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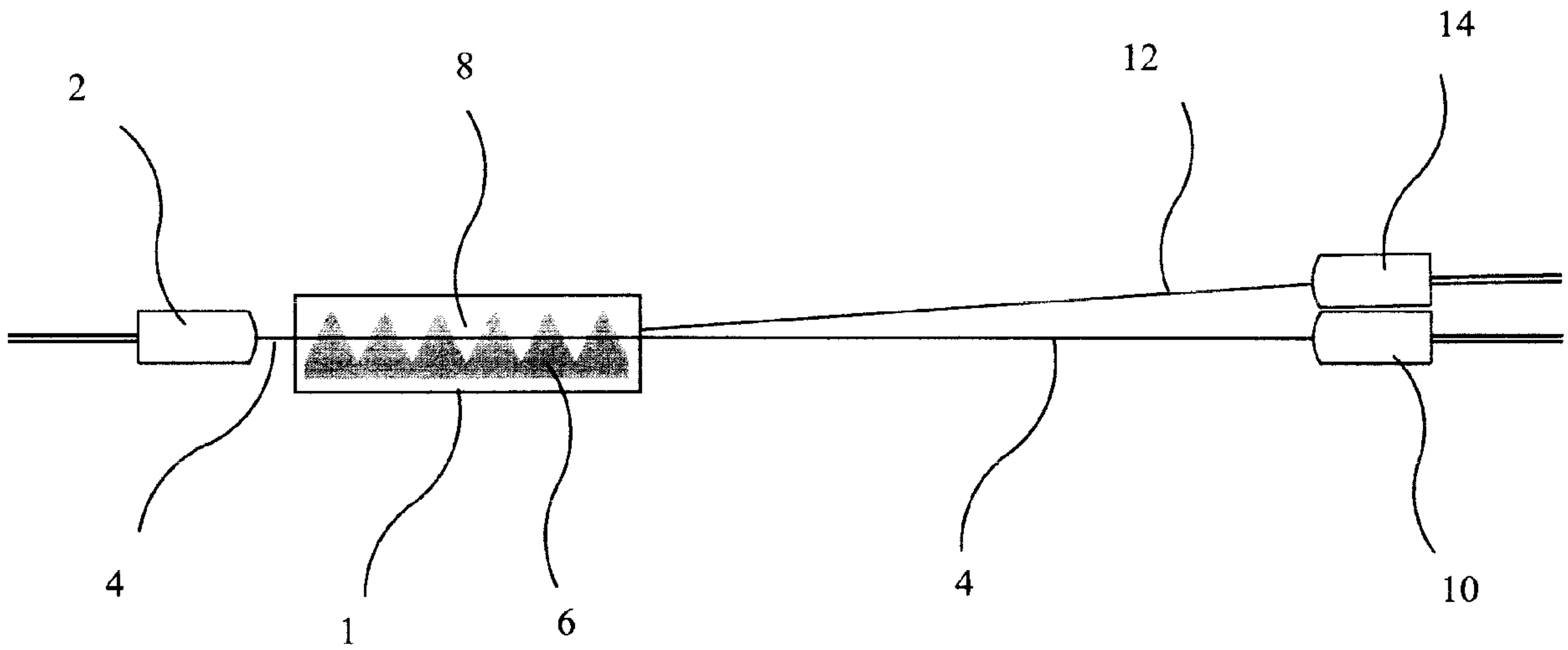
(54) Titre : COMMUTATEUR OPTIQUE COMPRENANT UN CRISTAL ELECTRO-OPTIQUE BASE SUR LA REFLEXION INTERNE TOTALE

(54) Title: OPTICAL SWITCH COMPRISED OF ELECTRO-OPTIC CRYSTAL BASED ON TOTAL INTERNAL REFLECTION



(57) Abrégé/Abstract:
Total internal reflection (TIR) is a well-known phenomenon/property of interaction between light wave and the interface formed by two types of optical materials. This feature has found many applications in optical engineering. As the reflective index of one material is changed through a controlled approach, the TIR condition may not be maintained and the light propagation path will be changed from a TIR manner to a transmission manner, or vice verse. This allows an optical switch to be built. There are a number of different ways to alert the reflective index of the materials under consideration. In this invention, a unique combination of process and method for electro- optic material manipulation and control is used to generate a structure for alerting the reflective index of one material, which forms an interface, or multiple interfaces to function as controllable TIR interfaces. This leads to a novel solution of TIR based optical switch design. Such a switch can operate over a wide range of spectrum. A properly designed optical switch based on this invention also operates independently from wavelengths and polarization of the incident light.

ABSTRACT

Total internal reflection (TIR) is a well-known phenomenon/property of interaction between light wave and the interface formed by two types of optical materials. This feature has found many applications in optical engineering. As the reflective index of one material is changed through a controlled approach, the TIR condition may not be maintained and the light propagation path will be changed from a TIR manner to a transmission manner, or vice verse. This allows an optical switch to be built. There are a number of different ways to alert the reflective index of the materials under consideration. In this invention, a unique combination of process and method for electro-optic material manipulation and control is used to generate a structure for alerting the reflective index of one material, which forms an interface, or multiple interfaces to function as controllable TIR interfaces. This leads to a novel solution of TIR based optical switch design. Such a switch can operate over a wide range of spectrum. A properly designed optical switch based on this invention also operates independently from wavelengths and polarization of the incident light.

OPTICAL SWITCH COMPRISED OF ELECTRO-OPTIC CRYSTAL BASED ON TOTAL INTERNAL REFLECTION.

1. Field/Background of the Invention

This invention describes a unique combination of process and method for electro-optic material manipulation and control to generate a structure for alerting the reflective index of a material, which forms one interface, or multiple interfaces to function as controllable TIR interfaces. This gives a novel solution of TIR based optical switch design for optical communication.

2. Description of Prior Art

Optical switches or optical switch matrix for fiber optical communication are essential components in optical networks. Since their function is so important that tremendous amount of R&D efforts has been dedicated to optical switch deploying many different techniques, each of which relies on one of the basic optical properties, including: TIR, reflection, refraction, interference/diffraction, waveguide, polarization, etc...

What remains in common as the specification for an optical switch includes: low insertion loss, low cross-talk, independence of polarization and wavelengths, fast switching speed, no moving part and simplicity of structure. While in practice it has been found that meeting all of the specification in one completed optical switch design is very challenging.

It is the intention of this invention to make use of TIR property of some electro-optic material to fulfill optical switches with optimized specification. While a number of existing patents show that TIR property has been used in optical switches implemented through different techniques. They are briefly reviewed in the following according to TIR implementing techniques:

<u>TIR is controlled by bubble generation:</u>

"Optical switch using bubbles", J. L. Jackel, U.S. Patent No. 4,988,157, granted on January 29, 1991. An optical switch, particularly useful as a bistable cross-connect matrix. Parallel input waveguides and parallel output waveguides are formed on a substrate at perpendicular angles so as to intersect. A 45° slot is formed across each intersection and is filled with a fluid having a refractive index matching the waveguide material. Electrodes are positioned adjacent the slots and are selectively activated to electrolytically convert the fluid to gaseous bubbles, thereby destroying the index matching across the slot and causing light to be reflected by the slot rather than propagating across the slot. In the presence of a catalyst, a pulse of opposite polarity or of sufficient size and of the same polarity will destroy the bubble.

"Fabrication of a total internal reflection optical switch with vertical fluid fill-holes", J. E. Fouquet, etc..., U.S. Patent No. 6,055,344, granted on April 25, 2000. An optical waveguide switching technique is described based TIR caused by thermally generated bubbles inside the index matching liquid which enables optical energy switching between waveguide.

TIR is varied by mechanical movement of index matching material:

"Optical switch", Hiroshi Terui , et al., U.S. Patent No. 4,365,862, granted on December 28, 1982. Waveguide optical switch based on TIR implemented by a movable dielectric chip with a refractive index matching between the substrate and waveguide core.

"Optical switch, and a matrix of such switches", J. Legrand, U.S. Patent No. 4,582,391, granted on April 15, 1986. Optical switch, TIR based, moving member controlled electromagnetically to change water presence.

"Optical switch and Q-switched laser", A. Chandonnet et al., U.S. Patent No. 5,444,723, granted on August 22, 1995. A length of an optical fiber having a core and a surrounding cladding is held by a block with a portion of said length having substantially all of its cladding removed on one side of the portion and being exposed, and an index overlay perturbation pad is mounted near and substantially parallel to the portion. A translator moves the pad between a first position in which the pad is sufficiently remote from the portion to allow total internal reflection in the portion and a second position in which the pad is sufficiently close to the portion to allow light to escape from the core.

TIR is controlled through the change of index of refraction by semiconductor:

"Optical switch", Kunio Tada, U.S. Patent No. 4,832,430, granted on May 23, 1989. Electrodes are provided in the vicinity of the switching region of a carrier injection type optical switch, and carriers are removed rapidly through these electrodes when the switch is turned OFF. TIR is controlled through semiconductor.

