rear end **516**, it also being understood that the terms forward and rear are for reference purposes only and refer to the fact that, as illustrated in FIG. **9**, the forward end is closest to the center wavelength selection mechanism **900** that delivers the light from a laser chamber, not shown and controls the angle of incidence of the light on the dispersive optical element **500** to select center wavelength.

It can be seen from FIG. **5** that applying a force to the back of the dispersive optical element as more fully described below and as is well understood in the art of such bandwidth control devices ("BCDs"), such as by holding the ends **514**, **516** in place and applying a horizontal force (again for reference only and as aligned to the directions previously described for reference purposes only) to the back face **506** of the dispersive optical element body **502** in the direction toward the body **502** may induce a cylindrical deformation of the front face **510**, and thus the dispersive optical element grating face **508**. This can deform the grating face into a convex cylindrical shape relative to the light incident on the grating face **508** from the center wavelength selection mechanism **900**. Similarly applying the force opposite to this direction can form the grating surface into a concave cylindrical shape vis-a vis the light incident from the center wavelength selection mechanism.

As can be seen in FIG. **5**, the application of a compressive force along the back face **506** of the dispersive optical element body **502** can shorten an unstressed length of the back face **506** of the dispersive optical element body **502** from a length L**1**, as an example, to a length L**2**. Thus forming the back face **506** as a compressively stressed face and the front face **510** (corresponding to the grating surface **508**) as a stressed face under tensile stress. For example, the grating back face **506** can be displaced from the respective back corners from the unstressed position to a stressed position of around 8 μm can form a curvature in the back face **506** on the order of about 1 km in radius of curvature, with a corresponding curvature in the front face **510** containing the grating surface **508**.

FIG. **6** is a side view of a dispersive optical element **500**, in accordance with aspects of an embodiment of the disclosed subject matter. The dispersive optical element **500** is shown under stress from a BCD applying force to the top surface **504**, such that a dispersive optical element grating having a plurality of surface grooves **210**, each having a reflective groove face, facing the forward end **514** and a groove opposing face facing in the opposite direction, each groove **210** generally perpendicular to the longitudinal axis of the grating face **508**, are deformed as shown. The deformation widens the grooves **210** along the extend from the top face **504** to the bottom face **512**, such that the reflective surfaces of the grooves **210** approach an angle β with respect to an unstressed longitudinal centerline axis of the grating face **508** toward the rear end **516** and a generally opposite angle α toward the forward end **514**.

FIGS. **7**A-**7**E are simplified schematics of various forms of actuators for applying force to a grating body, in accordance with aspects of embodiments of the disclosed subject matter. The actuators shown in FIGS. **7**A-E can be used in combination to apply force to two sides of the dispersive optical element **500**, thus forming a horizontal BCD and a vertical BCD. FIG. 7A illustrates schematically an actuator **702** connected to a pair of end blocks **704**A, **704**B by flexures **706** A, **706**A', **706**B and **706**B' connected to moving blocks **708**A, **708**B. The end blocks **704**A, **704**B are connected to the respective ends of a grating body (not shown in FIG. 7A) similarly to what is illustrated in FIG. **9**. One moving block **708**B is threaded and has passing through it, in a direction orthogonal to the longitudinal axis of the actuator **702** passing through end blocks **704**A, **704**B, a low pitch differential screw **710**.

The other moving block **708**A is operatively connected to a stationary block **712** by a preloading spring **714**, which may apply a tensile force between the end force blocks **704**A, **704**B by drawing the moving blocks **708**A, **708**B toward each other beyond some neutral moving block position. The resolution of the actuation can be 40 nm twist/turn of the differential screw. The range for twist-adjustment could be ±1 micron. For example 20 microns of travel of the moving block on the screw **[**5028**]** *710* can result in an 8 microns sag as illustrated schematically in FIG. **6**, i.e., 1 micron sag requires 2.5 micron travel range for the manual actuation with a resolution of 0.1 micron/turn.

FIG. 7B illustrates schematically a concept for lowering the applied forces during the adjustment. The actuator **720** has an end block **704**A attached to the grating body (not shown in FIG. 7B). FIG. 7B illustrates a BCD actuator that could be attached at blocks **704**A, **704**B to end mounted force plates on a grating body **502**, as described above, or the block may be held stationary and block positioned to push on the grating body (not shown in FIG. 7B) in the vertical direction. A shaft **722** is threadably engaging block **704**A and extends through bearings **724** on an end wall and an intermediate wall of a frame **726**. The shaft **722** may have attached to it a piston **728** with respective adjacent springs **730** intermediate the end wall and the piston **728** and the piston **728** and the intermediate wall. Rotating the shaft **722** moves the block **704**A with respect to the block **704**B and can apply force to end force plates on the ends of the grating or to the top of the grating, as noted above.

After adjustment the threaded shaft **722** could be locked as is well known by those skilled in the art to account for high forces induced by the illustrative OBCD, as can also be the case for other embodiments, such as those illustrated in FIGS. **7**A-E, **8** and **9**-**12**. Such a BCD, as illustrated in FIGS. **7**A-E and **8**, can deliver on the order of 1 micron of displacement (sag) of the BCD body for a given number of turns, e.g., approximately 25 turns of threaded shaft for BCD actuators of the type illustrated in FIG. **8**. This has been found to deliver about 160N of force causing such displacement, i.e., about 6 N/turn (160N/25 turns). 6N/thread pitch equals the spring rate and 25 turns*thread pitch equals the amount of travel.

