PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G02B 5/30	A1	(11) International Publication Number: WO 99/12061 (43) International Publication Date: 11 March 1999 (11.03.99)

(21) International Application Number: PCT/US98/14703

(22) International Filing Date: 15 July 1998 (15.07.98)

(30) Priority Data:
08/923,664 4 September 1997 (04.09.97) US

(71) Applicant: U.S.A. KAIFA TECHNOLOGY, INC. [US/US]; 388 Oakmead Parkway, Sunnyvale, CA 94086 (US).

(72) Inventors: LI, Wei-Zhong; 1829 Glacier Bay Terrace, San Jose, CA 95131 (US). AU-YEUNG, Vincent; 24965 La Loma Drive, Los Altos, CA 94022 (US). GUO, Qingdong; 1285 Torrance Avenue, Sunnyvale, CA 94089 (US).

(74) Agent: ALBOSZTA, Marek; 426 Lowell Avenue, Palo Alto, CA 94301 (US).

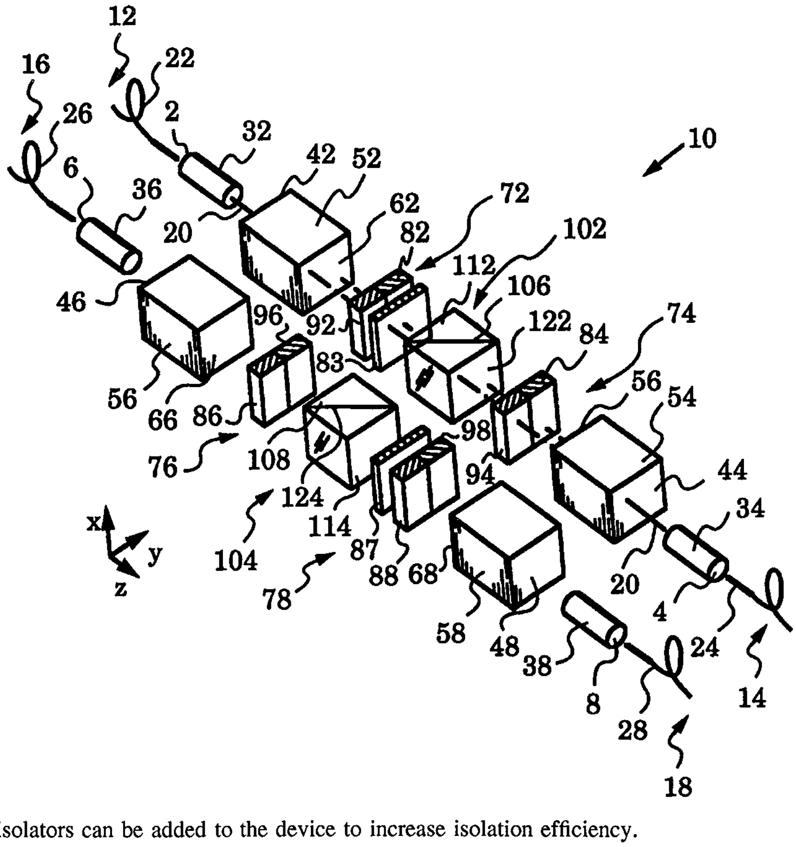
(81) Designated States: AU, CA, CN, JP, KP, KR, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: MULTIPORT NON-RECIPROCAL OPTICAL DEVICE

(57) Abstract

A multi-port non-reciprocal optical device with ports (12, 14, 16, 18) for receiving and emitting a light beam consisting of a first polarization and of a second polarization orthogonal to the first polarization. The device uses birefringent walk-off elements (52, 54, 56, 58), preferably birefringent crystals with optical axes oriented at 45 degrees to the axes defining the input facets of the birefringent crystal. The crystals are positioned between the ports to split the advancing light beam along a first diagonal into an ordinary beam of the first polarization and an extraordinary beam of the second polarization. Conversely, the walk-off elements combine the ordinary beam and the extraordinary beam on the reverse or return path along the diagonal to reconstruct the light beam. Paris of non-reciprocal rotation elements (72, 74, 76, 78) are placed in the paths of the ordinary and extraordinary beams to rotate the polarizations by 45 degrees and render them parallel or orthogonal, such that a polarization dependent deflecting element, e.g., a polarizing beam splitter/combiner (PSC) (102, 104) transmits or reflects both beams. The device can function as an optical circulator, isolator, attenuator or switch. Polarizers and/or free space isolators can be added to the device to increase isolation efficiency.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	**ES**	Spain	**LS**	Lesotho	**SI**	Slovenia
AM	Armenia	**FI**	Finland	**LT**	Lithuania	**SK**	Slovakia
AT	Austria	**FR**	France	**LU**	Luxembourg	**SN**	Senegal
AU	Australia	**GA**	Gabon	**LV**	Latvia	**SZ**	Swaziland
AZ	Azerbaijan	**GB**	United Kingdom	**MC**	Monaco	**TD**	Chad
BA	Bosnia and Herzegovina	**GE**	Georgia	**MD**	Republic of Moldova	**TG**	Togo
BB	Barbados	**GH**	Ghana	**MG**	Madagascar	**TJ**	Tajikistan
BE	Belgium	**GN**	Guinea	**MK**	The former Yugoslav Republic of Macedonia	**TM**	Turkmenistan
BF	Burkina Faso	**GR**	Greece			**TR**	Turkey
BG	Bulgaria	**HU**	Hungary	**ML**	Mali	**TT**	Trinidad and Tobago
BJ	Benin	**IE**	Ireland	**MN**	Mongolia	**UA**	Ukraine
BR	Brazil	**IL**	Israel	**MR**	Mauritania	**UG**	Uganda
BY	Belarus	**IS**	Iceland	**MW**	Malawi	**US**	United States of America
CA	Canada	**IT**	Italy	**MX**	Mexico	**UZ**	Uzbekistan
CF	Central African Republic	**JP**	Japan	**NE**	Niger	**VN**	Viet Nam
CG	Congo	**KE**	Kenya	**NL**	Netherlands	**YU**	Yugoslavia
CH	Switzerland	**KG**	Kyrgyzstan	**NO**	Norway	**ZW**	Zimbabwe
CI	Côte d'Ivoire	**KP**	Democratic People's Republic of Korea	**NZ**	New Zealand		
CM	Cameroon			**PL**	Poland		
CN	China	**KR**	Republic of Korea	**PT**	Portugal		
CU	Cuba	**KZ**	Kazakstan	**RO**	Romania		
CZ	Czech Republic	**LC**	Saint Lucia	**RU**	Russian Federation		
DE	Germany	**LI**	Liechtenstein	**SD**	Sudan		
DK	Denmark	**LK**	Sri Lanka	**SE**	Sweden		
EE	Estonia	**LR**	Liberia	**SG**	Singapore		

Multiport Non-Reciprocal Optical Device

FIELD OF THE INVENTION

This invention relates generally to non-reciprocal optical devices, and in particular to optical circulators, isolators and other optical devices using birefringent walk-off elements as polarization splitters and combiners (PSCs).

BACKGROUND OF THE INVENTION

Single mode optical fiber has gained rapid acceptance in a variety of actual and proposed optical communications systems (e.g., CATV, fiber to the home (FTTH), wavelength division multiplexed (WDM) transmission systems, and coherent communications). These technologies require versatile optical devices to perform functions such as isolating and routing of light beams.

Currently known optical isolators and circulators are only partially successful in satisfying the above requirements. To be practical these components must not only be easy and inexpensive to manufacture. In addition, they have to exhibit low insertion loss at the transmission wavelengths and high isolation of unwanted signals (e.g., reflection). Isolation is particularly critical in many systems sensitive to spurious reflection. For example, distributed feedback (DFB) lasers tend to be unstable when their output couples back into the lasing cavity. While expense is important in nearly all applications, it is particularly critical in high volume, low-cost projects such as FTTH. Isolation and expense are also common issues in systems using optical amplifiers. That is because reflections can induce an amplifier to oscillate.

The disadvantage of primary non-reciprocal function devices is that their characteristics depend on the polarization of the input light. To solve this problem and render the devices insensitive to different polarization states, PSCs were incorporated into primary non-reciprocal devices. In the resulting polarization independent units an input PSC divides the input light beam into two light beams of linear and mutually orthogonal polarizations. These two beams pass through a reciprocal rotator and a non-reciprocal rotator, and are then combined by an output PSC.

Several polarization independent optical circulators utilizing that technique are reported. Unfortunately, their isolation levels, which were about 25 dB for a single stage circulator, remain too low for practical use. This low figure is due to rather low extinction ratios of PSCs. Recently, attempts have been made at diminishing the degrading effects on isolation deriving from imperfect polarization separation of conventional PSCs.

Thus, Yohji Fujii reports in *High Isolation Polarization Independent Optical Circulator Coupled with Single-Mode Fibers* (Journal of Lightwave Technology, Vol. 9, No. 4, April 1991) how adding birefringent plates to a conventional optical circulator obtains higher isolation. The measured isolation ranged from 29.9 to 36.79 dB. Although this approach does yield a high degree of isolation, it also creates problems. The circulator structure is intricate and the fabrication of the cross-stack polarization beam splitters is very difficult.

In *Polarization Independent Optical Circulator having High Isolation over a Wide Wavelength Range* (IEEE Photonics Technology Letters, Vol. 4, No. 2, February 1992) Yohji discloses a circulator exhibiting the same desirable isolation characteristics. This circulator is made by replacing the cross-stack polarization beam splitter with a conventional PSC containing birefringent crystal blocks. Insertion loss and isolation of a four-port circulator made in this mãnner were measured at ≤ 1.9 dB and ≥ 42.3 dB, respectively. Unfortunately, four non-reciprocal rotators, eight reciprocal rotators, four birefringent crystal blocks and one common PSC are required to assemble such a circulator. This increases insertion loss, complexity and cost. Moreover, the use of many components with different thermal expansion coefficients results in poor mechanical and temperature stability in environments where wide temperature variations are experienced (e.g., FTTH).