"Integrated total internal reflection optical switch utilizing charge storage in a quantum well", G.W. Taylor, et al. U.S. Patent No. 5,329,137, granted on July 12, 1994. An optical switch comprises a heterojunction transistor having a source electrode, a gate, a mesa, and three self-aligned waveguides. A source of optical energy is applied to one of said waveguides, and a total internal reflection is created in the switch by inducing a change in refractive index under the gate by means of a charge applied from the source electrode.

TIR is controlled thermally:

"Thermally driven optical switch method and apparatus", R. R. Hayes, U.S. Patent No. 5,173,956, granted on December 22, 1992. Optical switching between two waveguides with a common cladding interguide region is achieved by passing a current through the interguide region to heat it and thereby alter its refractive index, and controlling the current to control optical switching between the two guides with TIR on and off.

TIR is controlled by incident optical power:

"Optical switch device", W. Chen, U.S. Patent No. 5,018,842, granted on May 28, 1991. An optical power limiter and switch, transparent at low light intensity and opaque at high intensity, is comprised of a pair of right triangular prisms separated by a liquid film whose refractive index changes in response to optical energy turning on or off TIR.

TIR is varied by elecrto-optically controlling poled and unpoled region of crystal:

"Low loss optical switch with inducible refractive index boundary and spaced output target", W. K. Bischel, etc..., U.S. Patent No. 5,911,018, granted on June 8, 1999. An optical waveguide switching technique is implemented based on TIR caused by elecrto-optically controlling poled and unpoled region of crystal for the application of optical display.

As shown above: (1) the prior art of using TIR mainly focused on waveguide switches/applications; (2) TIR come with a number of implementing techniques; (3) there is only one patent (No. 5,911,018) introducing TIR caused by elecrto-optically controlling poled and unpoled region of crystal, but for application of optical display. This situation is commented by Michikazu Kondo (U.S. Patent No. 4,618,210, granted on October 21, 1986.): "as a TIR switch requires an appreciable angle of intersection to achieve sufficiently low cross-talk, a substantial applied voltage is necessary. Since it usually is difficult to construct a high-voltage and yet high-speed driving circuit, a TIR switch is unsuitable for high-speed switching".

In another words, the variation of refractive index caused by elecrto-optically controlling poled and unpoled region of crystal is very small (on the order of $10^{-5} \sim 10^{-4}$). Thus it is not favored by TIR based bulk optical switches in the last decade.

One way to make use of the small variation of refractive index is to create a series of structure through elecrto-optically controlling poled and unpoled region of crystal, which has been used in a refraction based optical beam scanner, as described in the literature "Thin film electro-optic beam deflector using domain reversal in $LiTaO_3$" by Q. Chen, Y. Chiu, D. N. Lambeth, T. E. Schlesinger, D. D. Stancil, CTuN63, CLEO'93 Conference Proceedings, pp 196 et. seq., Optical Society of America. There are two patents which describe methods of implementing such optical scanner at different levels: U.S. Pat. No.4,614,408 and U.S. Pat. No. 5,317,446. The major drawback of using refraction based optical beam scanner in an optical switch is that the maximum switching angle between adjacent channels is about 0.6° for a typical design, and this switching angle is sensitive to the variation of the operating electrical field. While for the same design and operation condition, a TIR based optical switch can easily achieve 5° ~ 6° switching angle between adjacent channels and this angle is independent from the variation of the operating electrical field, which relaxes the engineering constraints of an optical switch design in many aspect and make its manufacture easier.

3. Summary of the Invention

The present invention provides a method for constructing an optical switch. Its switch format can be either 1 × 2, 1 × 3, 1 × 4, 2 x 2 or 4 × 4, etc... Here 4 × 4 format can be a cross connection switch matrix or not, but implemented in a bulk optical switch form. It is also possible to construct a N × N waveguide based switch matrix by using the same technique of this invention.

Such a switch has no moving part, but can switch at very fast speed ($10^{-8} \sim 10^{-10}$ second), important advantageous features for optical switch. Since switching is implemented by controlling the state of TIR, the cross-talk is extremely low and switching is not sensitive to the variation of operating electric field. Depending on the switch format and design approach, an optical switch may be built with simple structure, offer low insertion loss and operate independently from beam polarization and wavelength.

According to the invention, a 1 × N optical switch of simple structure comprises an input fiber collimator, one piece of electro-optic crystal functioning for beam switching and at least two, or more, output fiber collimators. The input fiber collimator has the input beam being collimated for propagating in the free space and entering the switching crystal, which offers the switching capability based on TIR property. The electro-optical crystal has very simple poled and unpoled structures. At any time, one of the output fiber collimators receives the switched beam in free space and couples it into the corresponding fiber.

According to the same principle of this invention, an 2 × 2 optical switch comprises two input fiber collimators, one piece of electro-optic crystal functioning for beam switching and two output fiber collimators. The two input fiber collimators have the input beams being collimated for propagating in the free space and entering the switching crystal, which offers the switching capability based on TIR property. The electro-optical crystal has very simple poled and unpoled structures. Each of the two output fiber collimators receives either output beam in free space and couples it into the corresponding fiber, respectively, depending upon the switch state. A different configuration of the 2 × 2 switch may require beam separating components, which will enable the overall size of the switch to be reduced significantly.

The switching technique of this invention relies on TIR feature. Over a given spectrum of interest, as long as TIR condition is maintained for the longest wavelength, the switch is capable to work for the all wavelengths, and its switching capability is not sensitive to the variation of operating electric field.

This invention will be better understood upon reference to the following detailed description in connection with the accompanying drawings.

4. Brief Description of the Drawing(s)

Fig. 1 is a schematic view of a prior art 1 × 2 switch comprised by elecro-optic crystal which has a complicated poled and unpoled structure, but its switching is implemented based on refraction of polarized beam.

Fig. 2 is a schematic view of a prior art 1 × 4 switch comprised by elecro-optic crystal which has a more complicated poled and unpoled structure, but its switching is implemented based on refraction of polarized beam.

Fig. 3 is a schematic view of the 1st embodiment for 1 × 2 switch comprised by elecro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of polarized or unpolarized beam.

Fig. 4 is a schematic view of the 2nd embodiment for 1 × 3 switch comprised by elecro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of polarized or unpolarized beam.

Fig. 5 is a schematic view of the 3rd embodiment for 1 × 4 switch comprised by elecro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of polarized or unpolarized beam.

Fig. 6 is a schematic view of the fourth embodiment for 2 × 2 switch comprised by elecro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of polarized or unpolarized beam.

Fig. 7 is a schematic view of the fifth embodiment for 2 × 2 switch similar to that of Fig. 6, but has a shorter axial dimension with the help of introduction of two beam separating prisms.

Fig. 8 is a schematic view of a sixth embodiment for 4 × 4 cross connection switch matrix comprised by electro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of a polarized or an unpolarized beam.

Fig. 9 is a schematic view of a seventh embodiment for 4 × 4 switch matrix comprised by electro-optic crystal which has a simple poled and unpoled structure, and its switching is implemented based on TIR of a polarized or an unpolarized beam.

Fig. 10 is a schematic view of an eighth embodiment for 4 × 4 switch matrix similar to that of Fig. 9, but comprised of four segments of electro-optic crystal instead of one single piece.

5. Description of the Preferred Embodiment

Fig. 1 shows a schematic illustration of a prior art refraction based optical scanner, but used as an 1 × 2 optical switch, which has an electrooptic prism structure inside the crystal, where grey area is poled and white area is unpoled. This kind of structure requires specific technique and complicated process for manufacture. The crystal 1 may be either $LiTaO_3$ or $LiNbO_3$ of ~ 0.5 mm thickness. Polarized and collimated light beam 4 of a diameter equal to ~ 0.5 mm emits from the input fiber collimator 2, then enters the crystal 1 and propagates through it. When there is no electric voltage applied between both surfaces of the crystal 1, light beam 4 will exit crystal 1, propagate in a straight path and enter the 1st output fiber collimator 10. When there is a electric voltage applied between both surfaces of the crystal 1, say 950 ~ 1,000 V, light beam 4 will propagate through a series of interfaces defined by area of low (grey) and high (white) reflective index, denoted by 6 and 8 in crystal 1. Now the beam propagation is through a curved path inside crystal 1. When beam exits crystal 1, it will propagate along path 12 and enter the 2nd output fiber collimator 14. For a typical design of prism structure inside the crystal and the voltage given above, the extra-ordinary beam (s wave) deflection angle is around 0.6°.

Fig. 2 shows the same contents as that of Fig. 1, but with two stages of prism structure within one piece of crystal for 1 × 4 optical switch. Again, for a typical design of such poled and unpoled prism structure inside the crystal, the beam deflection angles between adjacent channels are around 0.6°. The major drawbacks associated with this method are: prism structure comprised by poled and unpoled area inside the crystal is complicated to manufacture; the beam deflection angle is sensitive to the variation of operating voltage; the beam deflection angles between adjacent channels is so small that larger working distance, say 60 ~ 100 mm is required from the exit surface of the crystal to the output fiber collimators, in order to separate beams of 0.5 mm in diameter and to avoid cross-talk.

