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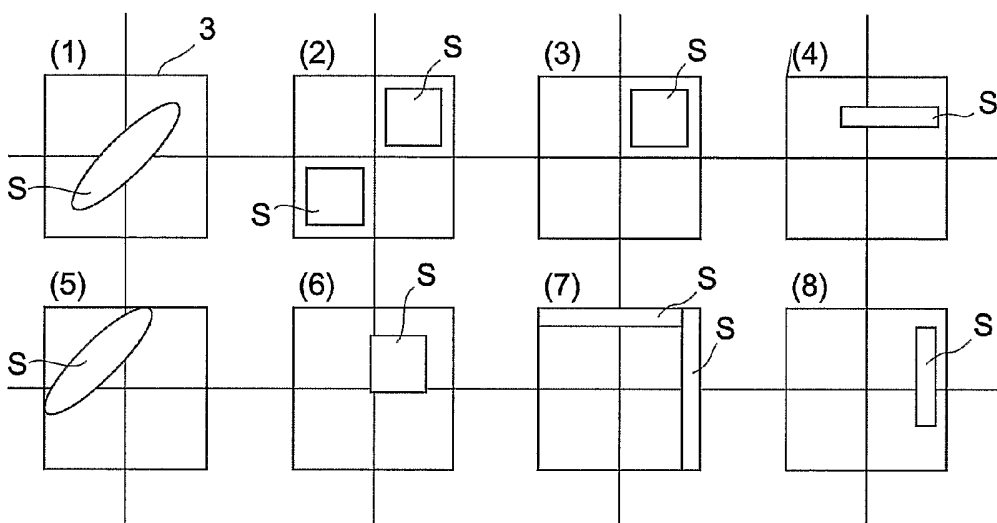
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(54) Title: OPTICAL DEVICE WITH OPTICAL WAVEGUIDE AND MANUFACTURING METHOD THEREOF



(57) Abstract: In an optical device of the invention, ions are implanted into at least a portion of an optical waveguide core having a substantially square or rectangular cross-section, and the ion-implanted portion is formed so as to be asymmetrical with respect to each of the vertical and horizontal line passing through the center of the cross-section of the optical waveguide core. Preferably the ion-implanted portion includes a central portion of the square or rectangular cross-section of the optical waveguide core, and is formed along any one of two diagonals.

DESCRIPTION

OPTICAL DEVICE WITH OPTICAL WAVEGUIDE AND MANUFACTURING
METHOD THEREOF

TECHNICAL FIELD

The present invention relates to the structure of an optical device which is an optical device with an optical waveguide, such as a planar optical waveguide, a polarization converter, an arrayed waveguide grating, and the like, and the manufacturing method thereof.

BACKGROUND ART

In recent optical communication techniques, the planar optical waveguide has drawn attention due to the benefit of the capability of optical integrated circuits, and has been well studied. In the optical waveguide, since the coefficient of thermal expansion of a silicon substrate is different from that of a silica-based glass layer constituting the waveguide, a stress is generated in the glass, which results in the optical waveguide having birefringence in many cases. Since there is such a birefringence in the optical waveguide and the polarization state of a beam propagating in the optical waveguide is maintained, there is a problem of polarization dependency in optical parts formed in the optical waveguide, for example in an arrayed waveguide grating, a Bragg reflection type grating, and the like, where a difference of operating wavelength depending on the polarization state occurs, specifically in the operating wavelengths of a TE polarized beam and a TM polarized beam. In order to solve this polarization dependency, for example in the case of the arrayed waveguide grating, a method of forming a groove in the arrayed waveguide and inserting a wave plate into the groove has been generally used (for example, Y. Inoue et. al. "Polarization mode converter with polyimide half waveplate in silica-based planar lightwave circuit" IEEE Photonics Technology Letter. Vol. 6, p. 626, 1994). The polarization dependency is decreased by inserting the wave plate, because the TE polarized beam of an incident beam is altered to the TM polarized beam after being propagated through the wave plate. As another conventional example, a method of inserting a lattice modulation type photonic crystal wavelength selection filter into the groove at the end of the arrayed waveguide has been disclosed (for example, Japanese Unexamined Patent

Publication No. 2003-255160). However, in these methods of inserting the wave plate or the filter into the groove, a process for forming a groove and an assembling process for inserting the wave plate or the filter into the groove are required, which causes a problem of making the whole process complicated, making the adjustment difficult, increasing the proportion of defective products, and as a result, increasing the cost.

DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

Taking the above problems into consideration, the present invention provides an optical device which has high performance, low proportion defective, and low price, by a method of solving the polarization dependency problem. In the optical waveguide core, a structure acting similarly to the abovementioned wave plate is formed. It alters the polarized beams, without forming a groove in the waveguide. Moreover, the invention provides a method for manufacturing such a structure acting similarly to the wave plate.