In U.S. Patent 5,471,340 Yihao Cheng and Gary S. Duck disclose a circulator consisting of polarization dependent displacement elements, Faraday rotators, half-wave plates and a mirror which reflects the light to the next port. One advantage of this system is that the same optical element is used to separate and combine the light beams. Thus, the problems associated with tight tolerances imposed on systems with numerous components are avoided. Unfortunately, this also means that large size birefringent materials are needed to achieve sufficient separation between two differently polarized beams for collimator alignments. Consequently, the size and cost of the device increase. Furthermore, the use of half-wave plates not only decreases the extinction ratio of polarization rotation, which again reduces the isolation of the circulator, but also increases manufacturing complexity because of the necessity for optical axis alignment.

U.S. Patent 5,319,483 to Krasinski et al. addresses a polarization independent low cross-talk optical circulator. This device uses reciprocal Faraday rotation elements for controlling the polarization of the light beams. The extinction rate for this circulator is fairly low. Furthermore, the overall structure of the device is complex and its many parts necessitate exact alignment procedures. As a result, the manufacture of this device is costly and difficult.

Similarly, U.S. Patents 5,212,586 to Van Delden and 4,464,022 to Emkey describe circulators which use reciprocal Faraday rotators and require many parts. Emkey attempts to solve the separation problem by suitably shaping (slotting) the components. Van Delden solution requires very precise alignment of output ports. In both instances the manufacture is complicated. Also, the isolation is not sufficient for practical applications in new technologies (e.g., FTTH or WDM communications).

Finally, in U.S. Patent 5,204,771, Koga discloses an optical circulator which takes advantage of a pair of Faraday rotators with opposite directions of rotation. Although this device has fewer elements, its construction still requires precise alignment of the optical axis for the rotation elements. The walk-off or beam separation technique used by Koga relies on large birefringent crystals. This results in the whole device being unnecessarily sizable. Furthermore, its isolation is also rather low.

Thus, there remains a need for a single mode optical circulator, or non-reciprocal device, which has a low insertion loss and high isolation, yet can be easily manufactured and exhibits good mechanical and thermal stability. To ensure simple and low-cost manufacture, such device should not rely exclusively on half-wave plates or other rotators which require precise alignment of the optical axis.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a multi-port non-reciprocal optical device, such as an optical circulator, an optical switch or an optical attenuator with low insertion loss and a high extinction ratio in polarization separation. In particular, the invention aims at achieving a high extinction ratio in the PSC.

Another object of the invention is to reduce the size of the device by optimizing the polarization separation performance of the birefringent walk-off elements.

It is also an object of the invention to employ non-reciprocal Faraday rotators in the device whenever possible and thereby reduce the optical axis alignment requirements imposed by reciprocal rotators. This will provide for simpler design and decrease the high rotation extinction ratio associated with reciprocal rotators.

Still another object of the invention is to ensure that the device makes use of the fewest parts possible and is easy to fabricate.

These and other objects and advantages will become more apparent after consideration of the ensuing description and the accompanying drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a multi-port non-reciprocal optical device with at least two ports for receiving and emitting a light beam. The light beam consists of radiation of a first polarization and of a second polarization orthogonal to the first polarization. A first birefringent walk-off element, preferably a birefringent crystal made of a material selected from among rutile, calcite and Yittrium Orthovanadate, is positioned between the ports. The walk-off element splits the advancing light beam along a first diagonal into an ordinary beam of the first polarization and an extraordinary beam of the second polarization. Conversely, the walk-off element combines the ordinary beam and the extraordinary beam on the reverse or return path along the diagonal to reconstruct the light beam.

A pair of reciprocal rotation elements, such as half-wave plates are placed in the paths of the ordinary and extraordinary beams to render the first and second polarizations parallel. This is done, for example, by rotating the first polarization by 45° and the second polarization by 45° as well, such that both polarizations are oriented in a common polarization direction. When necessary, a polarizer having its polarization axis parallel to the common polarization direction can be used at any stage in the device of the invention to ensure that only the correct polarization passes through. Any type of polarizing element can be employed for this purpose.

A polarization dependent deflecting element, e.g., a polarizing splitter combiner (PSC), receives the ordinary beam and the extraordinary beam. The deflecting element is characterized by a reflecting polarization and a transmitting polarization which is orthogonal to the reflecting polarization. The deflecting element can be a polarizing beam splitter. Preferably, the beam splitter is made of a pair of right angle prisms cemented hypotenuse-face to hypotenuse-face. Furthermore, a multilayer dielectric film is preferably placed between the pair of prisms. Thus, when the polarization of the ordinary and extraordinary beams correspond to the transmitting polarization the beam splitter passes them. In the other case, when the polarizations of these beams are parallel to the reflecting polarization, the beam splitter reflects both.

A pair of reciprocal rotation elements such as half-wave plates or non-reciprocal rotation elements, preferably non-reciprocal Faraday rotators such as latching Faraday rotators or ordinary Faraday rotators, is placed in the paths of the ordinary and extraordinary beams for rendering the first and second polarizations orthogonal. This is best accomplished by rotating the first polarization by 45° and also rotating the second polarization by 45°. If half-wave plates are used, a polarizer can be placed between the beam splitter and the half-wave plates to ensure that the polarizations of the two beams are parallel and that only the correct polarization passes through.

A second birefringent walk-off element is positioned between the ports for splitting the light beam or combining the ordinary and extraordinary beams. This element is analogous to the first one. Preferably, both walk-off elements have their optical axes oriented at 45° to the axes (x and y) defining input facets of the birefringent crystal.

The input ports are GRIN lenses. These are well-suited for receiving and emitting the light beam. Further, the light beam can be received and emitted by single mode or multi-mode optical fibers. The number of ports may vary.

The use of reciprocal rotators such as half-wave plates after the first walk-off element and before the last is desirable since non-reciprocal rotation elements such as Faraday rotators introduce optical path aberrations up to 1° due to tolerances in manufacturing. The aberration must be checked for each Faraday rotator. Half-wave plates are uniform, inexpensive and reliable. Circulators using half-wave plates have lower insertion losses, lower polarization dependent losses and higher overall efficiency.

A detailed description of the method is set forth below in reference to the drawing figures.

DESCRIPTION OF THE FIGURES

Fig. **1** is an isometric view of a multi-port non-reciprocal optical device according to the invention.

Fig. **2** is an isometric view of a walk-off element from the device of Fig. 1.

Fig. **3** is an isometric view of a pair of half-wave plates ad a polarizer from the device of Fig. 1.

Fig. **4A-C** are diagrammatic views illustrating the polarization rotations in the device of Fig. 1.

Fig. **5** is an isometric view of a pair of Faraday rotators from the device of Fig. 1.

Fig. **6** is a plan top view of a different non-reciprocal optical device according to the invention.

Fig. **7A-C** are diagrammatic views illustrating the polarization rotations in the device of Fig. 6.

Fig. **8** is a plan top view of yet another non-reciprocal optical device according to the invention.

Fig. **9A-C** are diagrammatic views illustrating the polarization rotations in the device of Fig. 8.

Fig. **10** is a plan top view of a three-port circulator according to the invention.

DETAILED DESCRIPTION

An embodiment of a four port non-reciprocal optical device **10** according to the invention is shown in Fig. 1. For clarity device **10** is depicted in an exploded but aligned state. A Cartesian coordinate system is used to clearly identify the various directions and orientations. Device **10** has four ports **12**, **14**, **16** and **18** fed by corresponding optical fibers **22**, **24**, **26** and **28**. All ports **12**, **14**, **16** and **18** are designed for receiving and emitting light. Fibers **22**, **24**, **26** and **28** are multi-mode or single mode fibers. Lenses **32**, **34**, **36** and **38** assigned to corresponding ports **12**, **14**, **16** and **18** serve to couple light into and out of device **10**. It is preferable that faces **2**, **4**, **6**, **8** of lenses **32**, **34**, **36**, **38** be slanted and coated. The slant acts to limit unwanted back reflection while the coating improves the in-coupling efficiency. Techniques to achieve this result are well-known in the art. In the present embodiment lenses **32**, **34**, **36**, **38** are of the GRIN-type and their faces **2**, **4**, **6**, **8** are slightly inclined.

A light beam **20** enters device **10** through port **12**. Once admitted it is incident on an input facet **42** of a birefringent walk-off element **52**. In fact, element **52** is one of four analogous walk-off elements **52**, **54**, **56** and **58** having corresponding input facets **42**, **44**, **46** and **48**. Suitable materials for elements **52**, **54**, **56** **58** include rutile, calcite, Yittrium Orthovanadate and the like. In other words, walk-off elements **52**, **54**, **56**, **58** are birefringent crystals.

The optical axes **90** of all elements **52**, **54**, **56**, **58** are in the plane oriented at 45° to the axes defining input facets **42**, **44**, **46** and **48**. This is shown in detail by Fig. 2 using element **52** as an example. A vector **91** defines the 45° angle to the sides of facet **42**. Optical axis **90** is oriented an an angle θ to vector **91**. In fact, vector **91** and optical axis **90** define the above-mentioned plane which is inclined at 45° to the x-z plane. The magnitude of angle α is obtained from the well-known relation:

$$\tan(\alpha) = \left(\frac{n_o^2}{n_e^2} - 1\right) \frac{\cot(\theta)}{1 + \frac{n_o^2}{n_e^2}\cot^2(\theta)}$$

In the present case θ is the angle described by vector **91** and is thus equal to 45° (θ = 45°). When light beam **20** is split into an ordinary beam **130** and an extraordinary beam **132** the two experience difference refractive indices inside crystal **52**. In particular ordinary beam **130** sees the refractive index n_o and extraordinary beam **132** experiences the refractive index n_e.