The basic working principle of this invention is described in details for better understanding in the section of the 1st embodiment, as shown in Fig. 3 for a 1 × 2 optical switch based on the TIR method introduced in this invention. It consists of an input fiber collimator 202, a piece of electooptic crystal 200 and two output fiber collimator 208 and 210. The electooptic crystal can be either $LiTaO_3$ or $LiNbO_3$, or others with high electooptic coefficient. Its thickness is around 0.4 ~ 0.5 mm. Inside the crystal, a very simple poled and unpoled structure is created: which are interfaced with each other by a straight line at an angle of ~ 1°. Since many commercially available electrooptic materials are ferroelectric, they exhibit a residual polarization which can be induced electrically by subjecting the material to a high voltage field. In crystal 200, only one of the grey and white areas is electrically poled. Then the poling directions of the two areas are opposite. As a linear material, the change of refractive index of Δn may be expressed by:

$$\Delta n = 0.5 \times n^3 \times r \times V/t$$

where n is the unperturbed refractive index of the crystal, r is the linear elecrtooptic coefficient, V is the magnitude of the controlling electrical field and t is the thickness of the crystal. The sign of the electrooptic coefficient, r, and hence the sign of Δn, depend on the direction of the applied electric field relative to the poling direction. This will maximize the impacts of variation of Δn at given controlling electrical field, which is a merit of deploying poled and unpoled structure within the said crystal.

Since electrooptic materials tend to be anisotropic, both n and r will be of different values for ordinary beams (p wave) and extra-ordinary beams (s wave). Usually an extra-ordinary beam (s wave) exhibits a Δn that is about three times of that of an ordinary beam (p wave) under a given operating condition. This implies that the TIR requirements are easier to achieve for extra-ordinary beams (s wave) in terms of operating voltage and the length of TIR surface. When the TIR requirements are maintained only for extra-ordinary beams (s wave), the said switch is a polarization maintaining switch. If higher operating voltage is applied, or the incident beam's grazing angle is further reduced and the TIR surface length becomes longer, the TIR requirements are maintained not only for extra-ordinary beams (s wave), but also for ordinary beams (p wave), the said switch is a polarization independent switch. This is another attractive and important feature of this invention.

In Fig. 3, the collimated beam is launched from the input collimator 202 and enters the crystal 200 along the straight path 203. If there is no electrical field applied, the beam will propagate, exit the crystal 200 and enters the 1st input collimator 208. If there is a electrical field applied, which is applied in such a way that the white area of the crystal has a higher refractive index and the grey area of the crystal has a lower refractive index and TIR condition is met, then the beam is reflected at the interface 205, then exits the crystal 200 and propagates along path 207 to enter the 2nd collimator 210. This TIR based switch principle works for both ordinary beams (p wave) and extra-ordinary beams (s wave), but the ordinary beams (p wave) in general require a higher voltage of electrical field, or smaller grazing angle and longer TIR surface than extra-ordinary beams (s wave). As long as TIR is achieved for the ordinary beam (p wave), TIR is also set up for the extra-ordinary beam (s wave). Then a polarization independent 1×2 optical switch is obtained. For $LiNbO_3$ crystal of 0.4 mm thickness operated by 775 V electrical field, the switching angles between adjacent channels can be 2.3° for polarization independent switch and ~ 5° for polarization maintaining switch. If the switching electrical field is controlled by three phases, i.e. 0/0, +V/0 and 0/-V, then the 3rd channel is created at the interface between white and grey area based on refraction, then what is shown in Fig. 3 can be used as a design approach for 1×3 optical switch.

The refractive index n is a function of wavelength. For longer wavelengths the values of n become smaller regardless of the extra-ordinary beam or ordinary beam. When a stream of wavelengths are launched into the said switch, for example, from 1520 to 1620 nm of the whole C and L bands, as long as TIR is maintained for the longest wavelength, TIR is also maintained for all shorter wavelengths. This means the said 1×2 optical switch functions independently from wavelengths. This is another very attractive and important feature of this invention for the switch application in WDM/DWDM network system.

The above description of working principle of the TIR based switch together with its features for the 1st embodiment apply to all of other embodiments to be discussed below.

Fig. 4 shows the 2nd embodiment of a 1×3 optical switch based on the TIR method introduced in this invention. Its working principle is same as that of the 1st embodiment.

It consists of an input fiber collimator 302, one piece of electrooptic crystal 300, which has four poled and unpoled sections, three output fiber collimator 318, 320 and 322. Its switch controlling electrode has two separate sections: one is on the left and the other is on the right. A collimated beam emits from the input collimator 302 and propagate along the straight path 304 and enters the crystal 300. At switch position one: no electrical field is applied, beam will propagate along a straight path within the crystal 300 and exits, continues propagation along path 304 until entering the output collimator 318. At switch position two: controlling electrical field is applied on the left side electrode such that TIR is achieved at the interface of area 306 and 308 where beam is reflected. The reflected beam exits from crystal 300 and propagates along path 314 to enter the second output collimator 320. At switch position three: controlling electrical field is applied on the right side electrode such that TIR is achieved at the interface of area 310 and 312 where beam is reflected. The reflected beam exits from crystal 300 and propagates along path 316 to enter the third output collimator 322. Again, when TIR is achieved for ordinary beams (p wave), TIR is also set up for extra-ordinary beams (s wave). Wavelength independent feature is also achievable.

Fig. 5 shows the 3rd embodiment of a 1 × 4 optical switch based on the TIR method introduced in this invention. Its working principle is same as that of the 1st embodiment. It consists of an input fiber collimator 402, one piece of electrooptic crystal 400, which has five poled and unpoled sections, four output fiber collimator 434, 436, 438 and 440. Its switch controlling electrode has two separate sections: one is on the left and the other is on the right. A collimated beam emits from the input collimator 402 and propagates along the straight path 404 and enters the crystal 400. At switch position one: no electrical field is applied, beam will propagate along a straight path within the crystal 400 and exits, continues propagation along path 404 until entering the output collimator 434. At switch position two: controlling electrical field is applied on the left side electrode such that TIR is achieved at the interface of area 406 and 408 where beam is reflected. The reflected beam exits from crystal 400 and propagates along path 416 to enter the second output collimator 436. At switch position three: controlling electrical field is applied on the right side electrode such that TIR is achieved at the interface of area 412 and 414 where beam is reflected. The reflected beam exits from crystal 400 and propagates along path 418 to enter the third output collimator 438. At switch position four: controlling electrical field is applied on both sides of electrodes such that TIR is achieved at the interfaces of area 406 and 408, 410 and 414, where beam is reflected twice. The reflected beam exits from crystal 400 and propagates along path 420 to enter the forth output collimator 440. Again, when TIR is achieved for the ordinary beams (p wave), TIR is also set up for the extra-ordinary beams (s wave). Wavelength independent feature is also achievable.

The fourth embodiment is a more preferred one and is shown in Fig. 6, which is a 2 × 2 optical switch based on the TIR method introduced in this invention. This switch has a symmetrical structure. Its working principle is same as that of the 1st embodiment. It consists of two input fiber collimator 502 and 504, one piece of electrooptic crystal 500, which has a simple sandwich structure of poled and unpoled areas, two output fiber collimator 538 and 540. Its switch controlling electrode covers the whole areas of

520,522 and 524. Area 524 is very thin in order to minimize the beam walk-off as beams are switched. At switch position one: no electrical field is applied. A collimated beam emits from the input collimator 502, propagates along the straight path 506, penetrates crystal 500 and propagates along the straight path 530 to enter the output collimator 538. Meanwhile, a collimated beam emits from the input collimator 504, propagates along the straight path 508, penetrates crystal 500 and propagates along the straight path 532 to enter the output collimator 540. At switch position two: controlling electrical field is applied such that TIR is achieved at the interfaces of area 520 and 524, 522 and 524, where beam from collimator 502 along path 506 is reflected to path 532 to enter collimator 540, and beam from collimator 504 along path 508 is reflected to path 530 to enter collimator 538. Again, when TIR is achieved for the ordinary beams (p wave), TIR is also set up for the extra-ordinary beams (s wave). Wavelength independent feature is also achievable for WDM/DWDM requirements.