MEANS FOR SOLVING THE PROBLEM

In the present invention, in order to solve the above problems, ions are implanted into at least a portion of an optical waveguide core, and the ion-implanted portion is formed so as to be asymmetric with respect to each of the vertical and horizontal line passing through the center of the cross-section of the optical waveguide core. As a result, an optical device is constituted by forming a portion generating birefringence in the ion-implanted optical waveguide core, and it acts similarly to the wave plate. In such a method, there is no need for forming a groove in the optical waveguide, nor inserting another wave plate. Therefore, the process is simplified and adjustment is not necessary, and hence optical devices can be provided at low proportion defective and low cost.

Moreover, the ion-implanted portion includes a central portion of the square or rectangular cross-section of the optical waveguide core, and is formed along any one of the two diagonals. By having such a shape for the optical waveguide core cross-section, the portion generating the birefringence can be formed at the central portion having the strongest electric field of the lightwave, and along the diagonal. Therefore the TE polarized beam and the TM polarized beam of an incident beam can be alternated most effectively. By making such an effective structure, the amount of ions to be implanted may be kept low, and hence the time for the ion implantation process can be shortened, and the manufacturing

cost can be decreased.

By forming the portion generating the birefringence at least in a portion of the optical waveguide core, it becomes possible to obtain a planar optical waveguide having no polarization dependency or very low polarization dependency.

By forming the portion generating the birefringence at least in a portion of the optical waveguide core, it becomes possible to obtain, optical devices by themselves, a polarization converter which converts from the TE polarized beam to the TM polarized beam, and an arrayed waveguide grating which can reliably couple or branch multichannel lightwaves without polarization dependency.

Furthermore, the manufacturing method for an optical device with an optical waveguide of the present invention is a manufacturing method comprising: a step for forming a lower cladding on a substrate; a step for forming an optical waveguide core having a substantially square or rectangular cross-section, on the lower cladding; an ion implantation step for forming an ion-implanted portion so as to be asymmetric with respect to each of the vertical and horizontal line passing through the center of the cross-section of the optical waveguide core, on at least a portion of the optical waveguide core; and a step for forming an upper cladding on the lower cladding including the optical waveguide core. According to this manufacturing method, there is no need for a process for forming a groove in the optical waveguide, nor a process for inserting another wave plate. Therefore, the process is simplified and optical devices can be provided at low proportion defective and low cost.

Moreover, the ion implantation is performed by irradiating ions obliquely from the upper side to the cross-section of the optical waveguide core. According to this manufacturing method, it is not necessary to use a mask plate in the process of implanting ions into the optical waveguide core, and the manufacturing process can be shortened. Moreover, since the process of mask alignment can be omitted, the proportion defective and manufacturing cost can be decreased.

According to the optical device and the manufacturing method thereof of the present invention, the portion acting similarly to the wave plate can be formed on the overall optical waveguide or a portion thereof by ion implantation. Therefore, it is possible to readily manufacture a planar optical waveguide or an arrayed waveguide grating without polarization dependency, and a high performance polarization converter. Moreover, there is the effect of being able to decrease the proportion defective and the manufacturing cost.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A and FIG.1B are a perspective view and a cross-sectional view of a general optical waveguide, respectively.

FIG. 2 is a diagram for explaining a change in the plane of polarization due to birefringence of the optical waveguide core.

FIG. 3 is a partially enlarged view which enumerates examples of birefringent portions in a cross-section of an optical waveguide core according to the present invention.

FIG. 4A to 4C are diagrams for explaining manufacturing processes of optical devices with optical waveguides, according to the present invention.

FIG. 5 is a diagram for explaining briefly manufacturing process of the optical device with an optical waveguide, according to the present invention.

FIG. 6 is a schematic diagram of an arrayed waveguide grating according to the present invention.

FIG. 7A and 7B are conceptual diagrams of a directional coupler formed in a planar waveguide.

FIG. 8 is a conceptual diagram showing a cross-section of an ion-implanted core.

BEST MODE FOR CARRYING OUT THE INVENTION

Hereunder is a detailed description of preferred embodiments of the present invention, with reference to the drawings. FIG. 1 A and FIG. 1 B show a perspective view and a cross-sectional view of a general planar optical waveguide respectively. In FIG. 1, reference numeral 1 denotes a substrate, 2 denotes a lower cladding, 3 denotes an optical waveguide core, and 4 denotes an upper cladding. Silicon or silica glass is generally used for the substrate 1. The structure is such that the optical waveguide core 3 is embedded between the lower cladding and the upper cladding. If the refractive index of the optical waveguide core where beams are propagated is uniform, an incident beam into the optical waveguide is propagated through the optical waveguide, while the plane of polarization of the incident beam is kept. However, as shown in FIG. 2, if the optical waveguide core has birefringence to oblique direction in the cross-section, that is, if a refractive index n_e of an S portion in FIG. 2 is different from a refractive index n_o of the surrounding portion, the plane of polarization of a beam changes at passing through the optical waveguide core. In FIG. 2, a vertical polarized beam L propagates through the optical waveguide. As shown in FIG. 2,

the vertically polarized incident beam L can be resolved into two polarized beams Lt and Lp at angles of ± 45 degrees with respect to the vertical direction. If the refractive index of the optical waveguide core is uniform, the two polarized components are propagated with the same phase.