A walk-off distance D_{wo} in element **52** is defined as follows:

$$D_{wo} = a \tan(\alpha)$$

where a is the length of element **52** traversed by beams **130** and **132** as indicated. The reason for the separation of the two beams is due to the difference in the refractive indices. As a result, extraordinary beam **132** will travel forward or advance along a short diagonal **134** diverging quickly from the straight path taken by ordinary beam **130**. Of course, when ordinary beam **130** and extraordinary beam **132** are on their return path, they will be efficiently combined along diagonal **134**. This issue is important to the invention since it allows to minimize the size of birefringent crystals **52** through **58**.

During the walk-off, ordinary beam **130** will retain a first polarization **140** and extraordinary beam **132** will have a second polarization **142**. Polarizations **140** and **142** are orthogonal to each other.

Referring again to Fig. 1, output facets **62**, **64**, **66** and **68** face corresponding pairs of non-reciprocal rotation elements **72**, **74**, **76**, **78** each consisting of two individual rotators **82;92**, **84;94**, **86;96** and **88;98**. The rotation sense of each rotator **82;92**, **84;94**, **86;96** and **88;98** is discussed below.

Preferably, rotators **72** and **78** comprise half-wave plates **82;92**, **88;98** and polarizers **83** and **87**. The latter are used in the preferred embodiment to increase isolation, i.e., reduce light transmission from port **14** to port **12**. Of course, device **10** will also operate without polarizers **83** and **87**. Rotators **84;94**, and **86;96** are either regular Faraday rotators or latching Faraday rotators. The latter operate without a bias magnet and are consequently preferred. A person skilled in the art will know how to adapt either of these components to device **10**. It is important to note that the overall dimensions of device **10** can be minimized when using latching Faraday rotators **82;92**, **84;94**, **86;96** and **88;98** since the magnetic material is incorporated within such a rotator.

Fig. 3 illustrates the operation of rotation element **72** consisting of half-wave plates **82**, **92** and polarizer **83**. Half-wave plate **82** has a principle plane **85** oriented at an acute angle of 22.5° to first polarization **140**.

The polarization direction of polarized light entering a half wave plate will make an acute angle β with a principle plane of the half-wave plate. Half-wave plates work by introducing a phase shift between the component of polarization which is parallel to the optic axis of the half-wave plate and the component which is perpendicular to the optic axis. The result of this phase shift is a rotation of the polarization of the incident light by an angle of 2β.

In the present case, half-wave plate **92** has a principle plane **95** oriented at an acute angle of 22.5° to second polarization **142**. This causes second polarization **142** of extraordinary beam **132** to be rotated by 45° to the position shown. At the same time, first polarization **140** of ordinary beam **130** is also turned by 45°. The two 45° polarization rotations are opposite in sense so that polarizations **140** and **142** emerge parallel. Beams **130** and **132** pass through polarizer **83** whose transmission axis is aligned to pass the emerging first and second polarizations **140** and **142**. Polarizer **83** improves the isolation of device **10** as explained below.

Returning to Fig. 1, one notes two polarization dependent deflecting elements **102** and **104** positioned between pairs of elements **72**, **74**, **76**, **78**. In fact, elements **102** and **104** are polarizing beam splitters and combiners (PSCs). The property of splitters **102** and **104** dictates that light having a transmitting polarization will pass through splitters **102** and **104**. Meanwhile, light having a reflecting polarization will be reflected. This function is ensured by reflecting films **106** and **108**. The latter may be made of a multilayer dielectric films. Note that the transmission axes of polarizers **83** and **87** are aligned to ensure that only light of the correct polarization reaches birefringent walk-off elements **52** and **58**, thereby eliminating light of unwanted polarization being transmitted to port **12** and port **18**, and increasing isolation performance.

In general, beam splitters **102** and **104** are made of a pair of right angle prisms **112**; **122** and **114**; **124**. Multilayer films **106** and **108** are sandwiched by prisms **112**; **122** and **114**; **124**, which are cemented together hypotenuse-face to hypotenuse-face.

The operation of device **10** is best visualized by referring back to Fig. 1 and following the diagrams of Figs. 4A-4C. These drawings illustrate light beam **20** traveling from port **12** to port **14**, from port **14** to port **16** and from port **16** to port **18**. The polarization rotations are shown explicitly. After entering device **10** through port **12** in the direction indicated by arrow A, first and second polarizations **140** and **142** of beams **130** and **132** are "walked-off" in element **52** by distance D_{WO}. Then, rotators **82** and **92** rotate polarizations **140** and **142** by 45° clockwise and counter-clockwise, respectively. At this point, polarizations **140** and **142** are parallel to each other. Of course, polarizer **83** introduces no additional polarization rotation.

In beam splitter **102** polarizations **140**, **142** are aligned with the intrinsic transmitting polarization and are thus passed on to rotators **84** and **94**. Inside rotators **84** and **94** polarizations **140**, **142** are rotated by another 45° each and are again orthogonal to each other. Then, inside element **54**, following upon the return path, ordinary and extraordinary beams **130** and **132** are combined again, as indicated by merged polarizations **140**, **142**, and delivered to port **14**.

Clearly, device **10** is a circulator, since no light can return to original port **12** by following the path of light beam **20** from port **14** back to port **12**. Instead, as show in Fig. 4B, light beam **20** passes from port **14** to port **16** along the direction indicated by arrow B. The "walk-off" between beams **130** and **132** of polarizations **140** and **142** occurs in crystal **54**. Clockwise and counter-clockwise 45° rotations in rotators **84** and **94** render polarizations **140** and **142** parallel. In this state, polarizations **140** and **142** are aligned with the reflecting polarization of beam splitter **102**.

Beams **130** and **132** are consequently reflected by splitter **102** or, more precisely, by film **106** along a direction perpendicular to arrow B (x-direction) and travel to splitter **104**, where they are aligned with splitter's **104** reflecting polarization. Again reflected, this time along the direction of arrow B, beams **130** and **132** pass through rotators **86** and **96**. These rotate polarizations **140** and **142** by 45° to render them orthogonal. Crystal **56** reunites beams **130** and **132** into light beam **20**, and the latter exits device **10** through port **16**.

Fig. 4C shows how light beam **20** passes from port **16** to port **18** along the direction indicated by arrow A. As before, the "walk-off" takes place in crystal **56**. Rotators **86** and **96** induce 45° rotations of polarizations **140** and **142**, such that they are parallel and aligned with the transmitting direction of splitter **104**. Beams **130** and **132** thus pass through splitter **104** and polarizer **87** to rotators **88** and **98** to be rotated such that their polarizations **140** and **142** are again orthogonal. Crystal **58** rejoins beams **130** and **132** into light beam **20** which then issues forth through port **18**.

Fig. 5 illustrates the operation of pair of non-reciprocal rotation elements **74** consisting of rotators **84** and **94**. Corresponding magnetic fields $\mathbf{B_1}$ and $\mathbf{B_2}$ are generated by suitable sources such as permanent magnets. In the case of latching-type rotators **84**, **94** the material of rotators **84** and **94** is appropriately magnetized to set up fields $\mathbf{B_1}$ and $\mathbf{B_2}$. The direction of fields $\mathbf{B_1}$ and $\mathbf{B_2}$ determines how the polarization of light passing through rotators **84** and **94** is altered. In this embodiment fields $\mathbf{B_1}$ and $\mathbf{B_2}$ are anti-aligned to produce 45° contrary polarization rotations. This causes first polarization **140** of ordinary beam **130** to rotate by 45° to the position shown. At the same time, second polarization **142** of extraordinary beam **132** is also turned by 45°. The two 45° polarization rotations are opposite in sense. As a result, first and second polarizations **140** and **142** end up being parallel.

Device **10** is a multi-port non-reciprocal optical device, in particular a circulator, with a low insertion loss and a high extinction ratio in polarization separation. This is chiefly due to the use of walk-off elements **52**, **54**, **56** and **58**. In a three port circulator, as described below, polarization beam splitter **104** can be replaced by a highly reflective element such as a reflecting prism or a glass plate with a highly reflective coating while retaining the same advantages.

Further, the orientation of polarization axis **90** in the plane set at 45° to the sides of input facets of crystals **52**, **54**, **56** and **58** the polarization separation performance is optimized. The "walk-off" along diagonal **134** allows one to use non-reciprocal rotators **84;94** and **86;96** immediately past crystals **54** and **56**. This eliminates the need for precise alignment procedures (commonly required to properly orient the optical axes of half-wave plates), reduces the number of parts, and greatly simplifies the design of circulator **10** in comparison to prior art units.

Another circulator **200** according to the invention is shown exploded and in top plan view in Fig. 6. In this embodiment circulator **200** has four ports **202**, **204**, **206** and **208** equipped with lenses **212**, **214**, **216**, **218** and fed by optical fibers **222**, **224**, **226** and **228**. In this view it is apparent that the faces of lenses **212**, **214**, **216**, **218** are inclined to improve the in-coupling efficiency of light.

Birefringent walk-off elements **232**, **234**, **236** and **238** are set up as in the above-discussed embodiment for separating the input light into its ordinary and extraordinary component beams (not shown). Half-wave plates **242;252** and **248;258** are set on polarization dependent deflecting elements **260** and **264**. Non-reciprocal Faraday rotators **244;254** and **246;256** are set on polarization dependent deflecting element **262**. Elements **260** and **264** are prisms with reflective films **266** and **268**. Meanwhile, element **262** is a full beam splitter with reflecting film **280**.