The fifth embodiment is similar to the fourth embodiment and is shown in Fig. 6, which is also a 2 × 2 optical switch with symmetrical structure, but including two beam separating prisms, allowing the axial dimension of the switch to be reduced. It consists of two input fiber collimator 602 and 604, one beam separating prism 610 at input end, one piece of electrooptic crystal 600, which has a simple sandwich structure of poled and unpoled areas, one beam separating prism 630 at output end, two output fiber collimator 638 and 640. Its switch controlling electrode covers the whole crystal areas of 620,622 and 624. Area 624 is very thin in order to minimize the beam walk-off as beams are switched. At the input and output ends of the crystal 600, both the entrance and exit surfaces are polished with a small minus/plus angle that equals to the incident beam grazing angle such that beams will not experience any refraction as they enter and exit crystal 600. This eliminates another kind of beam walk-off between the ordinary beams (p wave) and extra-ordinary beams (s wave), which otherwise will lead to extra polarization dependent loss (PDL). As result of this, beam separating angle between the two output channels will be around 1.2°, which is too small to separate the two output beams within short distance and the two beam separating prisms are used to improve the situation. The switching function is fulfilled in the same way as the last embodiment. This embodiment is particularly useful for a polarization independent switch. Again, wavelength independent feature is also achievable for WDM/DWDM requirements.

Fig. 8 shows the 6th embodiment of a 4 × 4 cross connection switch matrix based on the TIR method introduced in this invention. Its working principle is same as that of the 1st embodiment. It consists of four input fiber collimators (720, 722, 724, 726), seven pieces of electro-optic crystal (702, 704, 706, 708, 710, 712, 714, 716), four output fiber collimators (780, 782, 784, 786). Each of those crystal piece has poled and unpoled sections. There are 15 pairs of switch controlling electrodes: each of them is placed over the interfaces of poled and unpoled sections. Collimated beams emit from the input collimator 720, 722, 724, 726 and propagates along the straight path 730, 732, 734 and 736, respectively. These four paths set up 16 intersection points with the four output path lines 770, 772, 774 and 776 defined by the four output collimators (780, 782, 784, 786). At any moment, four pairs of switch controlling electrodes will be turned on to set up TIR condition: which leads to 24 non-redundant cross-connection combinations between the four input collimators and four output collimators. When the intersection of path line 730 and 770 is needed to be selected, there will be three pairs of switch controlling electrodes turned on since the crystal-air interface always maintains TIR. Again, when TIR is achieved for the ordinary beams (p wave), TIR is also set up for the extra-ordinary beams (s wave). Wavelength independent feature is also achievable.

Fig. 9 shows the 7th embodiment of a 4 × 4 switch matrix based on the TIR method introduced in this invention. Its working principle is same as that of the 1st embodiment. It consists of four input fiber collimators (820, 822, 824, 826), one major piece of electro-optic crystal (800) plus two pieces of crystal (802, 804) for setting up entrance path for beam 830 and 836, four output fiber collimators (880, 882, 884, 886). The main crystal piece has five poled and unpoled sections, each of which functions as 2 × 2 switch node. There are 5 pairs of switch controlling electrodes: each of them is placed over the 2 × 2 poled and unpoled sections. Collimated beams emit from the input collimator 820, 822, 824, 826 and propagates along the straight path 830, 832, 834 and 836, respectively. Along these four paths light beams intersect with the five 2 × 2 switch nodes and the two air-crystal TIR surfaces and exit the crystal along the four output path lines 870, 872, 874 and 876 to enter the four output collimators (880, 882, 884, 886). At any moment, from zero to five pairs of switch controlling electrodes will be turned on to set up TIR condition: which leads to 24 non-redundant cross-connection combinations between the four input collimators and four output collimators. Compared with the 6th embodiment, this 4 × 4 configuration has the least redundancy of switching mechanism. It is a suitable design solution for polarization maintaining switch matrix, i.e. TIR is only achieved for the extra-ordinary beams (s wave), since it is feasible to fabricate the said switch matrix structure from a single piece of wafer (~ 4 inch in diameter) of electro-optic crystal in practice.

Fig. 10 shows the 8th embodiment of a 4 × 4 switch matrix based on the TIR method introduced in this invention. Its working principle is same as that of the 1st embodiment. It consists of four input fiber collimators (920, 922, 924, 926), four pieces of electro-optic crystal 902, 904, 906 and 908, four output fiber collimators (980, 982, 984, 986). Crystal 902 has one poled and unpoled section; crystal 904 and 908 have two poled and unpoled sections, respectively. Each of the poled and unpoled section functions as a 2 × 2 switch node. There are 5 pairs of switch controlling electrodes: each of them is placed over the 2 × 2 poled and unpoled sections. Collimated beams emit from the input collimator 920, 922, 924, 926 and propagates along the straight path 930, 932, 934 and 936, respectively. Along these four paths light beams intersect with the five 2 × 2 switch nodes and the two air-crystal TIR surfaces and exit the crystal along the four output path lines 970, 972, 974 and 976 to enter the four output collimators (980, 982, 984, 986). At any moment, from zero to five pairs of switch controlling electrodes will be turned on to set up TIR condition: which leads to 24 non-redundant cross-connection combinations between the four input collimators and four output collimators. Compared with the 6th embodiment, this 4 × 4 configuration also has the least redundancy of switching mechanism. Because separate segments of electro-optic crystal are used, TIR surfaces of longer length can be fabricated, and when TIR is achieved for the ordinary beams (p wave), TIR is also set up for the extra-ordinary beams (s wave). Wavelength independent feature is also achievable.