A desired sag (curvature) range of displacement at the center of the curve of from, −1 to +8 microns means that, without special provisions for opposite acting force, such as by spring force, like the pre-loading spring discussed in regard to aspects of the embodiment of FIG. **9** et seq, a push only actuator would not be satisfactory. As discussed herein with respect to FIG. **9** et seq, a push only actuator, such as a bellows can be preloaded with a spring, e.g., to the −1 setting.

Another form of actuator which could be attached to end force blocks on a grating or for in-line force application to the side/top of the grating could be as illustrated schematically in FIG. 7C, with a spring for preloading the actuator, e.g., to the −1 micron sag setting. As illustrated in FIG. 7C, an actuator **740** has an outer frame **742** and an inner frame **744**, with the inner frame top and bottom slideably engaging a rear wall **746**A and an intermediate wall **746**B of the outer frame **742** and an actuator driving mechanism **748** of one of the types noted elsewhere herein serving to apply a force intermediate the inner frame **744** and the outer frame **742** to shorten the distance between the end blocks **704**A, **704**B. The spring **750** can apply preloading force in the opposite direction.

FIG. 7D illustrates schematically an actuator **760** applying a lever arm **762** to apply the force on the end blocks **704**A, **704**B. A lever arm **762** is also included in other embodiments described herein. The lever arm **762** can reduce the force required to be applied by the actuator driving mechanism **764**. The driving mechanism **764** of FIG. **7**D applies force to the lever **762** which in turn pulls the blocks **704**A, **704**B toward each other through connector arm **766** pivotally attached to a shaft **768** attached to the end block **704**B. A spring **770** on the shaft **768** intermediate the right hand end block **704**B can apply pre-loading force.

FIG. 7E illustrates a similar actuator **780** with a lever **782** pivoted about a fulcrum **784** and pivotally connected to a shaft **786** draws and blocks **704**A, **704**B toward each other, with a spring **790** for pre-loading force. It should be understood that the actuators illustrated and described herein are merely exemplary and other types of actuators and combinations of types of actuators could also be used. Types of actuators can include hydraulic, pneumatic, piezoelectric, a motor, a stepper motor, electromagnetic and magnetostrictive to name a few.

FIG. **8** is a perspective view of a dual action bandwidth control device **800**, in accordance with aspects of an embodiment of the disclosed subject matter. The dual action bandwidth control device **800** includes a first bandwidth control device **802** and a second bandwidth control device **804**, arranged, respectively on the back face **506** of the dispersive optical element body **502** and on the top face **504** of the dispersive optical element body **502**. A pair of end blocks (force plates) **704**A, **704**B on either end and adapted to apply force to the body **502** from both BCDs **802**, **804**.

Each of the BCDs **802**, **804** include a BCD frame **806**A, **806**B, respectively. The respective frames **806**A, **806**B, include a respective BCD frame forward bulkhead **808**A, **808**B, a BCD frame rear bulkhead **810**A, **810**B and a BCD frame intermediate bulkhead **812**A, **812**B. The respective rear bulkheads **810**A, **810**B includes a BCD frame rear bulkhead finger **814**A, **814**B each with a cylindrical mounting shaft opening (not shown).

A BCD cylindrical actuator shaft **816**A, **816**B extend through the front bulkhead **808**A, **808**B and intermediate bulkhead **812**A, **812**B and terminate on one end with a BCD shaft stop mechanism. A BCD shaft bearing extends through the front bulkhead **808**A, **808**B and include a BCD shaft bearing flange. A BCD threaded bushing extends through the forward force plate **704**A and is internally threaded and receives a threaded portion of the BCD shaft.

A pair of L brackets **160** are glued respectively to the forward end **514** and the rear end **516** of the dispersive optical element body **502** and have suitable attachment mechanism to attach the respective end force plate **166** to the dispersive optical element body **502**. The force plate **704**A includes two pairs of force plate clamps, each with a force plate clamp tightening screw to tightly grip a respective rear bulkhead finger attachment pin of the rear and top BCDs **802**, **804**. The respective attachment pins each extend through a respective attachment pin bushing.

A BCD piston **820**A, **820**B is secured to the shaft **816**A, **816**B, e.g., by a set screw or other suitable fastener, and separated by each of a forward compression spring **822**A, **822**B and a rear compression spring **824**A, **824**B by a piston thrust bearing, having a thrust bearing plastic ring.

In operation the respective shaft **816**A and/or **816**B are rotated, manually or automatically, e.g., by a rotary stepper motor, or a linear stepper motor with a linear to rotary motion converter, responsive to a bandwidth controller actuator positioning signal. The rotating the shafts compresses the respective springs **822**A, **822**B and **824**A, **824**B and exerts a force on the respective frame **806**A, **806**B toward or away from the front end force plate **704**A, depending on the direction of rotation of the respective shaft **816**A, **816**B and exerts a force on the rear end force plate **704**B through the respective finger **814**A, **814**B to put the respective face **506**, **504** in tension or compression. The BCD **802** affects the grating face as illustrated schematically in FIG. **5** and the BCD **804** affects the grating face **508** as illustrated in FIG. **6**.