The operation of this embodiment is explained by the diagrams in Figs. 7A-C. For the purpose of this discussion it will be assumed that the same light beam **20** as used in the previous embodiment is introduced into port **202** along the direction indicated by arrow A. Once again, a "walk-off" by distance D_{WO} takes place in element **232** to yield ordinary and extraordinary beams **130** and **132** with orthogonal polarizations **140** and **142**. Rotators **242** and **252** turn these polarizations by 45° to render them parallel and aligned with the reflecting direction of prism **260** and beam splitter **262**. Consequently, beams **130** and **132** are reflected by film **266** along arrow C into beam splitter **262**. There, beams **130** and **132** are once again reflected by film **280** along arrow B to rotators **244** and **254** and subsequent element **234**. Recombined light beam **20** exits circulator **200** through port **204**.

When light beam **20** is introduced through port **204** it passes through element **234** and separates into beams **130**, **132** which pass through rotators **244**, **254** to splitter **262**. The direction of propagation is indicated by arrow A. Both beams **130** and **132** have their polarizations **140** and **142** aligned with the transmitting direction of splitter **262** and thus continue on their path to rotators **246** and **256**. The latter rotate polarizations **140** and **142** to render them orthogonal and pass beams **130** and **132** to element **236**. Here, light beam **20** is reconstructed and then emitted through port **206**.

The progress of beam **20** from port **206** to port **208** along arrows B, C and A is illustrated in Fig. 7C. The steps and polarization rotations are closely related to those explained in Fig. 7A.

Device **200** is an efficient, simple and low-cost circulator endowed with the aforementioned advantages. Its geometry, in particular the arrangement of ports **202**, **204**, **206** and **208** makes it suitable for many different applications.

Yet another embodiment of a device **300** according to the invention is illustrated in Fig. 8. Except for the different geometrical arrangement of ports **302**, **304**, **306**, **308** and a different set of polarization independent deflecting elements **342**, **346**, **350**, **352** and polarization dependent deflecting elements **344** and **348** this device is similar to the previous embodiments. It has fibers **312**, **314**, **316**, **318** coupled into device **300** through lenses **322**, **324**, **326**, **328** leading to walk-off elements **332**, **334**, **336** and **338**. Furthermore, device **300** also has half-wave plates **362;372**, **368;378**, polarizers **382**, **388**, and non-reciprocal Faraday rotators **364;374**, **366;376**. As in the previous embodiments, polarizers **382** and **388** are optional and their main function is to improve the isolation efficiency of device **300**.

In operation device **300** proves to be an optical circulator. The diagrams of Figs. 9A-C show how light beam **20** propagates from port to port. This process is analogous to those described above. In particular, Fig. 9A shows the progress of beam **20** from port **302** to port **304** along directions indicated by arrows A, B and C. Fig. 9B shows beam **20** on its path from port **304** to **306** through four deflecting elements **344**, **346**, **350** and **348**. Finally, the passage of beam **20** from port **306** to **308** can be seen in Fig. 9C.

The additional advantage of circulator **300** is that all ports **302**, **304**, **306** and **308** are arranged on the same side. This is advantageous for applications under geometrical constraints from all but one side.

Fig. 10 illustrates yet another non-reciprocal optical device **400** with three ports **402**, **404** and **406**. Device **400** functions as a circulator and uses fibers **412**, **414**, **416** in conjunction with lenses **422**, **424** and **426** for efficient transmission of light. It also has three walk-off elements **432**, **434** and **436** arranged facing three sides of a beam splitter **450**. The latter has half-wave plates **462;472**, **464;474** and polarizers **482**, **484** on the sides facing elements **432** and **436**, and non-reciprocal Faraday rotators **466;476** on the side facing element **434**.

Standard free-space isolators **492** and **494** are placed between lenses **422**, **424** and walk-off elements **432** and **434** to increase isolation of port **404** to port **402**, and port **406** to port **404**. Isolator **492** only transmits light in the direction shown by arrow B.

Device **400** operates according to the same principles as the previous embodiments. The advantage of its design resides in the efficient use of a single beam splitter **450**. Further, losses due to multiple reflections and scattering are minimized in this structure. Ports **402**, **404** and **406** are far apart for easy access and connection.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. In particular, the structures discussed above can be used as optical isolators, attenuators or switches. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A multiport optical non-reciprocal device comprising:
   a) at least two ports for receiving and emitting a light beam having a first polarization and a second polarization orthogonal to said first polarization;
   b) a first birefringent walk-off means positioned between said at least two ports for splitting said light beam when advancing along a first diagonal into an ordinary beam of said first polarization and an extraordinary beam of said second polarization, and for combining said ordinary beam and said extraordinary beam when returning along said first diagonal into said light beam;
   c) a first pair of non-reciprocal rotation means placed in the paths of said ordinary beam and of said extraordinary beam for rendering said first polarization and said second polarization parallel;
   d) a polarization dependent deflecting means for receiving said ordinary beam and said extraordinary beam, said polarization dependent deflecting means having a transmitting polarization and a reflecting polarization orthogonal to said transmitting polarization;
   e) a second pair of non-reciprocal rotation means placed in the paths of said ordinary beam and of said extraordinary beam for rendering said first polarization and said second polarization orthogonal;
   f) a second birefringent walk-off means positioned between said at least two ports for splitting said light beam when advancing along a second diagonal into said ordinary beam of said first polarization and said extraordinary beam of said second polarization, and for combining said ordinary beam and said extraordinary beam when returning along said second diagonal into said light beam.

2. The device of claim 1, wherein said first birefringent walk-off means and said second birefringent walk-off means comprise birefringent crystals.

3. The device of claim 2, wherein each one of said birefringent crystals has an optical axis in a plane inclined at 45° to the axes defining input facets of said birefringent crystals.

4. The device of claim 1, wherein said polarization dependent deflecting means is at least one polarizing beam splitter.

5. The device of claim 4, wherein said at least one polarizing beam splitter comprises a pair of right angle prisms cemented hypotenuse-face to hypotenuse-face.

6. The device of claim 5, further comprising a multilayer dielectric film between said pair of right angle prisms.

7. The device of claim 1, wherein said first pair of non-reciprocal rotation means render said first polarization and said second polarization parallel to said transmitting polarization.

8. The device of claim 1, wherein said first pair of non-reciprocal rotation means render said first polarization and said second polarization parallel to said reflecting polarization.

9. The device of claim 1, wherein said first pair of non-reciprocal rotation means comprises a first pair of non-reciprocal Faraday rotators which render said first polarization and said second polarization

parallel by rotating said first polarization by 45° and by rotating said second polarization by 45°.

10. The device of claim 1, wherein said second pair of non-reciprocal rotation means comprises a second pair of non-reciprocal Faraday rotators which render said first polarization and said second polarization perpendicular by rotating said first polarization by 45° and by rotating said second polarization by 45°.

11. The device of claim 1, wherein said first pair of non-reciprocal rotation means and said second pair of non-reciprocal polarization rotation means comprise a first pair of latching Faraday rotators and a second pair of latching Faraday rotators.

12. The device of claim 1, wherein said first pair of non-reciprocal rotation means and said second pair of non-reciprocal polarization rotation means comprise a first pair of Faraday rotators and a second pair of Faraday rotators.

13. The device of claim 1, wherein said at least two ports comprise GRIN lenses for shaping said light beam for reception by said device and for shaping said light beam for emission from said device.

14. The device of claim 1, wherein first birefringent walk-off means and said second birefringent walk-off means are made of a material selected from the group consisting of rutile, calcite and Yittrium Orthovanadate.

15. The device of claim 1, further comprising optical fibers for receiving and emitting said light at said at least two ports.

16. The device of claim 15, wherein said optical fibers are all single mode fibers.

17. The device of claim 15, wherein said optical fibers are all multi-mode fibers.

18. The device of claim 1, comprising at least three ports arranged to sequentially pass said light beam between said four ports such that said device is a circulator.

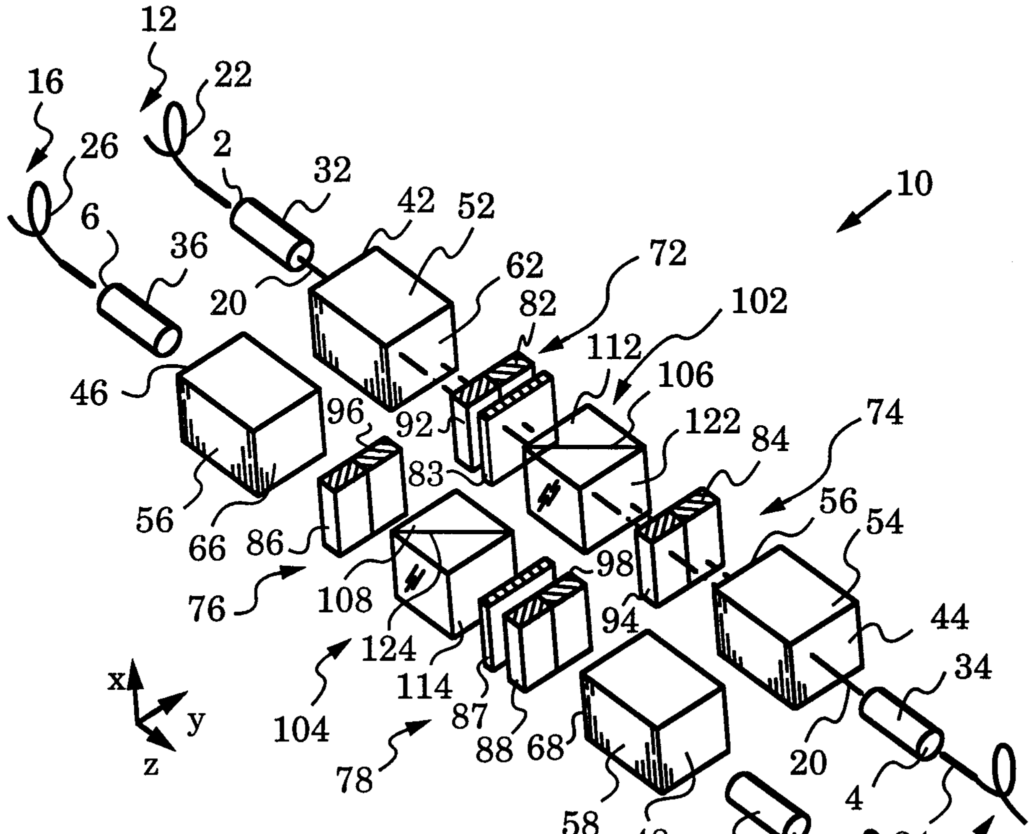

12
16
22
26
2
32
6
36
42
52
10
62
72
20
82
102
46
112
106
96
92
122
84
74
83
56
54
56
66
86
98
76
108
94
44
124
34
114
104
x
y
z
87
88
68
20
78
58
48
4
24
38
8
28
14
18