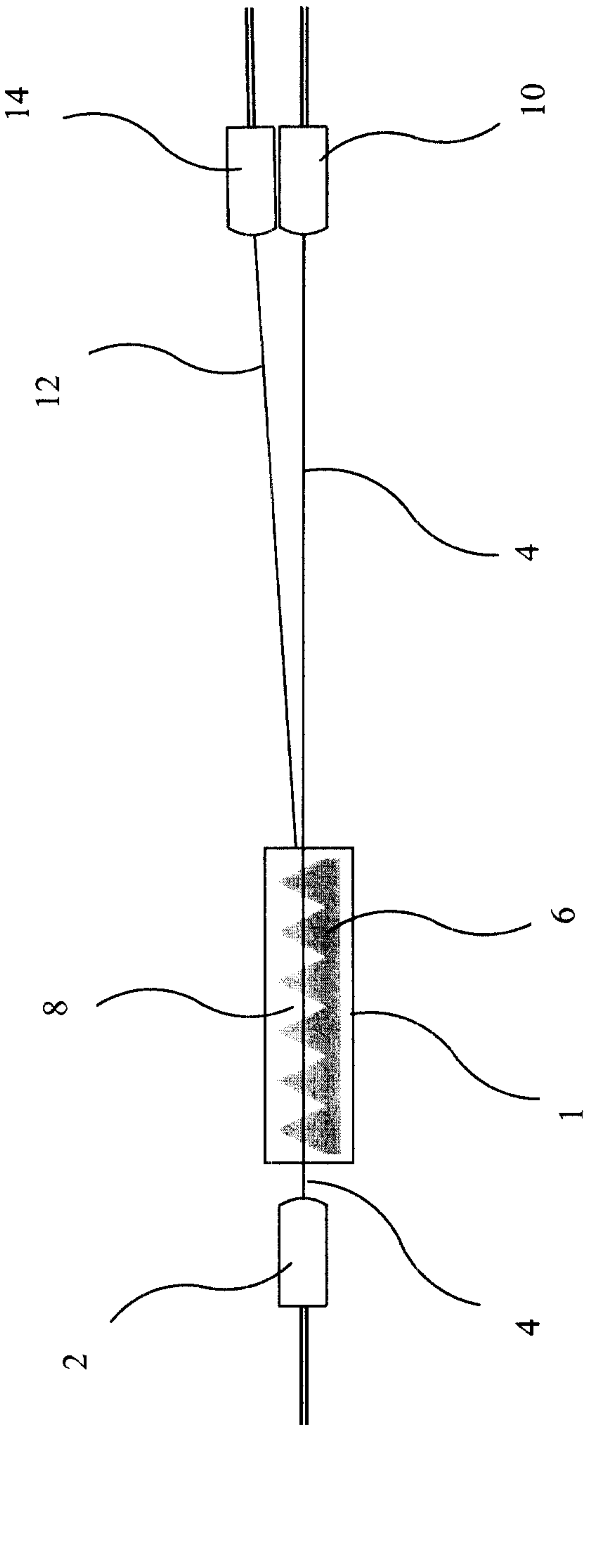


Fig. 1

Prior art

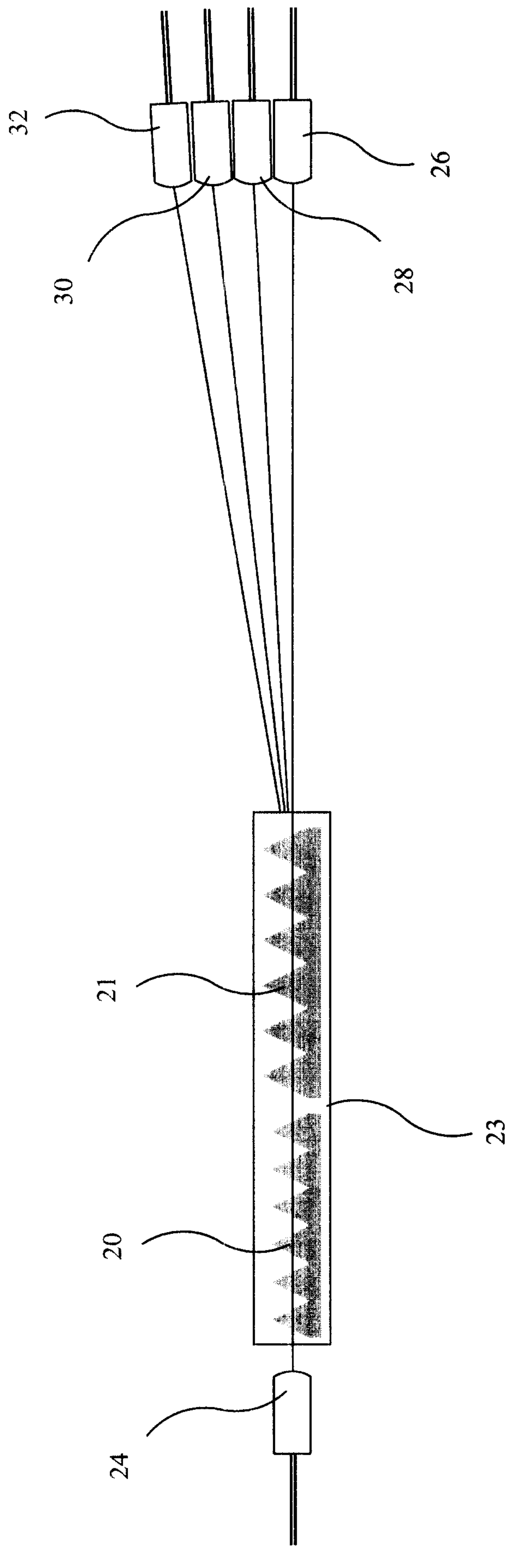


Fig. 2

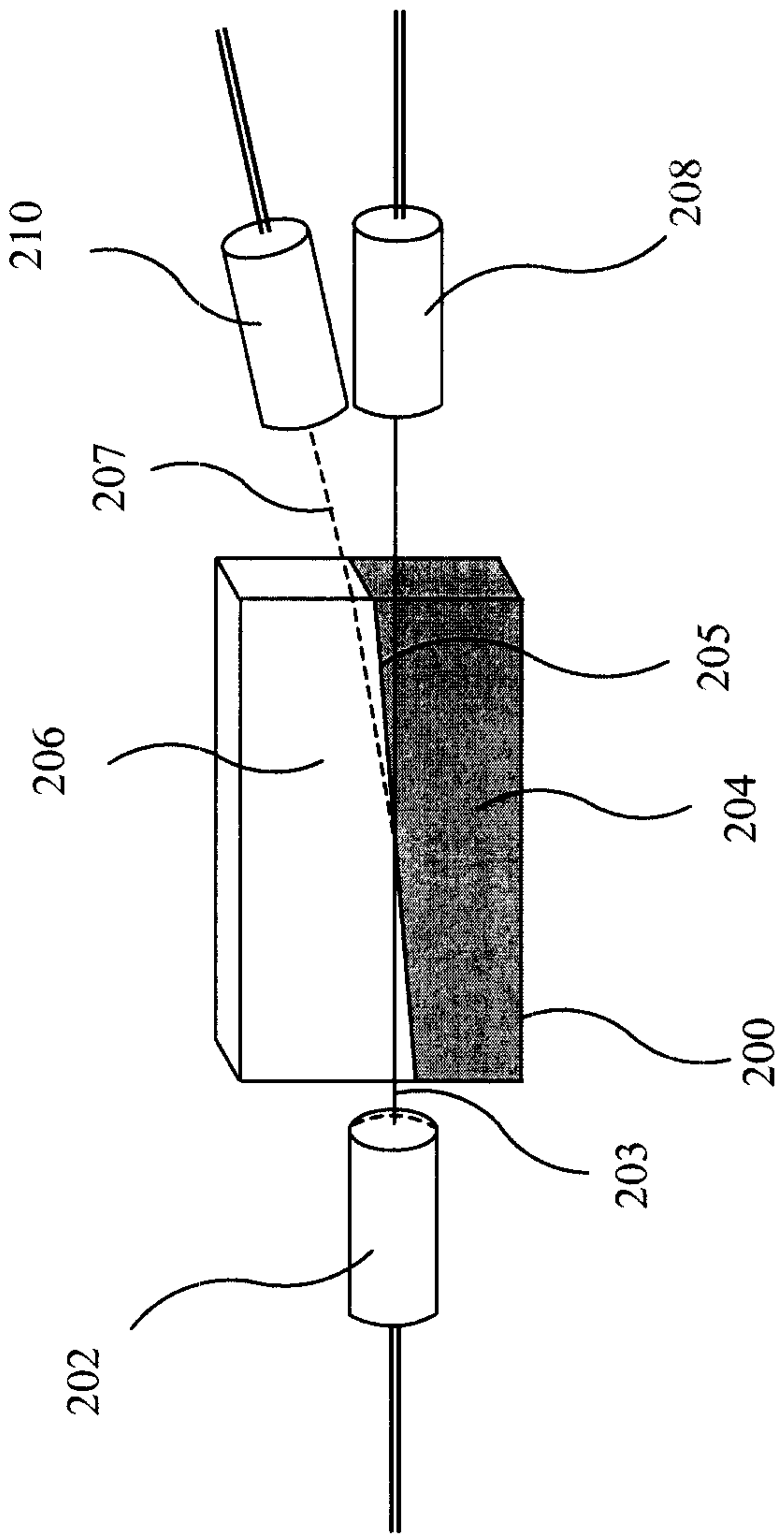


Fig. 3 (a)

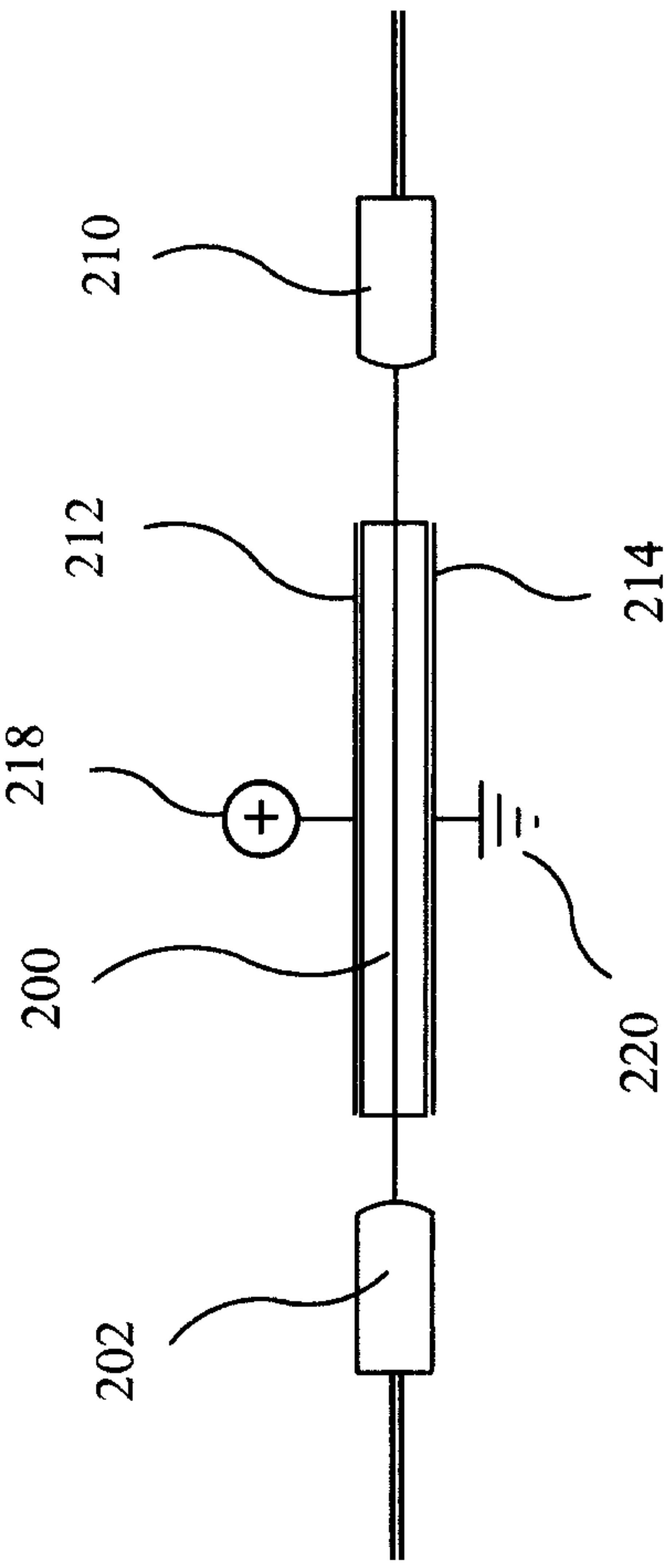


Fig. 3 (b)