However, as shown in FIG. 2, if there is the birefringent portion S to the oblique direction of 45 degrees in the optical waveguide core, and if the refractive index n_e of the S portion is greater than the refractive index n_o of the surrounding portion, the propagation speed of the polarized component Lp which is oriented to the same direction as that of the birefringent portion S, is slower than another component Lt. On the other hand, the propagation speed of the polarized component Lt oriented to an angle of 90 degrees with respect to the birefringence portion S, remains unchanged. As a result, a phase shift occurs between the two components, so that the plane of polarization of the incident beam changes. If the refractive index n_e of the S portion is less than the refractive index n_o of the surrounding portion, the direction of changing the plane of polarization becomes opposite. The plane of polarization is still changed. Assuming that the refractive index of the overall optical waveguide core is n_o and the refractive index of the birefringent portion is n_e , the phase shift between the two polarized beams, that is the phase difference Δ , can be expressed as follows.

$$\text{Equation 1} \quad \Delta = 2\pi d(n_e - n_o)/\lambda$$

Where, λ denotes the wavelength of the incident beam, and d denotes the length of birefringent portion. When $\Delta = \pi$, the emitting beam is changed into a linear polarized beam with the polarized plane of the perpendicular direction to the incident beam, that is the horizontal polarized beam.

Such change of the polarization plane due to the birefringence does not only occur at the shape of core, as shown in FIG. 2. If a birefringence is formed asymmetrically with respect to both of the vertical and horizontal lines passing through the center of the optical waveguide core, the abovementioned effect is obtained as well. These examples are enumerated in FIG. 3. They are some embodiments. There are many other examples that satisfy the abovementioned conditions.

Among these examples, a structure as shown in FIG. 2, in which the ion-implanted portion is formed at the central portion on the square or rectangular cross-section of the optical waveguide and along any one of the two diagonals, is the most effective.

There are mainly two methods for making a refractive index change in the optical waveguide material by ion implantation. The first method for changing the refractive index is the method of transforming the optical waveguide material itself by applying energy to the optical waveguide material by ion implantation. For example, if ions are implanted into a silica-based glass that is the most typical as the optical waveguide material, then the ion-implanted area is densified and the refractive index is increased. Another method for changing the refractive index is the method of chemically bonding the ions (atoms and molecules) implanted into the optical waveguide material by ion implantation to the optical waveguide material. For example, implanting germanium ions into the silica glass makes the chemical bond, and an increase of the refractive index is obtained. In this method for changing the refractive index using the chemical bond, many combinations between the optical waveguide material and the ions to be implanted are already known.

Hereunder is a specific description of an embodiment of the present invention. In this embodiment, a method for increasing the refractive index by densifying the silica-based glass by ion implantation is described. The amount of increase in the refractive index that can be induced by implanting ions into the optical waveguide of the silica-based glass, is about 0.001. That is, $n_e - n_o = 0.001$. The length d for obtaining the phase difference $\Delta = \pi$ for an optical wavelength $\lambda = 1.55\mu\text{m}$ that is an optical communicating wave band, is calculated from equation 1 and a length of 0.775mm is obtained. By implanting ions into an area of a length of 0.775 mm in the optical waveguide and giving a refractive index increase of 0.001 to the optical waveguide core, polarization converter which corresponds to the wave plate for alternating two polarized beams can be formed.

Moreover, When N_i is the refractive index changed by the ion implantation, n_e can be expressed by;

$$\text{Equation 2} \quad n_e = n_o + N_i$$

Therefore, equation 1 becomes as follows;

$$\text{Equation 3} \quad \Delta = 2\pi d N_i / \lambda$$

As shown in equation 3, for obtaining the desired Δ value, the length d to be ion-implanted and the refractive index change N_i induced by the ion implantation are inversely proportional. Since N_i is generally proportional to the amount of implanted ions, the length d is inversely proportional to the amount of implanted ions. If the amount of implanted ions is larger, the length d is shorter, while the amount of implanted ions is smaller, the length d is longer.