FIG. 1

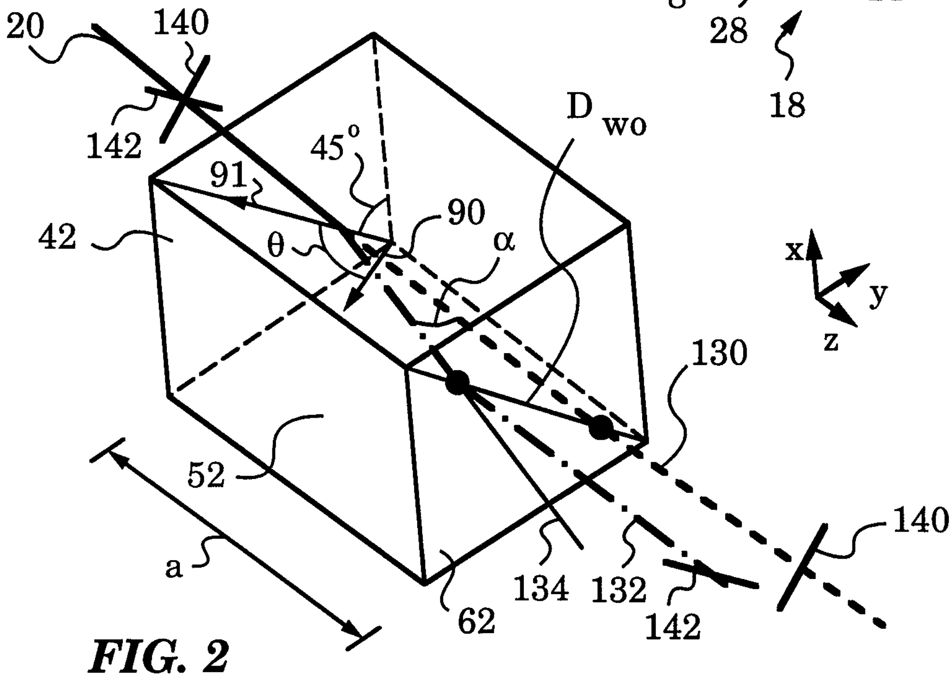

20
140
142
D wo
45°
91
90
42
θ
α
x
y
z
130
52
a
134
132
140
142
62

FIG. 2

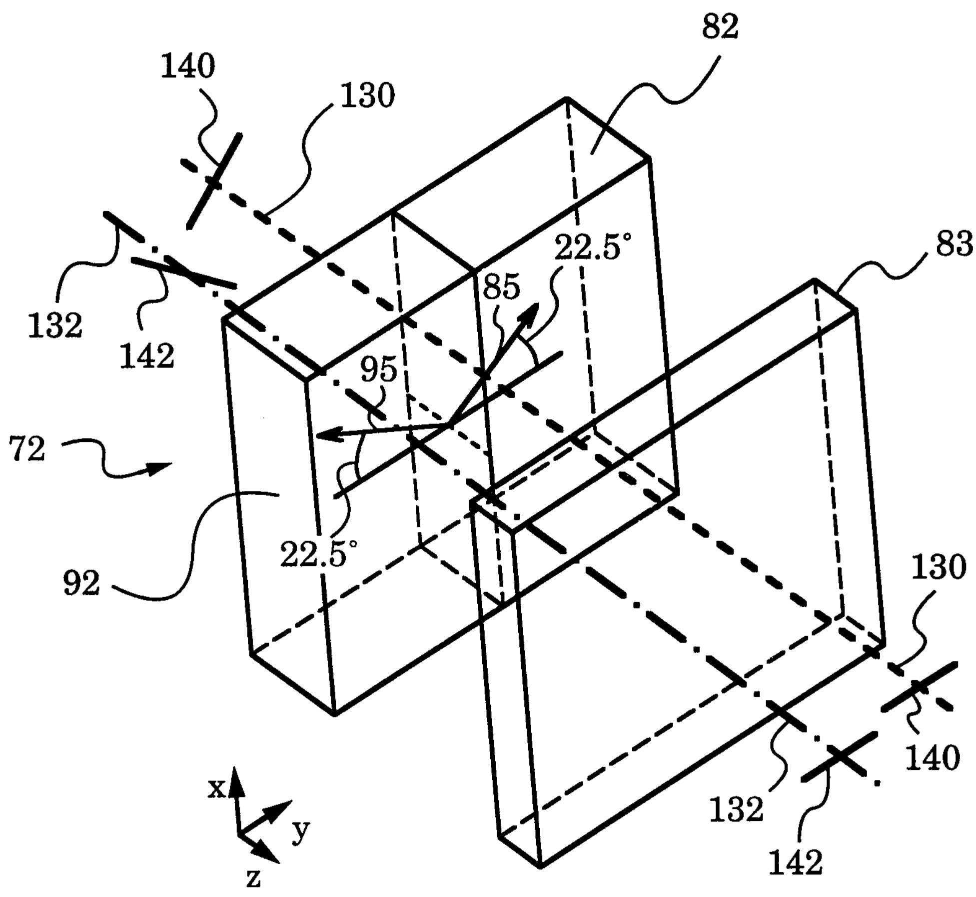

82
140
130
83
22.5°
85
132
142
95
72
92
22.5°
130
140
132
142
x
y
z

FIG. 3

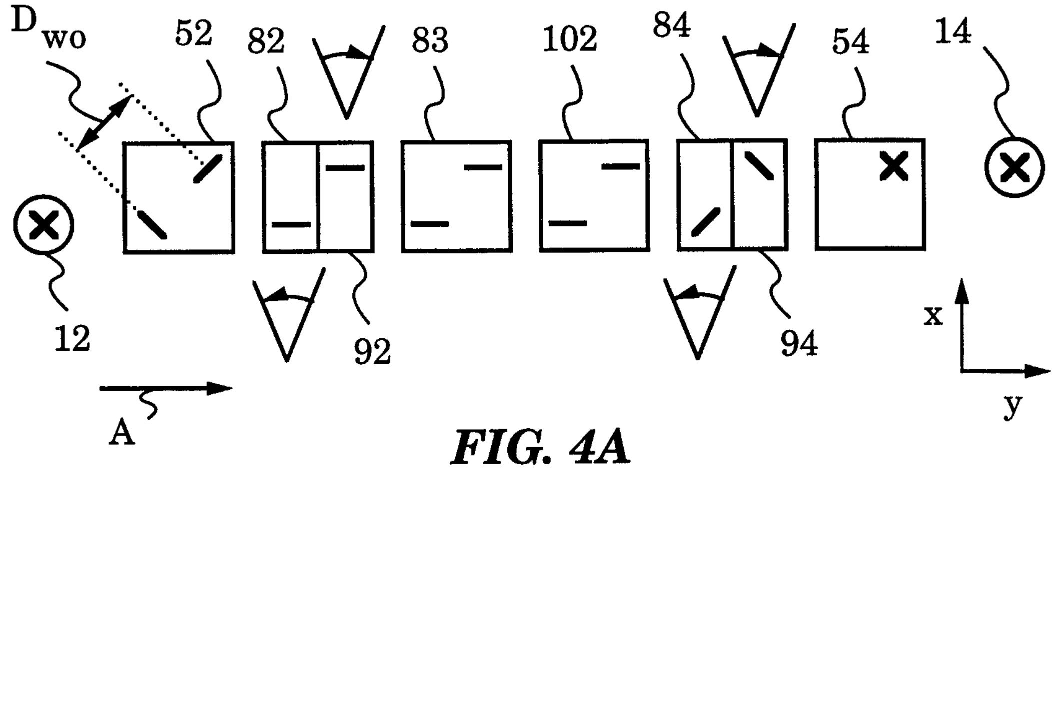

D wo
52
82
83
102
84
54
14
12
92
94
x
y
A

FIG. 4A

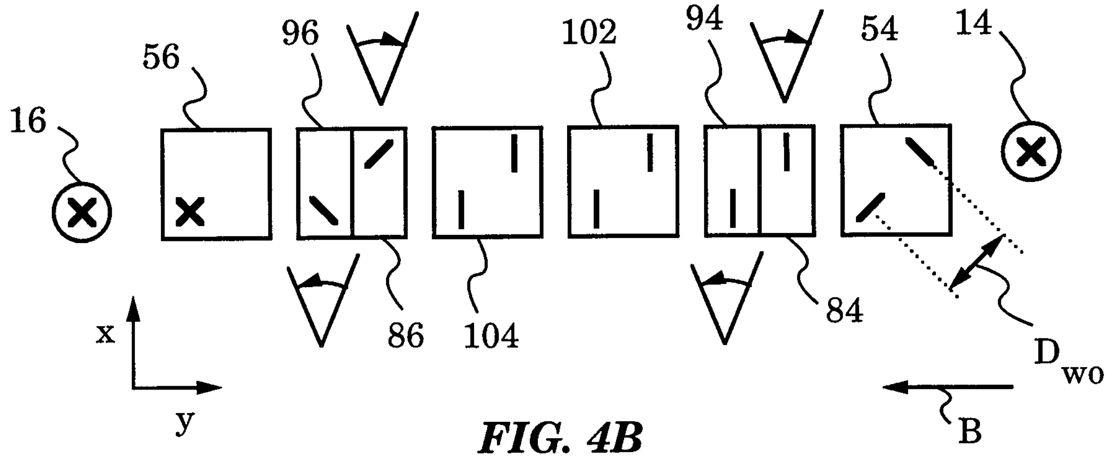