Such a dual acting bandwidth control device **800** can serve to twist the dispersive optical element body **502** as discussed above, affecting the bandwidth of the light amplified in the laser chamber (not shown) with which the dispersive optical element is associated as a center wavelength/bandwidth selection mechanism. The bandwidth may be affected differently for full width half max ("FWHM"), the bandwidth of the spectrum measured at the half of the maximum intensity peak point on the spectrum sidewalls and for E95%/E95, the width of the spectrum containing 95% of the intensity centered on the center wavelength of the spectrum. The intercoupling of the two BCDs **802**, **804** may be such that the independence of the impacts on FWHM and E95 may be sufficiently compromised, or other detrimental effects, may result in the dual acting bandwidth control device **800** being less than ideal for bandwidth selection and control.

FIGS. **9-12** illustrate another dual acting bandwidth control mechanism **900**, in accordance with aspects of an embodiment of the disclosed subject matter. As shown in FIG. **9**, the dual acting bandwidth control mechanism **900** utilizes a front end force plate **704**A and rear end force plate **704**B, illustrated in more detail in FIG. **14**A. FIG. **14**A is a perspective view of a force plate **704**A, **704**B, in accordance with aspects of an embodiment of the disclosed subject matter. FIG. **14**B is a perspective view of a front end **514** or a rear end **516** of a dispersive optical element body **502**, in accordance with aspects of an embodiment of the disclosed subject matter.

The force plate **704**A, **704**B, has multiple mounting pads **1402**, formed by horizontal slots **1404** and vertical slots **1406** dividing a mounting face **1408** into the respective pads **1402**. Some or all of the mounting pads **1402** may have placed thereon glue dots **1410**, **1410'**, **1410"** to attach the respective force plate **704**A, **704**B to the front end **514** or rear end **516** of a dispersive optical element body **502**. The selected arrangement of the respective glue dots **1410**, **1410'**, **1410"** can localize the shear forces accordingly. As shown in FIG. **14**B, the regions **1412** do not have glue dots placed thereon. As a result, the shear forces are not applied to the front surface **508** of the dispersive optical element body **502** and are instead applied more to the rear surface.

The selected location of the respective glue dots **1410**, **1410'**, **1410"** can localize an optimum pivot location. An optimum pivot location is a location where the vertical BCD and the horizontal BCD are minimally affected by each other. For example in an optimum pivot location, adding or reducing the amount of force the vertical BCD applies to the dispersive optical element body **502** does not substantially reduce or increase the force applied by the horizontal BCD on the dispersive optical element body **502**. Similarly, in an optimum pivot location, adding or reducing the amount of force the horizontal BCD applies to the dispersive optical element body **502** does not substantially reduce or increase the force applied by the vertical BCD on the dispersive optical element body **502**.

The flexture elements described herein act to substantially decouple or isolate the force vectors from the vertical BCD from reducing or increasing the force applied by the horizontal BCD on the dispersive optical element body **502**. The flexture elements described herein also act to substantially decouple or isolate the force vectors from the horizontal BCD from reduce or increase the force applied by the vertical BCD on the dispersive optical element body **502**.

It should be noted that the respective glue dots **1410**, **1410'**, **1410"** are shown differing sizes and/or strengths so as to add yet another dimension of localizing the shear stresses in the desired locales of the front end **514** or rear end **516** of a dispersive optical element body **502**. The force plate **704**A, **704**B may also include a pair of horizontal BCD mounting bracket shelves **1414** and vertical (Orthogonal) BCD ("OBCD") mounting surfaces **1416**.

Turning again to FIGS. **9-12** there is illustrated an orthogonal (e.g., vertical) BCD ("OBCD") which may apply tensile or compressive stress to the dispersive optical element body **502** in a manner to effect the progressive widening of the grooves **210** as shown partly schematically in FIG. **6**. The dual acting bandwidth control mechanism has a pair of rear mounting brackets **902**, which can be made, e.g., of Invar, and serve to connect the rear force plate **704**B through a pair of mounting bracket fingers each extending into a respective shelf **141** and a mounting bracket angle arm, respectively attached to a top or bottom arm of horizontal BCD attachment yoke **904** yoke as well as connection by bolting to the yoke. Similar brackets **902** couple the bottom of the yoke **904** to the rear end force plate **704**B. The BCD attachment yoke **904** has a mounting yoke bearing to receive a shaft **906**. The shaft **906** includes a flexure **910**. Each thrust bearing **912** may have an extension.

Forward mounting brackets **902'** similarly couple the forward force plate **704**A to the top and bottom of a forward end flexured mounting plate **914** having a flexure element **916** connecting it to a horizontal BCD flexure coupling plate **918**, connected to the forward end **920** of the horizontal BCD **922** by a similar flexure link (not shown) within the space **924** shown in more detail in FIGS. **13**A, **13**B. Horizontal BCD **922** is substantially similar to BCDs **802**, **804** discussed in the related text and shown in FIG. **8**.