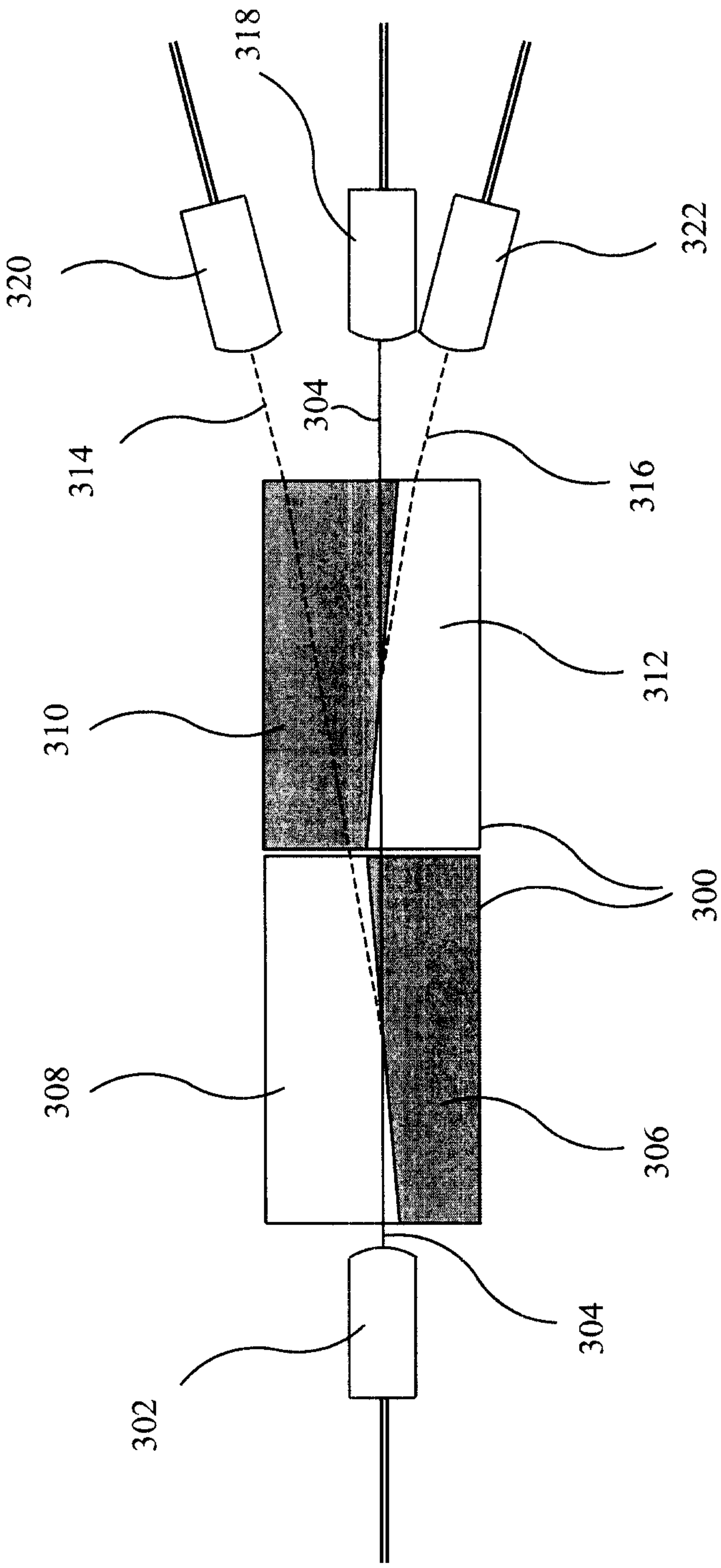


Fig. 4

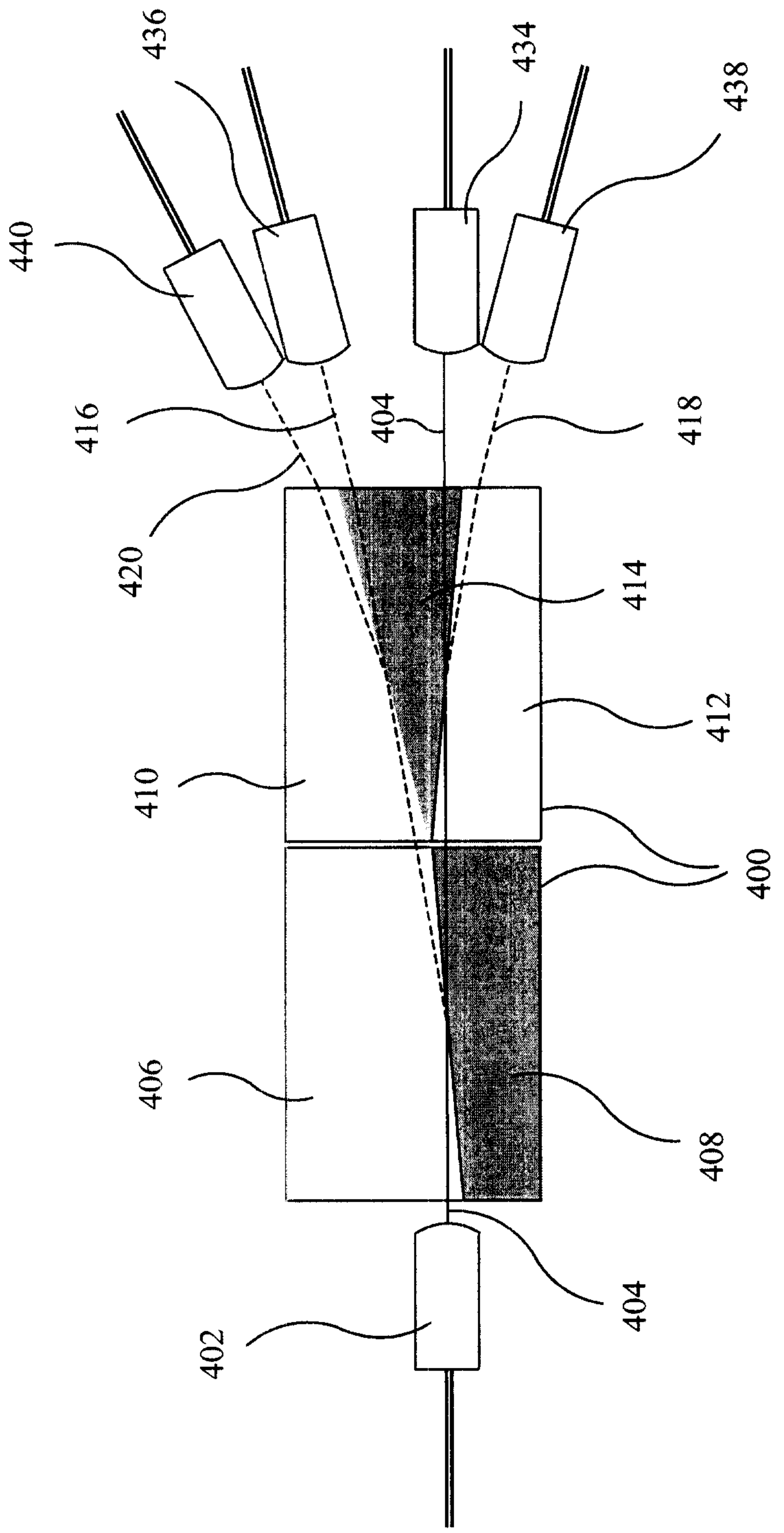


Fig. 5

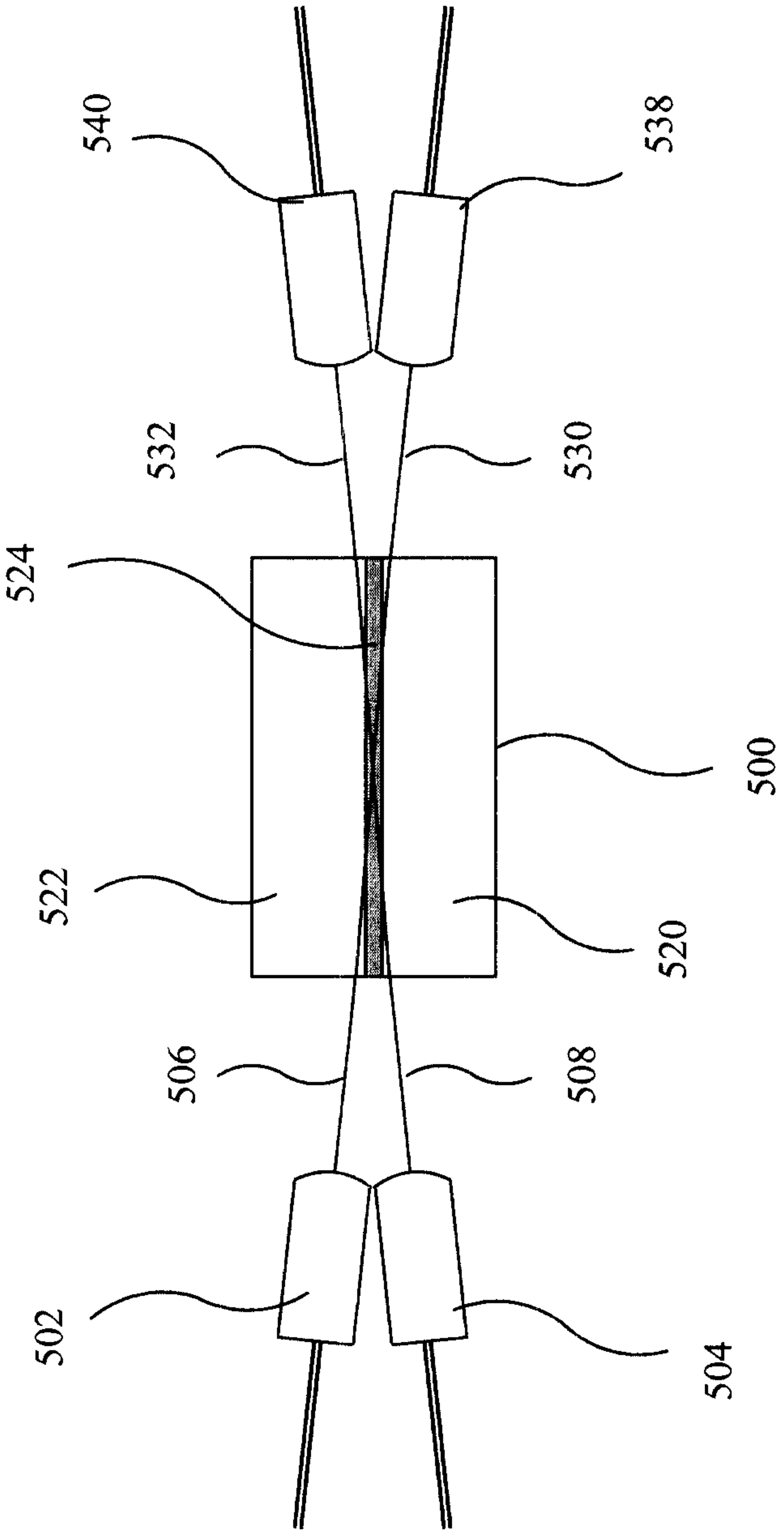


Fig. 6

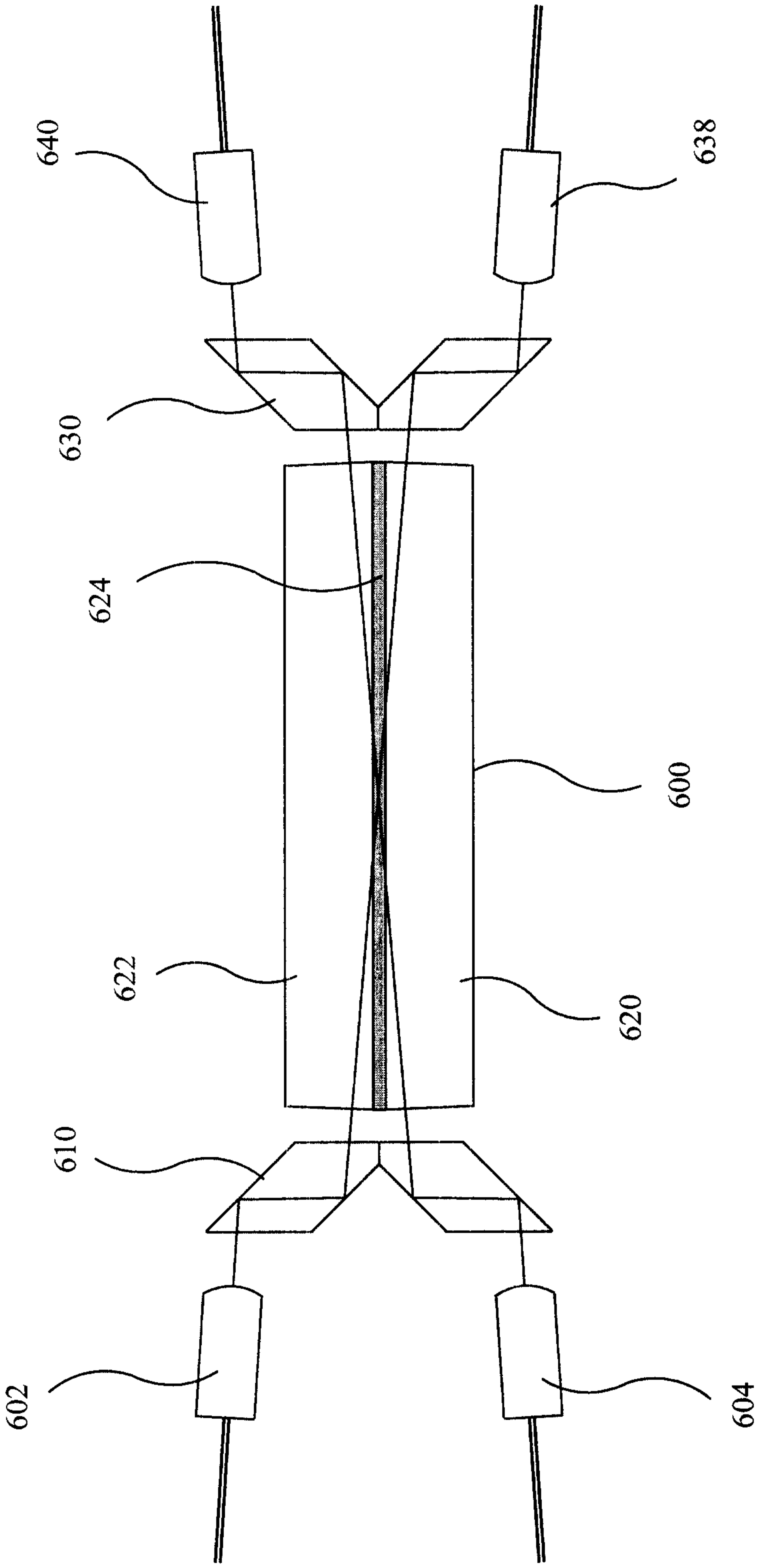


Fig. 7