56
96
102
94
54
14
16
86
104
84
x
y
D_{wo}
B

FIG. 4B

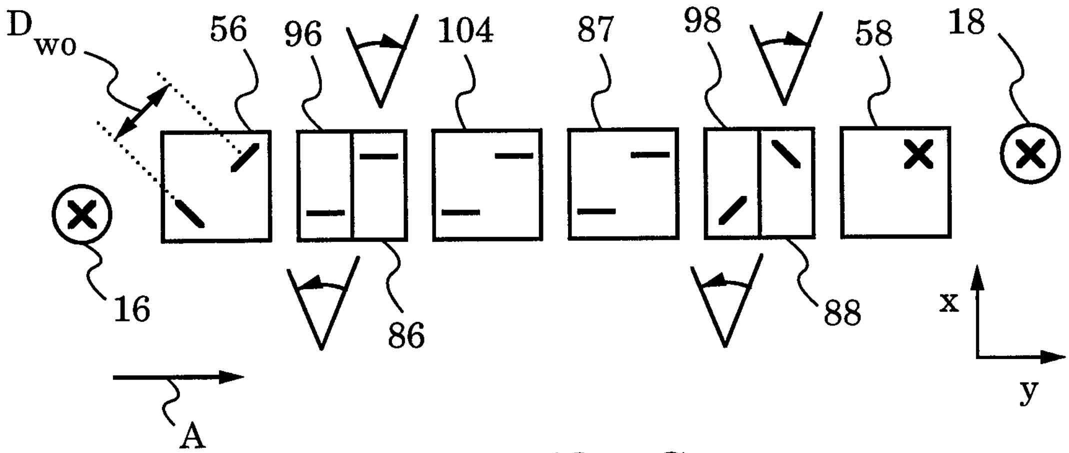

D_{wo}
56
96
104
87
98
58
18
16
86
88
x
y
A

FIG. 4C

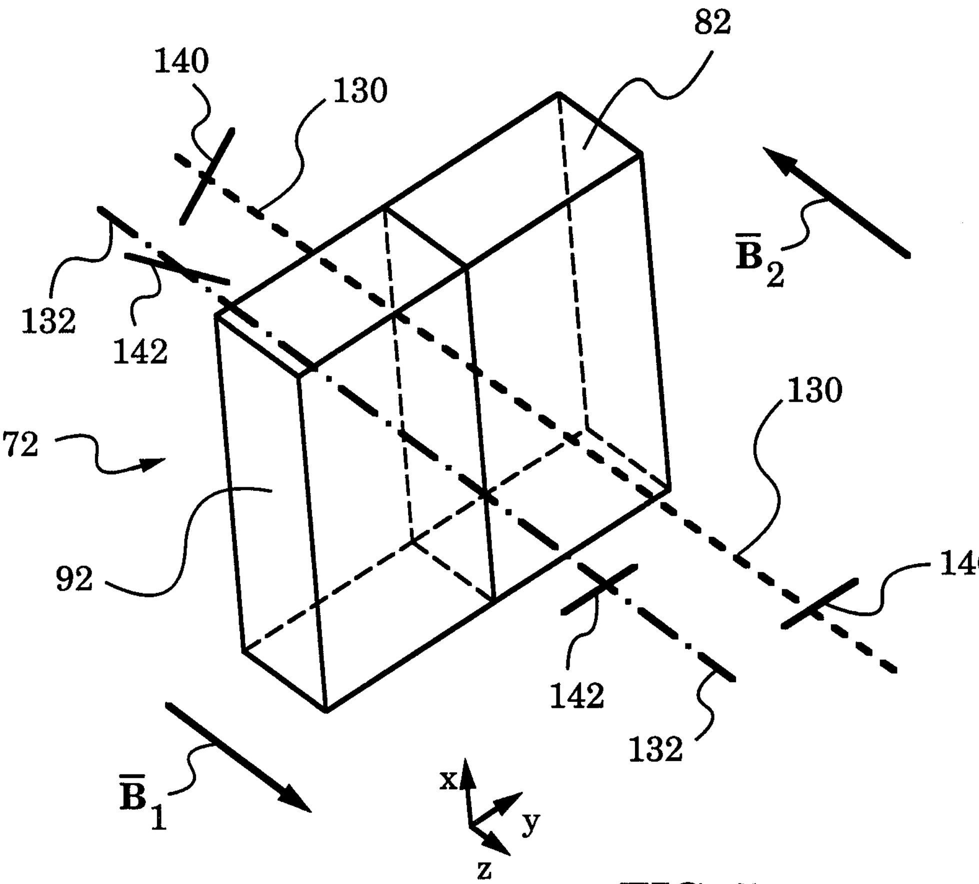

82
140
130
132
142
72
92
130
140
142
132
B2
B1
x
y
z

FIG. 5

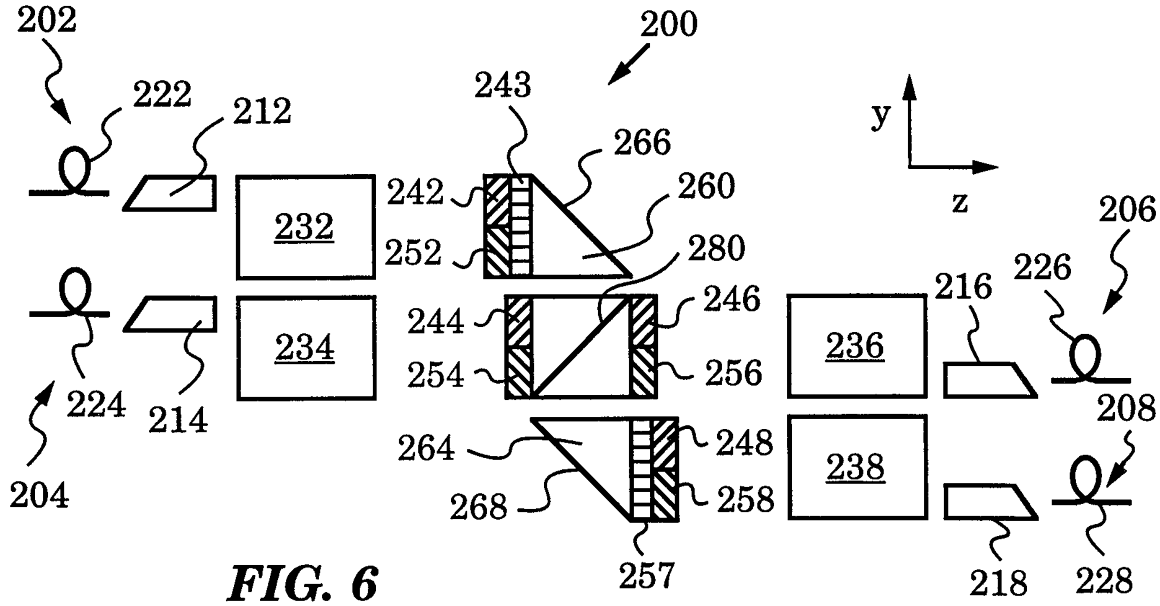
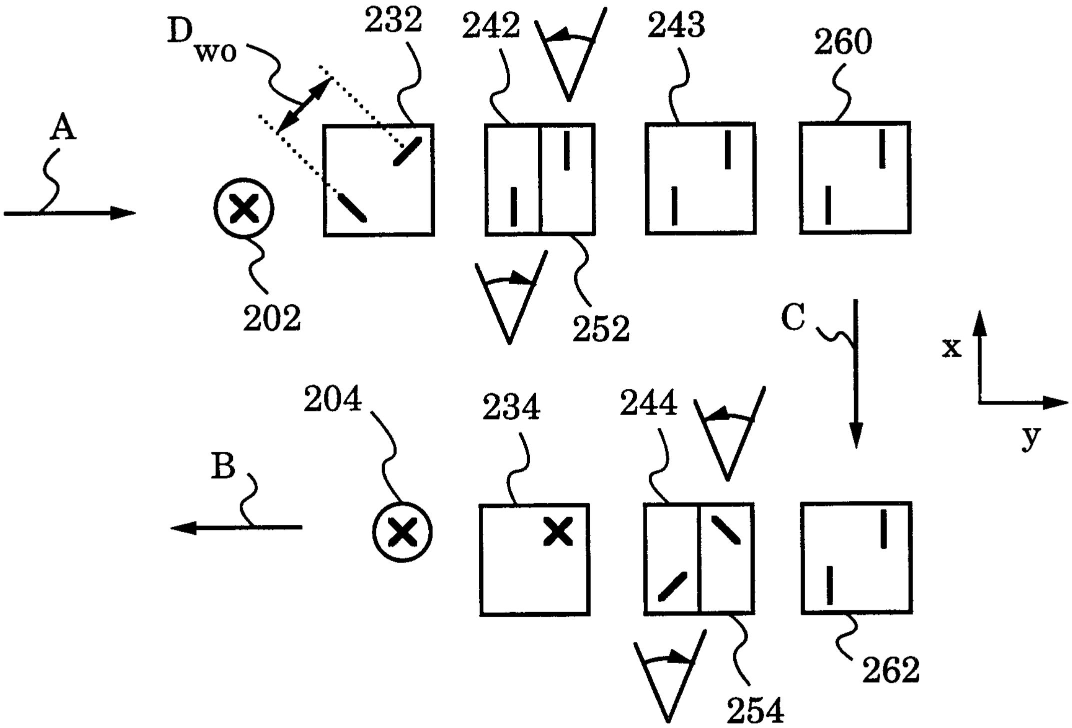
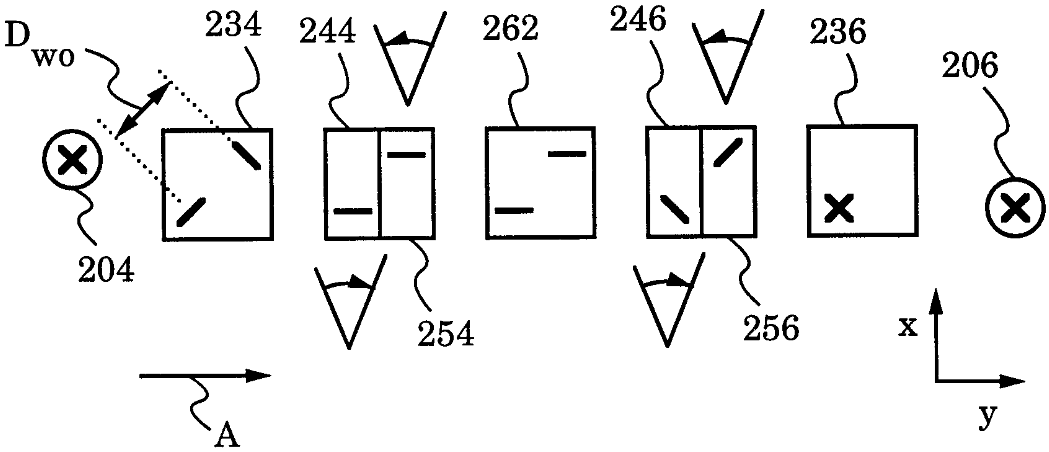