FIGS. **13**A and **13**B are perspective views of flexured elements **916**, **918**, in accordance with aspects of an embodiment of the disclosed subject matter. The flexured elements **916**, **918** and end blocks **300** may be made of Invar. The OBCD can have one or more, e.g., a front and a rear, flexured elements connecting the OBCD to the respective front and rear force plates **704**A, **704**B, e.g., by being bolted to the OBCD mounts **904**. The flexured elements **916**, **918**, have a flexured connector end block connector **1302**, screw holes **1304** and a flexured connector end bock wall **1306**. The connector block **1302**, as shown, forms an actuator L bracket **1308** although it should be understood the flextured elements **916**, **918** could be any sort of connector. The connector plate **1306** includes connector openings **1310** that can be threaded if desired. The flexure **916**, **918** allows for rotation of the blocks **1302**, **1306** with respect to each other about the axis formed by the length of the flexure **1312**.

Referring again to FIG. **9** the OBCD actuator **900** includes an OBCD actuator frame **930**. The OBCD actuator frame **930** includes a pair of top horizontally extending ridges, a rear wall, and a bottom wall. The rear wall is connected, e.g., by bolting to a tapering beam **932**. The tapering beam **932** includes longitudinal structural members **934** and vertically extending structural stiffeners **936**. The tapered beam **932** may be connected to a flexured end plate **940** which may be connected to the L bracket portion of the connector member by threaded connectors, such as bolts. The flexured end plate **940** element includes a flexure **942**.

The actuator frame **930** may include a pair of top horizontal beams to which may be mounted, as by bolting, an actuator frame support brace. An actuator bellows **950** can be made of aluminum or stainless steed. The actuator bellows **950** is attached to the frame **930**, as by bolting to the frame rear wall attaching to a hollow cylindrical bellows rear plate. The actuator bellows **950** is also be attached through a cylindrical bellows front plate by bolting with bolts to an actuator lever arm **952**. The actuator bellows **950** can also include a bellows actuation fluid or liquid.

The actuator lever arm **952** is coupled to a downwardly extending angle arm **954**. The angle arm **954** is coupled to a thin flexure sheet **960** extending horizontally from the frame bottom wall as well as thin flexure sheets **962** extending between the lever arm **952** generally in line with a centerline axis of the lever arm angle arm **954**. The end of the angle arm **954** is also be attached to the connector block **964** by a thin flexure sheet **966**.

Together the flexure sheets **960**, **962**, **966** form a pivot point in the lower extent of the angle arm **952** at the intersection of the planes of the flexure sheet **960** and flexure strips **962**, about which the actuator lever arm **952** pivots when the bellows **950** expands or contracts, applying force through the flexure **966** to the connector block **940** and thence to the forward force plate **704**A through the forward flexured connector **940**.

The frame **950** has an overhang **972**. The overhang **972** includes a cylindrical passage **974** receiving a preloading spring **976**, which may also be received in a cylindrical opening **978** in the upper end of the lever arm **952**. The passage **974** can also include a threaded spring compression mechanism **980**. The threaded spring compression mechanism **980** applies compressive force to the spring **976** to preload the dispersive optical element body **502** to put a bend in the body **502** in the opposite direction than that applied when the actuator bellows expands.

The bellows **950** may be expanded or collapsed from some central position, e.g., the preloaded position established under the influence of the preloading spring **976**, by the application of pressure through the introduction or removal of a gas, fluid or liquid into or out of the bellows **950** through fluid opening **982** in the bellows end plate. The pressurizing gas, fluid or liquid may come from an actuator fluid delivery system **984**, through fluid delivery tubing **986**, supported by a fluid delivery system tubing support **988**.

It will be understood by those skilled in the art that the above described OBCD can apply a force to the dispersive optical element along its top, e.g., a compressive force, which can exert a force on the centerline axis of the body in the vertical direction (again understanding that throughout horizontal and vertical are in relation to an orientation of the line narrowing module such as shown in FIG. **8** as a top view of the module, and not in relation to any actual orientation of the module when in actual use, which, indeed may be, e.g., with the plane of the paper in the vertical plane and the top view of FIG. **10** actually being a side view, relative to horizontal and vertical in the installed module in use). Such force can deform the grooves of the dispersive optical element in the direction show in the side view (again oriented to the view of the line narrowing module in FIG. **10** as a top view) of FIG. **6**.

A controller **980** is coupled to the OBCD actuator **900**. The controller can include a feedback loop analyzing the bandwidth of the light beam reflected from the reflective surface and adjusting the shape, e.g., bending, of the reflective surface accordingly, by adjusting the forces applied by the actuators. The controller **980** can include software and hardware for operating the OBCD actuator **900** and for analyzing the bandwidth of the light beam reflected from the reflective surface and adjusting the shape of the reflective surface. The controller **980** can be linked to or include other controllers such as a central server or system controller (not shown) and a pressure controller, not shown, such as a QB1T controller, made by Proportion Air of McCordsville, Ind. Such a controller can use a 4-20 mA input current to set the pressure from 0 to a maximum pressure defined by the bandwidth tuning range desired and the mechanical design. Fore example, 5 or 10 bar can be used as maximum pressure.

The required pressure (twist) to reach an OBCD tuning range of 300 fm has been found to be very reasonable with the design illustrated as an example of FIGS. **5**-**8** and was determined to be somewhat less that had been expected in some instances. Crosstalk between HBCD and OBCD is small, e.g., less than about 20 nm induce sag in the HBCD.