Next description is respect to a method of forming birefringence by ion implantation. The description is respect to the formation of birefringence satisfying the abovementioned conditions in the optical waveguide core of a typical straight planar optical waveguide as shown in FIG. 1. FIG. 4 A, FIG. 4 B, and FIG. 4 C show manufacturing processes of the straight planar optical waveguides. Regarding the planar optical waveguide, firstly in step A, a silica-based glass layer is formed as a lower cladding 2 on the substrate 1 such as a silicon substrate by a method such as a vapor phase deposition method. However, if the substrate 1 itself becomes the lower cladding, then for example a silica glass substrate may be used as the substrate 1. In such a case, the lower cladding is formed by optically flattening the surface of the substrate 1 by polishing or the like. In step B, a glass layer is formed as a optical waveguide core 3 on the lower cladding by a method such as a vapor phase deposition method. Next, in step C, an etching mask (not shown) is formed on this layer which becomes the optical waveguide core 3, so as to give the shape of the desired optical waveguide core, by photolithography, and is then reshaped by reactive ion etching. Furthermore, in step D, the upper cladding 4 is formed by a method such as a vapor phase deposition method. The same glass material as the lower cladding 2 is generally used for the upper cladding 4. The shape of the optical waveguide core reshaped in step C is generally square or rectangular, but in some cases, it may be a shape similar to a trapezoid or a shape similar to top-pointed pentagon, depending on the reshaping method. However these can be essentially regarded as rectangular.

The above birefringence is formed by ion implantation during the process. The method is shown in FIG. 4. In the method shown in FIG. 4 A, after completing step B, ions are implanted into the portion to be the optical waveguide core, via a mask plate 5 having a cross-sectional triangular projection as shown in FIG. 4A. After completing step C in the method shown in FIG. 4 B, and after completing step D in the method shown in FIG. 4 C, then similarly to the method shown in FIG. 4 A, ions are implanted into the portion to be the optical waveguide core, via the mask plate 5 having the cross-sectional triangular projection. Ions are implanted by selecting the acceleration energy so as to stop in the optical waveguide core. At the ion-implanted portion 6, the refractive index is induced to increase due to the implanted ions. As a result, birefringence having approximately the same inclination as that of the slope of the triangular projection can be formed in the optical waveguide core.

The birefringence formed by the abovementioned processes has a similar shape to those of (1) and (5) enumerated in FIG. 3. Birefringence in shapes other than those enumerated in FIG. 3 can also be readily formed by selecting the appropriate mask and the acceleration energy of the ions at the ion implantation. For example, in order to form the birefringence in the shape shown in (3) of FIG. 3, the optical waveguide may be covered with a mask to avoid ion implantation into the left half of the optical waveguide core 3. Then ions may be implanted by selecting the acceleration energy so as to implant ions into the top half of the optical waveguide core 3. In order to form the birefringence in the shape shown in (2) of FIG. 3, after forming the birefringence in the shape shown in (3) of FIG. 3 by the abovementioned method, a mask covering the right half of the optical waveguide core 3 may be set, and then ions may be implanted by selecting the acceleration energy so as to implant ions into the bottom half of the optical waveguide core 3.

In case of transformation of the optical waveguide material (densification in the present example) as mentioned above, ions to be implanted may be any ions such as hydrogen, helium, boron, and phosphorus. Since heavy ions require a high energy to be accelerated to a high speed, and the resistance from the implanted glass materials against the ions is also increased, it is difficult for such ions to penetrate the material deeply. Therefore, in this example, hydrogen ions were implanted which are the lightest and are readily accelerated, and hence readily penetrate the material more deeply. In case of the refractive index change due to the chemical bond, of course, the ions to be implanted are required to contain elements to induce the refractive index change by chemical reaction. However, even in this case, there are a plurality of candidates for the ion species to induce the refractive index change. The acceleration energy can be kept low when light ions are selected.

In the manufacturing method of the optical waveguide according to the present invention described above, the mask plate is used when implanting ions into the optical waveguide core. However, in forming the birefringence in the shape of (7) enumerated in FIG. 3, a method requiring no mask plate may be used in the process of the ion implantation. In this process, in the step after completing step C of the manufacturing process in FIG. 4 B, as shown in FIG. 5, by irradiating ion beams obliquely from upper side into the optical waveguide core without using the mask plate, birefringence in the shape of (7) of FIG. 3 can be formed in the optical waveguide core.

As shown above, the phase difference between the plane of polarization of an incident beam and the plane of polarization of the emitting beam is determined depending on the shape of the ion-implanted portion in the optical waveguide core, the amount of implanted ions, and the length of the ion-implanted portion. Therefore, by controlling the three parameters, an optional polarization converter such as a $1/2$ wave plate, a $1/4$ wave plate, or the like can be designed and formed in the optical waveguide.

Moreover, in an optical device such as an arrayed waveguide grating comprising the optical waveguide shown in FIG. 6, by forming a polarization converter 10 at the center of the arrayed waveguide, it becomes possible to obtain an arrayed waveguide grating which can reliably couple or branch multichannel lightwaves without polarization dependency.

Furthermore, in a planar optical waveguide having a location where it is desired to decrease polarization dependency, the structure for changing the plane of polarization as mentioned above may be applied to this location without specifying the length of the ion-implanted portion. Since the plane of polarization is always changed in this ion-implanted portion, this portion has no polarization dependency. Moreover, by applying the structure for changing the plane of polarization as mentioned above to almost all of the planar optical waveguide without specifying the location, a planar optical waveguide having no polarization dependency may also be produced.