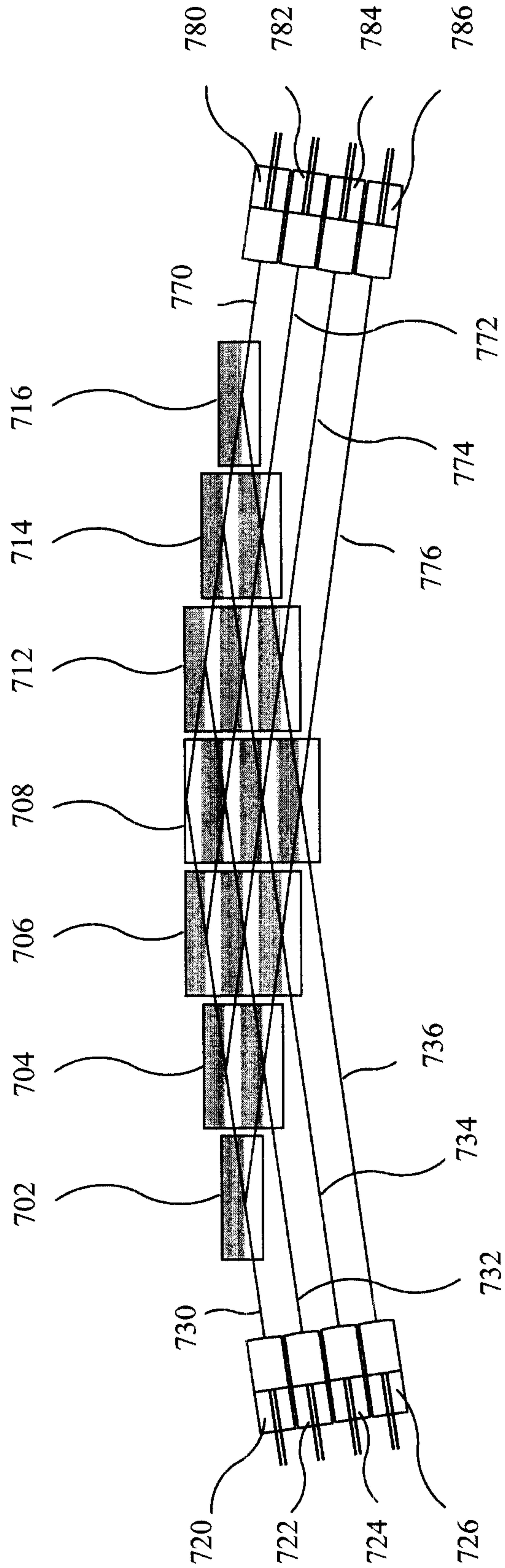

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Fig. 8

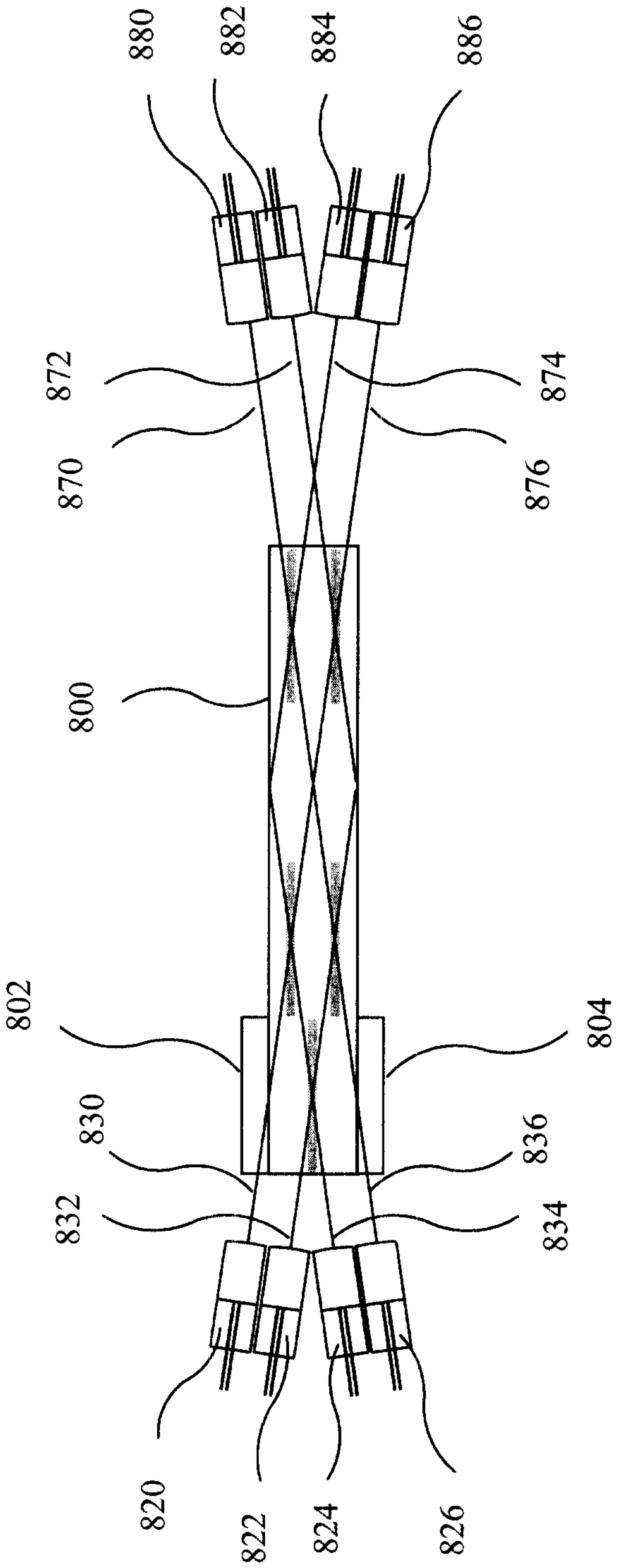
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Fig. 9