The flexured elements, such as the sheet **960** and strips **962**, **966**, and the connectors **940** may be made of a very low CTE material like Invar. It is understood that other materials with low thermal expansion may be used in the mechanical design, such as machined parts from ULE glass.

The frames and tapered beam may be made of aluminum, including the connector block **940** and flexure **1312**, such a 7075 aluminum, as may the flexure sheet **960** and strip flexures **962**, **966** forming the pivot point of the actuator lever arm **952** connected to the forward end of the actuator bellows **950**.

The flexured end block **914** as well as the rest of the BCD housing frame **922** and intermediate flexure plate **916** may also be made of Invar or aluminum or other suitable material having low CTE and good strength, or a suitable combination of the two. The actuator frame **930** may also be made of aluminum, such as 7075 aluminum. The plates **902** may be made of Invar or aluminum or the like.

Applicants have determined that such deformation can extend the upper limit of the BW tuning range in such an LNM to >0.50 pm, e.g., with a range margin to cover a 0.25 to 0.50 pm system BW tuning specification.

Effects on bandwidth have been shown to survive the amplification laser in a seed laser amplifier laser configuration, such as a power oscillator, like a power ring amplifier ("PRA"). Bandwidth vs Magnification, in, e.g., a variable magnification Line Narrowing Module, such as described in U.S. Pat. No. 7,366,219 referenced above, can be shifted by approximately 70 fm, with, however, beam profiles and divergence profiles not significantly altered by the vertical applied force, at the levels of grating deformation produced according to aspects of the disclosed subject matter, e.g., on the order of that illustrated in FIG. **5**. With higher magnification in the incident beam on the dispersive optical element the applied force can making the relation between force and bandwidth modification approximate linearity. It has been found that the horizontal BCD curve, can be shifted by approximately ½ turn for such a range of vertical force\BW shift. It has also been shown that a shift of 70 fm via application of force in the vertical direction on the dispersive optical element body **502** does not introduce major degradation of wavelength stability, especially compared to demagnification alone, and the bandwidth continues to trace a trusted standard as a check to on-board metrology even after vertical force is applied.

It has also been determined that the OBCD according to aspects of the disclosed subject matter, as illustratively described above, can serve to significantly mitigate bandwidth resonances, effectively acting as an adaptive optic to match the incoming wavefront. The latter can have distortions due to passage through acoustic gas perturbations, which impact bandwidth. By fine-adjusting the OBCD in the neighborhood of zero grating vertical deflection, such bandwidth perturbations are minimized, in comparison with those occurring in normal LNM utilization to date.

It has also been found to be very useful to use the OBCD, according to aspects of the disclosed subject matter, in combination with a variable aperture at the entrance of the Line Narrowing Module containing the OBCD mechanism. An aperture limiting the size of the beam incident on the grating, whose dimension parallel to the direction of the grating grooves can be adjusted, further allows control of the light's bandwidth when the grating is under static, fixed bending. This combination is useful, for example, when optimizing simultaneously both the bandwidth and divergence properties of the beam.

Another variation of the disclosed subject matter is to use the OBCD actuation in combination with beam expansion in the vertical direction, generally parallel to the direction of the grooves. For a fixed grating vertical deflection, expanding or reducing the incident beam on the grating in the vertical direction produces tuning of the bandwidth, as a wider\narrower range of wavelengths are selected by the chirped grating and included in the overall reflected spectrum.

In addition the OBCD illustratively described above does not conflict with utilization of the existing horizontal BCD.

The vertical bending of the grating block **502** has been seen to produce a non-uniform groove spacing ("fanning") and tilt of the groove lines with respect to the vertical axis. In Littrow, rays incident on the central part of the grating are diffracted back along the direction of incidence. However, rays incident on the far right of the grating are no longer diffracted in-plane because the grooves are tilted: rays are back-diffracted at a slight downward angle B with respect to the incident direction A, as illustrated in FIG. **6**. Beam rays incident on the left end of the grating are similarly diffracted at the same small angle B with respect to the incident beam, but with the opposite sign. Therefore, the light beam returning from the grating exhibits a twist as a result of the groove change in orientation.

Applicants have made a rough estimate of grating deformation from Zygo interferometric measurements required for various bandwidth tuning targets. By way of example: for a tuning range of 250 fm (250 fm-500 fm) the measured wavefront twist induced is 100 μrad, which corresponds to a radius of curvature R=3.5 Km and a grating bending sag of 4.4 um. For a tuning range of 1.2 pm (0.25-1.45 pm), the radius of curvature decreased to approximately 0.98 Km, and the induced grating sag was 16 um. This deflection produced a wavelength chirp, top to bottom of the grating, of 0.21 pm/mm FIG. **15**A is a graph **1500** of E95 bandwidth, in accordance with aspects of an embodiment of the disclosed subject matter. The E95 bandwidth tuning is compared to a level of grating vertical bending, e.g., wavefront twist from Zygo interferometry.

For comparison, the radius of curvature of a typical grating with adjusted horizontal BCD is of the order of about 40 Km and a maximum induced sag is about 0.63 um.