Such an example is shown as follows. The optical device is called a directional coupler. FIG. 7 A shows a conceptual diagram of a directional coupler formed in a planar optical waveguide, and FIG. 7 B is a perspective view thereof. As shown in FIG. 7, a directional coupler is an optical device in which two cores 20a and 20b are formed to be partially adjacent to each other, and is used for transferring a beam propagating through one core into the other core, at this adjacent portion called coupling portion 21. This transfer is generally called coupling, and the ratio of the intensity of the transferring beam to that of the incident beam is called the coupling ratio. The coupling ratio is determined by characteristics such as the length of the coupling portion 21, the distance between the two cores at the adjacent portion, the shape of the cores, the refractive index of the cores, and the refractive index of the cladding 22. It is possible to transfer all beams input from one core to the other core. Moreover it is possible to divide them in a desired ratio. However, regarding the directional coupler formed in this planar optical waveguide, it is known that it is difficult to decrease the polarization dependency, and the polarization dependency has been high.

For the sample, at first a SiO₂ glass of 1 mm thickness was prepared as the substrate and the lower cladding. Then a layer to be an optical waveguide core 23 of 6 μm thickness was formed thereon by a chemical vapor deposition method (CVD method). Then, this core layer was shaped so as to form the directional coupler. This directional coupler was such that the cross-section of the core was a square of 6 x 6 μm, the distance between the two cores in the coupling portion was 3 μm, and the length of the coupling portion was 120 μm. After shaping the core, as shown in FIG. 5, ions were implanted obliquely from upper side at an angle of 45 degrees to the cross-section of this optical waveguide core. The implanted ions were hydrogen ions, and the ion implantation was performed so as to implant the ions at a depth of about 2 μm from the core surface. The amount of implanted ions was about $1 \times 10^{16}/\text{cm}^2$. Moreover, the ions were implanted into the overall coupling portion. FIG. 8 shows the cross-section of the ion-implanted core of this sample. Then, the upper cladding made of a SiO₂ glass with 20 μm thickness was formed by a CVD method.

According to comparing the polarization dependency between the directional coupler produced as described above, and a directional coupler produced by a similar process but without the ion implantation process, a decrease of the polarization dependency in the ion-implanted sample was observed by 2 to 3 dB. In this way, by using the present invention, an optical device having low polarization dependency can be produced.

The present invention is not to be limited by this example, and configurations which can obtain a similar effect by substituting or modifying a substantially equivalent concept by a person skilled in the art, also belong within the scope of the present invention.

CLAIMS

1. An optical device with an optical waveguide core having a substantially square or rectangular cross-section, wherein ions are implanted into at least a portion of said optical waveguide core, and said ion-implanted portion is formed so as to be asymmetric with respect to each of the vertical and horizontal line passing through the center of the cross-section of the optical waveguide core.
2. The optical device with an optical waveguide core having a substantially square or rectangular cross-section according to claim 1, wherein said ion-implanted portion includes a central portion of the square or rectangular cross-section of the optical waveguide core, and is formed along any one of two diagonals.
3. The optical device according to either one of claim 1 and claim 2, wherein said optical device is a planar optical waveguide.
4. The optical device according to either one of claim 1 and claim 2, wherein said optical device is a polarization converter.
5. The optical device according to either one of claim 1 and claim 2, wherein said optical device is an arrayed waveguide grating.
6. The optical device according to any one of claim 1 through claim 5, wherein in said optical device, polarization dependency of said optical device is reduced.
7. A manufacturing method for an optical device with an optical waveguide comprising:
 - a step for forming a lower cladding on a substrate;
 - a step for forming an optical waveguide core having a substantially square or rectangular cross-section, on the lower cladding;
 - an ion implantation step for forming an ion-implanted portion so as to be asymmetric with respect to each of the vertical and horizontal line passing through the center of the cross-section of said optical waveguide core, on at least a portion of said

optical waveguide core; and

a step for forming an upper cladding on the lower cladding including said optical waveguide core.

8. The manufacturing method for an optical device according to claim 6, wherein the ion implantation is performed by irradiating ions obliquely from upper side of the cross-section of said optical waveguide core.