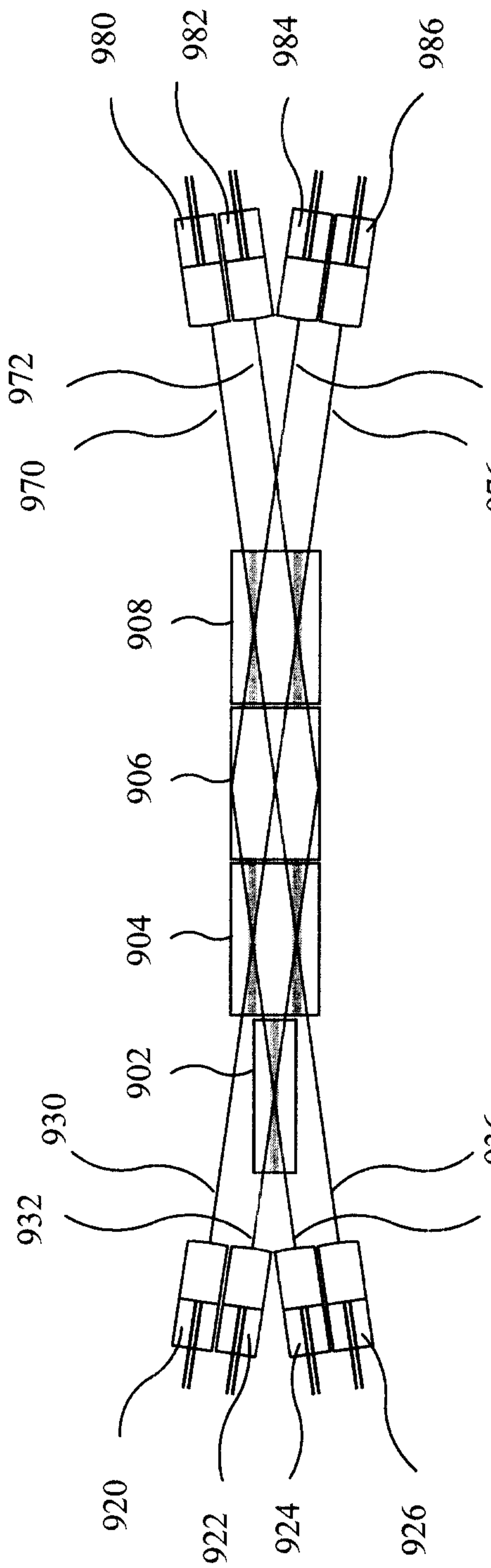
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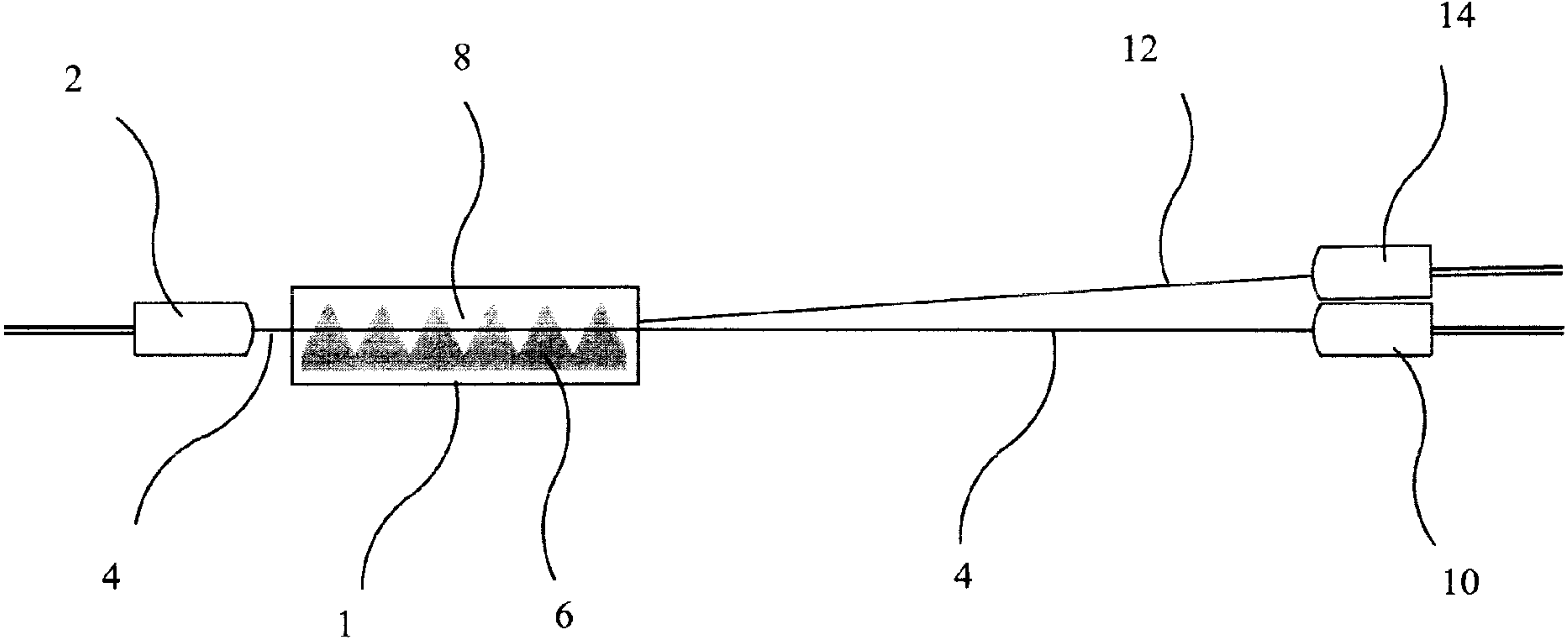
Fig. 10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