With regard to the effect of modifying bandwidth via utilization of an OBCD, one must consider the coupling between horizontal and vertical BCDs, beam parameter changes, and metrology, such as changes in spectral shape that can modify the on-board metrology tracking a trusted measuring instrument, such as an LTB spectrometer, especially for E95.

Coupling between vertical and horizontal BCD has been minimized to a negligible horizontal BCD compensation, e.g., less than about 20 nm of induced sag.

The following Table I indicates parameters achieved due to the utilization of a dual acting bandwidth control mechanism according to aspects of an embodiment of the disclosed subject matter as illustrated in FIGS. **5**-**8**.

TABLE I

	OBCD (pneumatic)
Tuning speed	0.2-1.5 pm full range
Actuator Speed	Less than about 1 second, full range of actuation
Actuator pre-load	adjustable, about 10% of full range of deflection in the opposite direction to pneumatic operation
Automated actuation resolution	Less than about 10 fm of E95 resolution
Pressure range for pneumatic actuation	0-5 bar is the preferred range, can vary depending on application

Applicants had considered a number of actuator options, such as pneumatic, as illustrated; piezo-electric material, or other similar actuatable deforming material such as magnetostrictive material; a motor attached to the manual lead through shaft, such as may be used with an embodiment such as shown in FIG. **8**; electro-magnetic; hydraulic (perhaps an equal or better solution that shown in FIGS. **5**-**8**, and similar in design, though also perhaps more expensive. Criteria considered were technical risks, power dissipation, speed, necessary LNM modifications, the availability of GRAS materials for such an actuator, and lifetime. For various reasons the embodiment according to what is illustrated in FIGS. **9**-**12** was determined to be most suitable, though one or more of these options, especially, e.g., a hydraulic embodiment, could be utilized and achieve more or less the same results as are envisioned for the disclosed subject matter of FIGS. **9-12**.

Regarding the pneumatic embodiment illustrated in FIGS. **9-12**, lifetime was found to be a function of the pressure controller life and robustness of the mechanical components transmitting the force to the dispersive element's body. Generally acceptable optical materials (GRAs materials) could be used in the construction of the line narrowing module (LNM). A 100 mm diameter bellows was determined to be able to apply 2500N of force with a 3 bar (43 psi) gas pressure in the bellows, such as helium or air pressure. The device is a push only controller, thus necessitating a spring mechanism or the like for applying force to the grating body **502** in the opposite direction if necessary, e.g., for pre-loading.

The utilization of a plurality of independent glue dot receiving surfaces has been adopted, as illustrated in FIGS. **14**A and **14**B to reduce the risk of glue dot de-bonding at the end blocks **704**A, **704**B over the life of the vertical BCD (the OBCD) actuator. This can avoid the possibility of wavefront distortion at the end portions of the grating, e.g., had it been necessary to resort to full area gluing instead of the former glue dots design, not employing the individual surfaces of FIG. **14**A.

Since manual actuation may be needed for adjusting the twist of the grating body **502**, e.g., to define a baseline for an automatic actuation, the horizontal BCD, according to existing BCD design may still be utilized. In addition controlling the grating curvature in two different planes may have other beneficial results, such as more sensitivity in selecting/controlling bandwidth, independent selection/control of FWHM over E95, etc.

FIG. **15**B is a perspective view of another apparatus **1550** for bending a dispersive optical element, such as a grating, according to aspects of an embodiment of the disclosed subject matter. As illustrated in FIG. **15**A, a horizontal BCD is shown in the orientation of FIG. **5**, i.e., with the grating face **508** on the bottom and the top of the grating body **502** facing frontward as viewed in FIG. **14**A, i.e., generally in the plane of the paper. Two end force blocks/plates **704**A, **704**B are shown attached to the forward and rear ends of the grating body **502**, e.g., by gluing, and each can have a flexure plate **1554**, which may be integral with the respective end plate **704**A, **704**B. Each of the flexure plates **1554** are each coupled to a pair of rod holders **1560**. The rod holders **1560** each hold is coupled to a respective end of a respective rod **1562**.

The actuator **1570** includes bellows **1572** or other expansive or contractive mechanism. The bellows **1572** are coupled to a flexure plate **1574**. Each flexure plate **1574** is coupled to a flexure element **1554**. Each flexure element **1554** is coupled to the respective ends of the respective rods **1562** through rod ends **1560**.

In operation, as the actuator **1570** is expanded, e.g., by introduction of a pressurized fluid such as a liquid, e.g., hydraulic oil or water, or a gas, e.g., helium or nitrogen or air into the bellows **1572**, a force is exerted on the two end plates **1574** pulling them together generally in a plane through the centerline axes of the rods **1562**, thus bending the grating face **508**. It will be understood that the grating face bending mechanism **1550** shown in FIG. **15**B could also be oriented to deform the grating face as illustrated in FIG. **6**, that is, generally parallel to the grating top surface **504**.