1/10

FIG. 1A

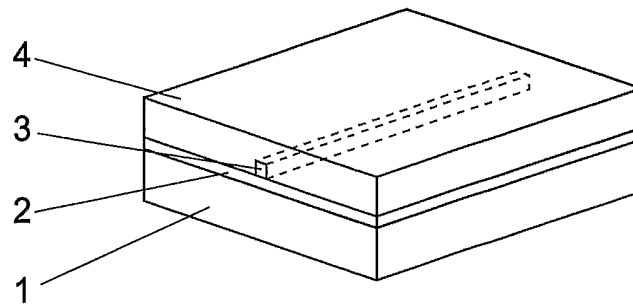


FIG. 1B

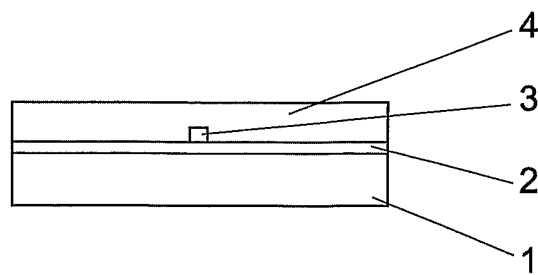
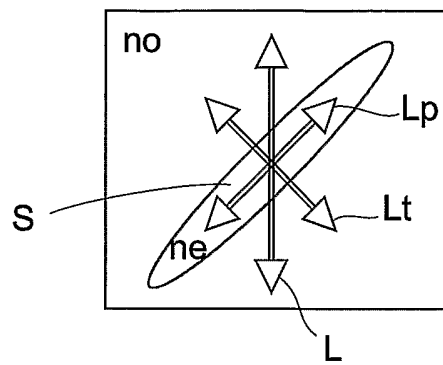