202
200
222
212
243
266
260
242
232
252
280
244
234
246
254
256
236
216
226
206
224
214
204
264
268
248
258
238
208
257
218
228
y
z

FIG. 6



D
wo
232
242
243
260
A
202
252
C
x
y
204
234
244
B
254
262

FIG. 7A



D
wo
234
244
262
246
236
206
204
254
256
x
y
A

FIG. 7B

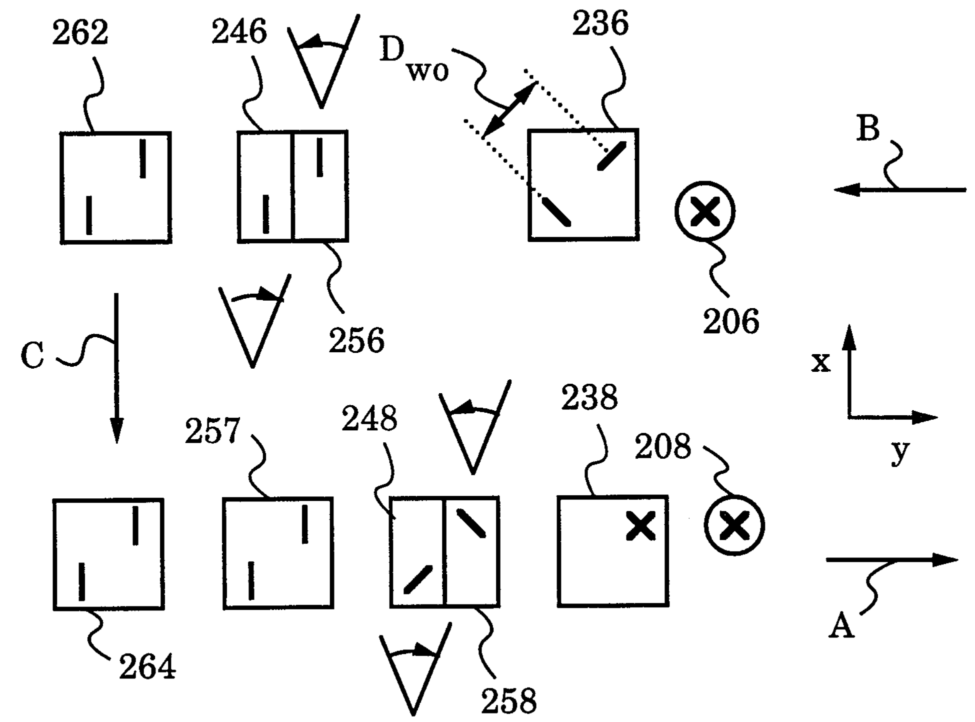

262
246
256
D
wo
236
B
206
C
257
248
238
208
x
y
264
258
A

FIG. 7C

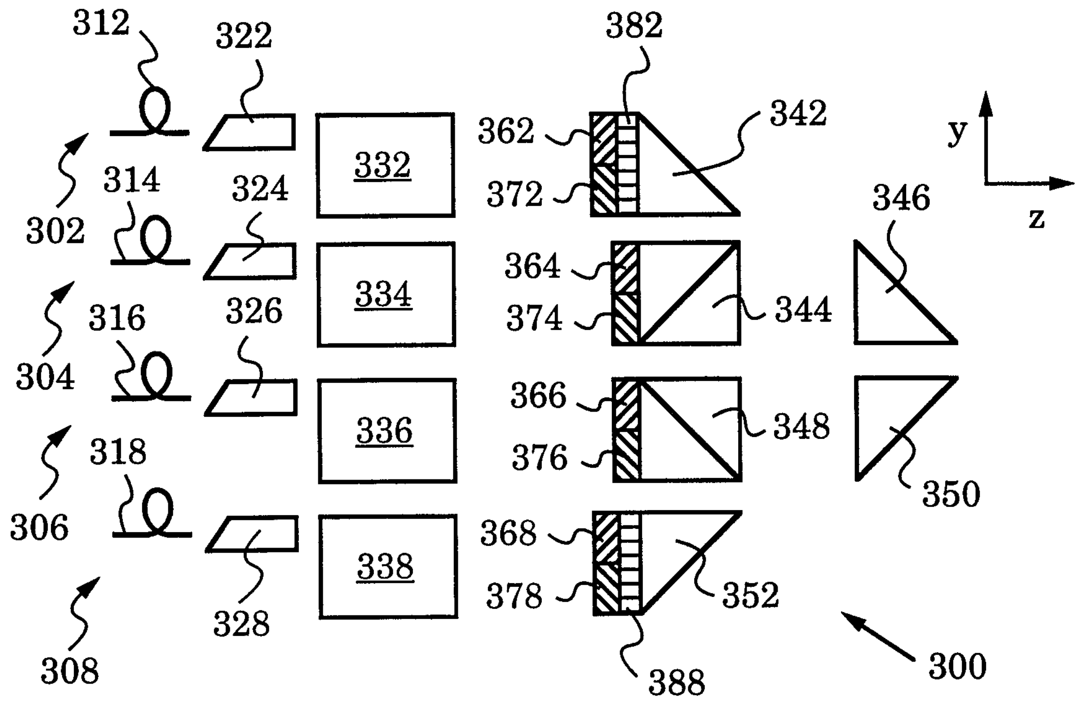
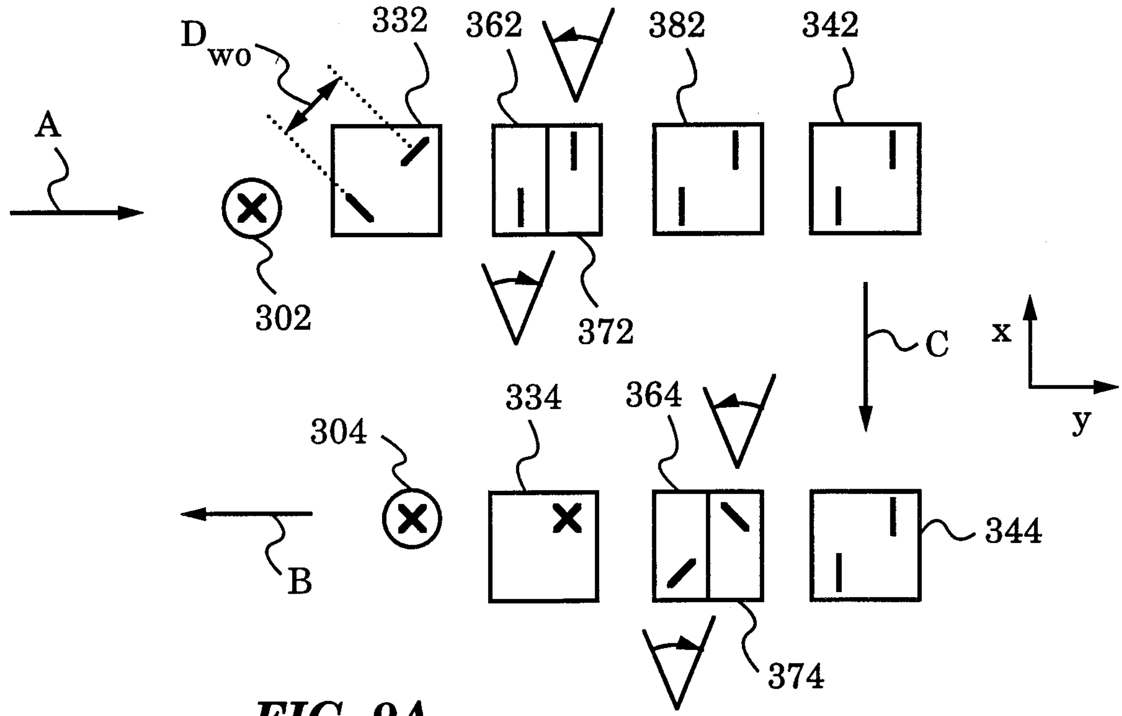
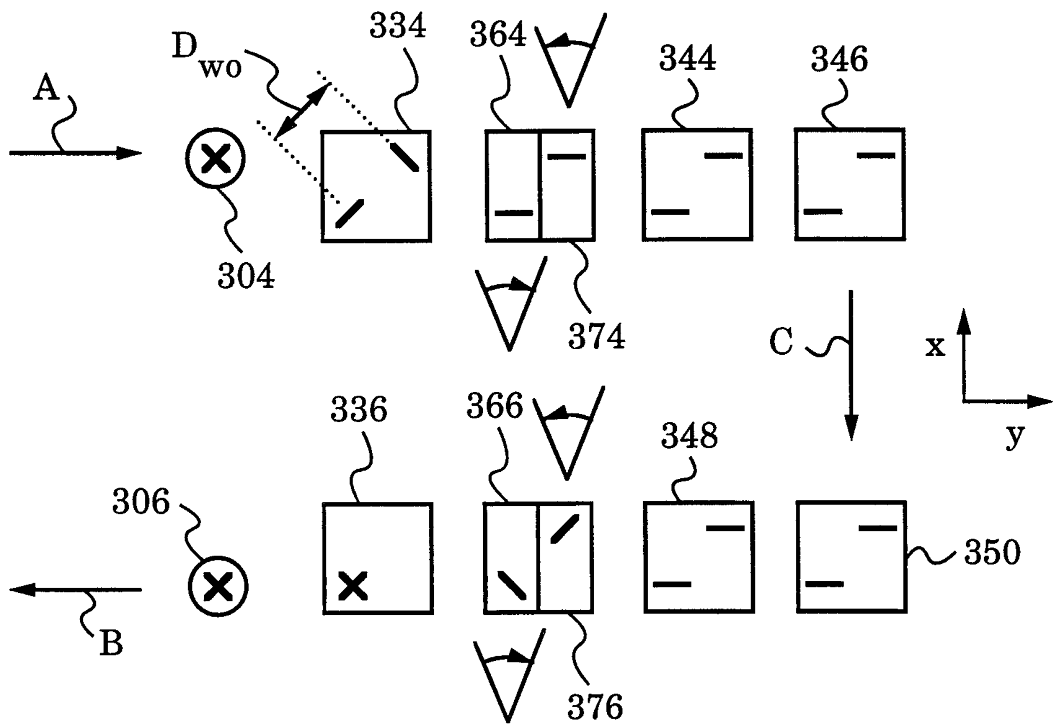