The grating body deforming mechanism **1550** as illustrated in FIG. **15**B can, therefore provide a simple method to unidirectionally bend the grating body **502** for increasing bandwidth while minimizing materials and compensating for temperature changes. A curve is induced in a grating by generating the tensile force between the two ends. The tensile members, e.g., the rods **1562** and flexures **1554** can are made of the same material as the grating body **502**, which may be selected to have a relatively very low coefficient of thermal expansion, or such other with a relatively very low CTE, such as Invar®, or another materials that combines very low CTE with lighter weight, in order to minimize the thermal expansion difference between the grating substrate body **502** and the disclosed subject matter. Any residual thermal expansion differential of the combination of the flexures **1554** and rods **1562** can be compensated by maintaining a constant pressure in the bellows **1572**, and thus, a constant force. The embodiment of FIG. **15**B can provide a force amplifier with gains greater than 7×. The flexures **1554** could also be made of a suitable light weight metal, such as aluminum, e.g., 7075 aluminum.

FIGS. **16**A and **16**B schematically illustrate a flexured grating mount **1600** that may be useful according to aspects of an embodiment of the disclosed subject matter. The grating mount **1600** can be attached to the floor of a LNM housing **1002** as shown in FIG. **10**. In addition to other flexured connections to allow for differential thermal expansion between the grating made, e.g., of ULE and the mounting/housing made of aluminum, there may be utilized flexures **1602** to account for deformation of the grating body **502** by such as the OBCD. It will be understood that the flexures that have been used in the past to account for differential thermal expansion operated in a plane that generally allowed for accounting for deformation of the grating body **502** by the prior form of BCD, herein sometimes referred to as the HBCD.

The bending of the grating body is accommodated by the OBCD, flexured mounting points **1602** allowing for movement of tarts **1608** of the grating in a plane perpendicular to the surface of the mounting **1608** are added. These may take the form, by way of example, of one or a plurality of vertical flexure mounts, i.e., in line with the force applied to the grating top to account for the deformations such as illustrated partly schematically in FIG. **6**. The flexures **1602** include slots **1606**, which may generally be in a U shape, but could also have, e.g., squared corners, forming tongues **1608** that allow for flexure in the direction normal to the two surface of the grating mount. These could also be formed to have a vertical pre-stressed upward displacement to account for any negative bend in the form, e.g., of the referenced −1 μm pre-loading bend.

By examining the impact of multiple action, such as dual action, application of bending force to the grating body, i.e., in two planes a large change of ratio of FWHM and E95, different measures of bandwidth, for different levels of force applied to the pertinent actuator, e.g., the bellows of the embodiment of FIGS. **9-12** suggest significant change of spectral line shape with grating twist. Twisting the grating can lead to a rotation of the beam profile, which may appear more severe after the MO, but may be somewhat masked after the amplifier stage, such as a PRA stage. There may also be a vertical shift of the beam, which could also be a result of the relative alignment of the MO and PRA beam axes.

It will be understood that the bellows **950**, **1572** according to aspects of embodiments of the disclosed subject matter may be operated by pressurized fluid, either compressible, such as pressurized air or gas, such as, helium, i.e., pneumatically, or non-compressible fluid, such as hydraulic oil of water, i.e., hydraulically and the term pressurized fluid is meant to cover both types of actuators.

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

What is claimed is:

1. A bandwidth selection mechanism comprising:

a dispersive optical element having a body including a reflective face of dispersion including an area of incidence extending in a longitudinal axis direction along the reflective face of the dispersive optical element;

a first end block, disposed at a first longitudinal end of the body;

a second end block, disposed at a second longitudinal end of the body, the second longitudinal end being opposite the first longitudinal end;

a first actuator mounted on a second face of the dispersive optical element, the second face being opposite from the reflective face, the first actuator having a first end coupled to the first end block and a second end coupled to the second end block, the first actuator being operative to apply equal and opposite forces to the first end block and the second end block to bend the body along the longitudinal axis of the body and in a first direction **[**normal**]** *perpendicular* to the reflective face of the dispersive optical element; and

a second actuator mounted on a third face of the dispersive optical element, the third face being **[**normal**]** *perpendicular* to the reflective face, the second actuator having a first end coupled to the first end block with a first flexture and a second end coupled to the second end block with a second flexture, the first actuator being operative to apply equal and opposite forces to the first end block and the second end block to bend the body along the longitudinal axis of the body, in a second direction perpendicular to the reflective face of the dispersive optical element, the second direction also being perpendicular to the first direction the second actuator including a pressurized fluid force application mechanism.

2. The bandwidth selection mechanism of claim **1**, wherein the pressurized fluid force application mechanism is a pneumatic mechanism.

3. The bandwidth selection mechanism of claim **1**, wherein the pressurized fluid force application mechanism is a hydraulic mechanism.

4. The bandwidth selection mechanism of claim **1**, wherein the pressurized fluid force application mechanism is variable.

5. The bandwidth selection mechanism of claim **1**, further comprising:

a manual preload adjustment at constant, fixed deflection on at least one of the first actuator and the second actuator.

6. The bandwidth selection mechanism of claim **5**, further comprising a feedback control loop on the second actuator in response to a spectral parameter of the light.

7. The bandwidth selection mechanism of claim **1**, further comprising a pneumatic actuation and feedback control loop on at least one of the first actuator and the second actuator, in response to spectral parameters of the light.

8. The bandwidth selection mechanism of claim **1**, further comprising a variable aperture positioned between the incident beam and the reflective face of the dispersive optical element.

9. The bandwidth selection mechanism of claim **8**, wherein the variable aperture has a variable dimension along a direction of bending of the second actuator.