FIG. 2



3/10

FIG. 3

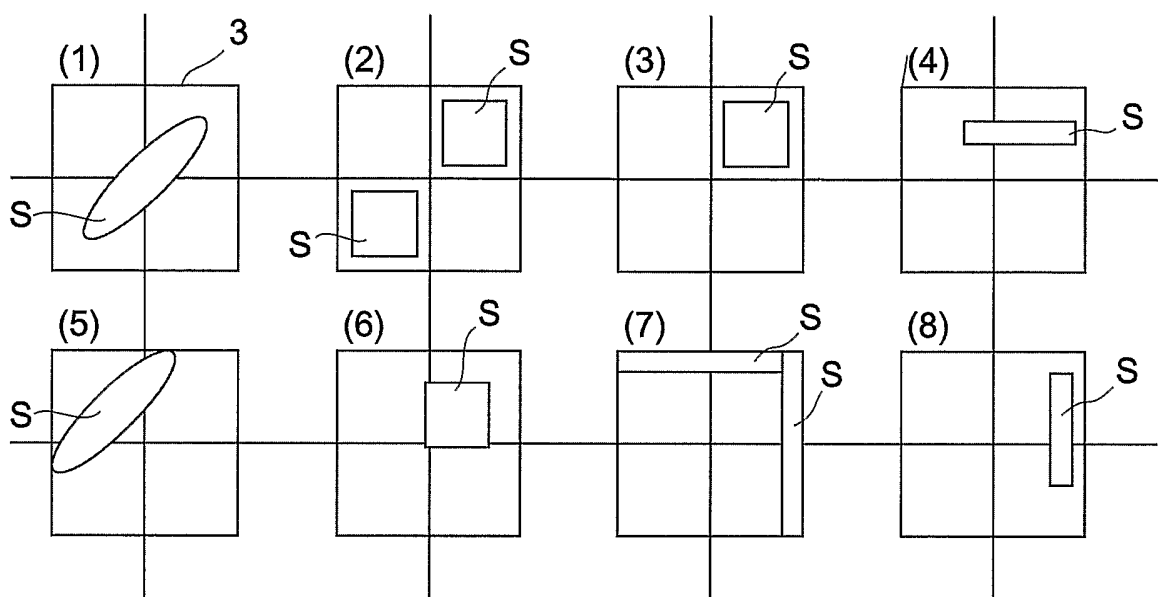


FIG. 4A

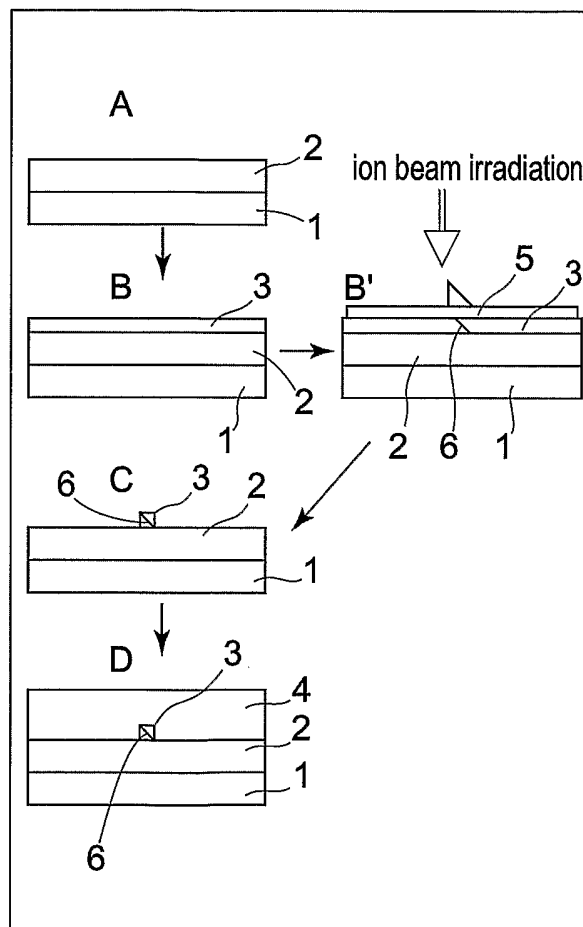
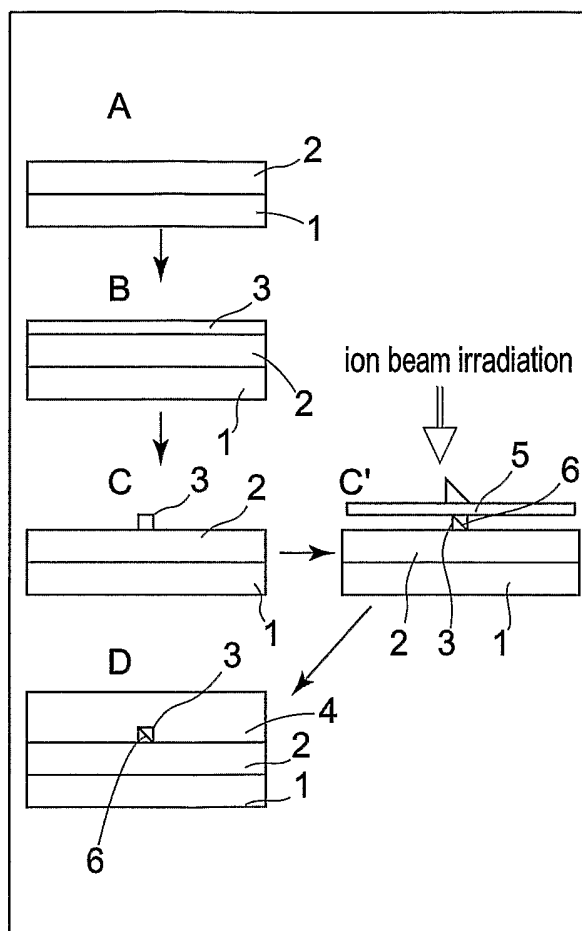
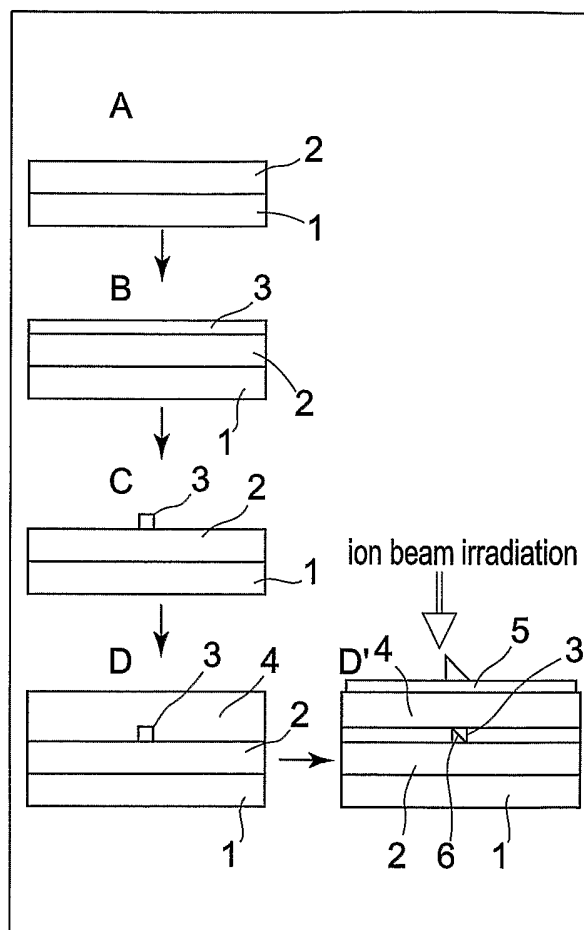


FIG. 4B



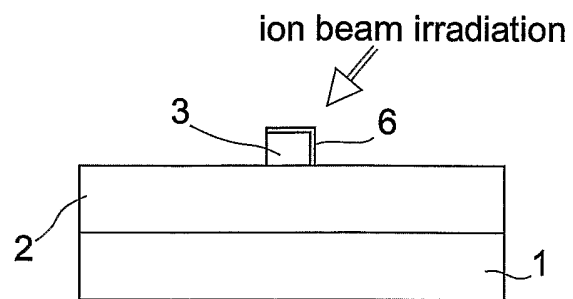
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FIG. 4C