312
322
382
362
342
372
302
314
324
332
y
z
346
364
334
374
344
304
316
326
366
348
336
376
350
306
318
368
338
378
352
328
308
388
300

FIG. 8



D
wo
A
332
362
382
342
302
372
C
x
y
334
364
304
344
B
374

FIG. 9A



D
wo
A
334
364
344
346
304
374
C
x
y
336
366
348
306
350
B
376

FIG. 9B

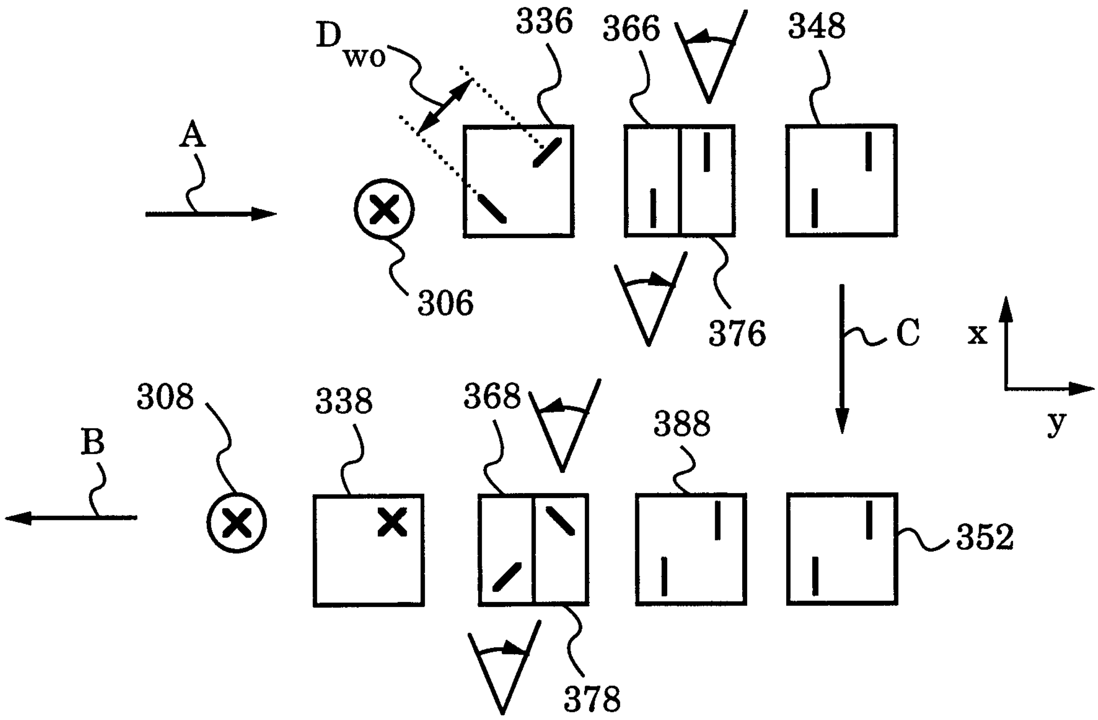

D
wo
336
366
348
A
306
376
C
x
y
308
338
368
388
B
352
378

FIG. 9C

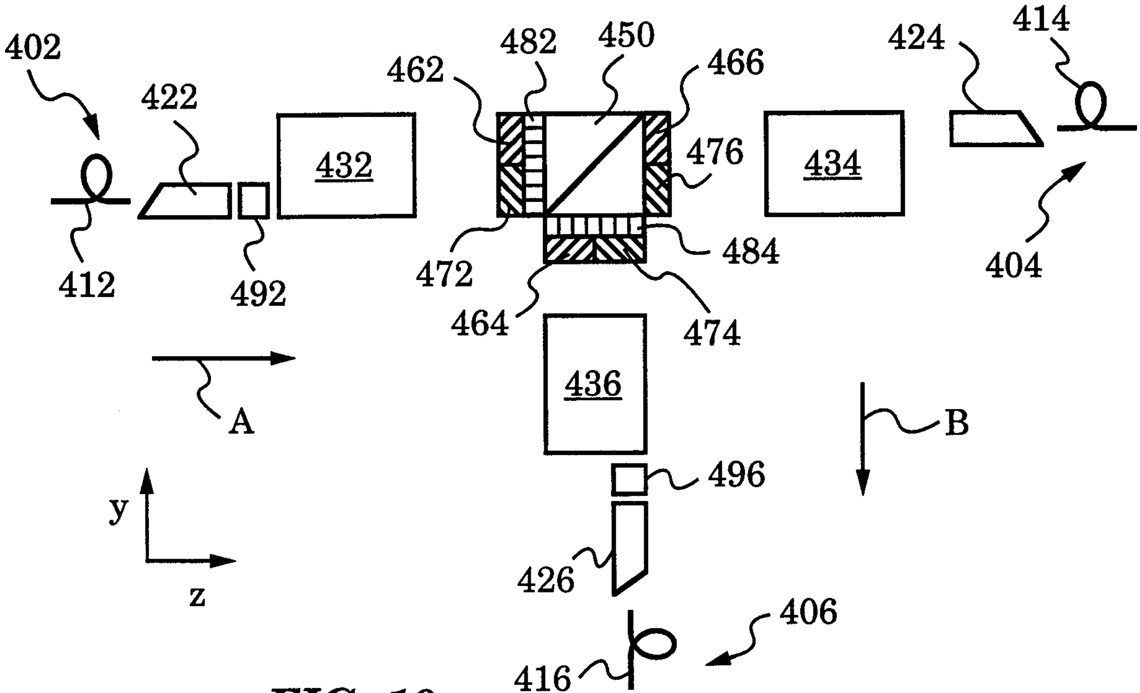

402
422
462
482
450
466
424
414
432
476
434
412
492
472
484
404
464
474
436
A
B
y
z
496
426
406
416

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/14703

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G 02 B 5/30
US CL :359/484
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/484, 494, 495, 497, 652, 654
385/11

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

NONE

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

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P ----- Y	US 5,689,593 A (Pan et al.) 18 November 1997, (18/11/97) see figure 1	1-4, 7-11, 12-18 ---------- 5, 6
Y	JP A 55-35329 (NIPPON) 12 March 1980, (12/03/80) see entire document	5, 6

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 SEPTEMBER 1998	26 OCT 1998

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer
CRAIG CURTIS
Telephone No. (703) 308-1721