10. The bandwidth selection mechanism of claim **1**, further comprising a light beam expander for expanding an incident a light beam across the area of incidence.

11. A method of selecting bandwidth comprising:

expanding an incident light beam across an area of incidence of a reflective surface of a dispersive optical element;

bending the reflective surface of the dispersive optical element with a first bending force applied by a first actuator in a first direction **[**normal**]** *perpendicular* to the reflective face of the dispersive optical element;

bending the reflective surface of the dispersive optical element with a second bending force applied by a second actuator in a second direction perpendicular to the reflective face of the dispersive optical element, the second direction also being perpendicular to the first direction; and

decoupling the second bending force through at least one flexture so that decoupled second force does not increase or decrease the first force.

12. The method of claim **11**, wherein in bending the reflective surface of the dispersive optical element in the first direction uniformly varies a spacing between dispersive features on the reflective surface as a function of position in the first direction.

13. The method of claim **11** further comprising:

modifying a dimension of the incident light beam upon the reflective surface to encompass different regions of the bent reflective surface.

14. The method of claim **11**, wherein the reflective surface is bent in **[**alt**]** *at* least one of the first direction and the second direction in response to feedback from a property of the reflected light beam.

15. A bandwidth selection mechanism comprising:

a dispersive optical element having a body including a reflective face of dispersion including an area of incidence extending in a longitudinal axis direction along the reflective face of the dispersive optical element;

a first end block, disposed at a first longitudinal end of the body;

a second end block, disposed at a second longitudinal end of the body, the second longitudinal end being opposite the first longitudinal end;

a first force device having a first end coupled to the first end block and a second end coupled to the second end block, the first force device being operative to apply a first force to the first end block and apply a second force the second end block to bend the body along the longitudinal axis of the body and in a first direction perpendicular to the reflective face of the dispersive optical element, the first force and the second force being equal and opposite; and

a second force device having a first end coupled to the first end block and a second end coupled to the second end block, the second force device being operative to apply a third force to the first end block and apply a fourth force to the second end block to bend the body along the longitudinal axis of the body, in a second direction perpendicular to the first direction, the third force and the fourth force being equal and opposite.

16. The bandwidth selection mechanism of claim 15, wherein at least one of the first force device and the second force device includes at least one of a piezoelectric actuator, an electromechanical actuator, a motor, a stepper motor, *electromagnetic actuator, magnetostrictive actuator or a pressurized fluid force application mechanism and wherein the pressurized fluid force application mechanism includes at least one of a pneumatic mechanism or a hydraulic mechanism.*

17. The bandwidth selection mechanism of claim 16, wherein the pressurized fluid force application mechanism is variable.

18. The bandwidth selection mechanism of claim 15, further comprising:

a manual preload adjustment at constant, fixed deflection on at least one of the first force device and the second force device.

19. The bandwidth selection mechanism of claim 18, further comprising a feedback control loop on the second force device in response to at least one parameters of the light.

20. The bandwidth selection mechanism of claim 16, further comprising a pressurized fluid force and feedback control loop on at least one of the first force device and the second force device, in response to at least one parameter of the light.

21. The bandwidth selection mechanism of claim 15, further comprising a variable aperture positioned between the incident beam and the reflective face of the dispersive optical element.

22. The bandwidth selection mechanism of claim 21, wherein the variable aperture has a variable dimension along a direction of bending of the second actuator.

23. The bandwidth selection mechanism of claim 15, further comprising a light beam expander for expanding an incident a light beam across the area of incidence.

24. The bandwidth selection mechanism of claim 15, wherein the first force device is mounted adjacent to a second face of the dispersive optical element, the second face being opposite from the reflective face.

25. The bandwidth selection mechanism of claim 15, wherein the second force device is mounted adjacent to a third face of the dispersive optical element, the third face being perpendicular to the second face.

26. The bandwidth selection mechanism of claim 15, wherein the first end of the second force device is coupled to the first end block through a first flexture and the second end of the second force device is coupled to the second end block through a second flexture, the first flexture and the second flexture decouple the second force and the first force.

27. The bandwidth selection mechanism of claim 15, wherein the second direction is perpendicular to the reflective face of the dispersive optical element.

28. A method of selecting bandwidth comprising:

expanding an incident light beam across an area of incidence of a reflective surface of a dispersive optical element;

bending the reflective surface of the dispersive optical element with a first bending force applied by a first force device in a first direction perpendicular to the reflective face of the dispersive optical element; and

bending the reflective surface of the dispersive optical element with a second bending force applied by a second force device in a second direction perpendicular to the first direction.

29. The method of claim 28, wherein in bending the reflective surface of the dispersive optical element in the first direction uniformly varies a spacing between dispersive features on the reflective surface as a function of position in the first direction.

30. The method of claim 28, further comprising:

modifying a dimension of the incident light beam upon the reflective surface to encompass different regions of the bent reflective surface.

31. The method of claim 28, wherein the reflective surface is bent in at least one of the first direction and the second direction in response to feedback from at least one parameter of the reflected light beam.

32. The method of claim 28, further comprising decoupling the second bending force through at least one flexture so that the decoupled second force does not increase or decrease the first force.

33. The method of claim 28, wherein the second direction is perpendicular to the reflective face of the dispersive optical element.

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