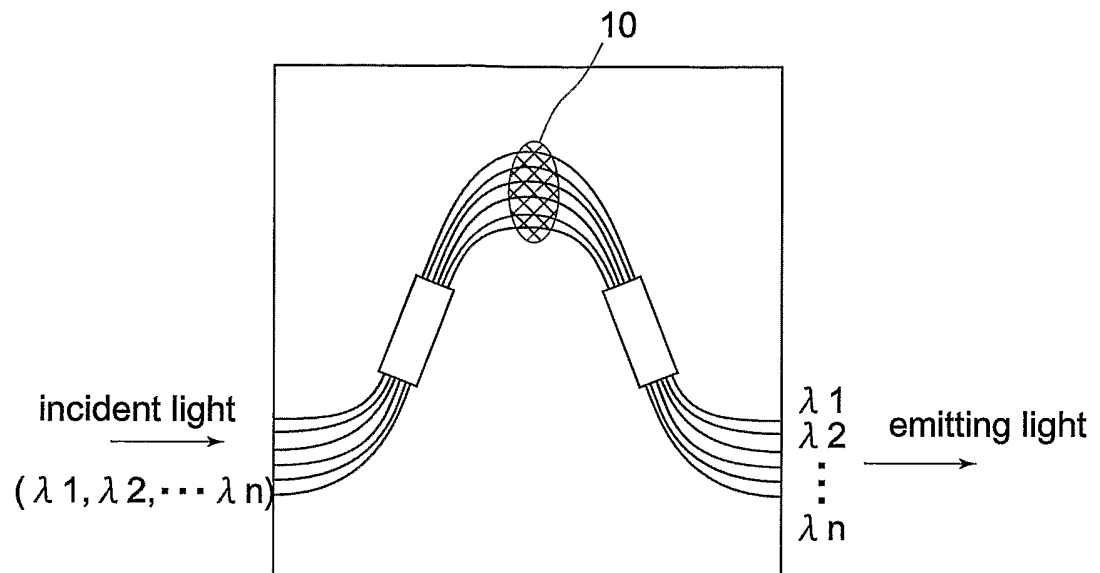
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FIG. 5



8/10

FIG. 6



9/10

FIG. 7A

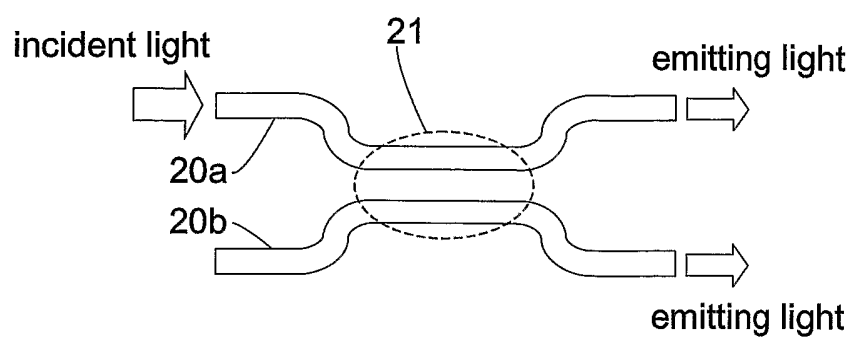
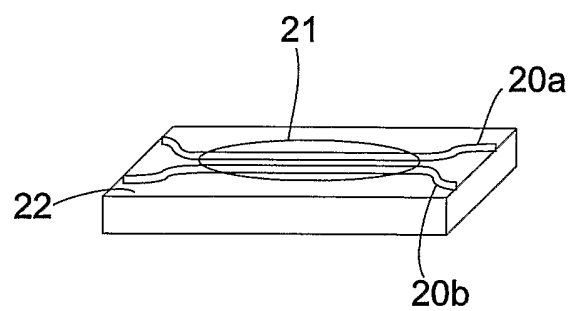
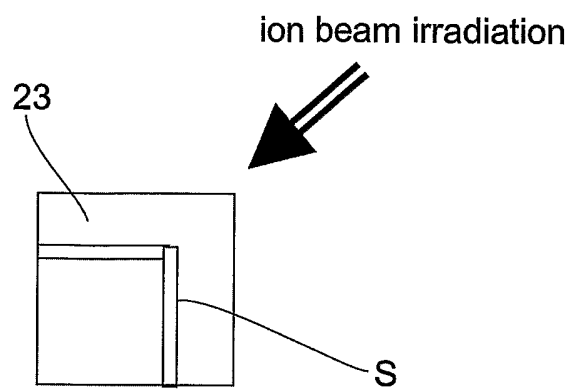


FIG. 7B



10/10

FIG. 8



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2005/003250

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl.⁷ G02B6/122, 6/13

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)

Int.Cl.⁷ G02B6/10, 6/122, 6/13

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

Published examined utility model applications of Japan 1922-1996
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 Registered utility model specifications of Japan 1996-2005
 Published registered utility model applications of Japan 1994-2005

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

JICST ファイル (JOIS)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1369715 A1 (National Institute of Advanced Industrial Science and Technology) 2003.12.10, paragraphs [0045]-[0055], FIG. 3 & US 2003/223715 A1 & JP 2004-12538 A & CA 2430352 A	1-8
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☒ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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