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(54) MULTICORE OPTICAL FIBER

(71) Applicant: **SUMITOMO ELECTRIC INDUSTRIES, LTD.**, Osaka (JP)

(72) Inventors: **Takemi HASEGAWA**, Osaka (JP); **Tetsuya HARUNA**, Osaka (JP); **Hirotaka SAKUMA**, Osaka (JP); **Takahiro SUGANUMA**, Osaka (JP); **Shin SATO**, Osaka (JP); **Yuto KOBAYASHI**, Osaka (JP)

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(57) **ABSTRACT**

A multicore optical fiber includes a plurality of cores along a fiber axis and cladding surrounding the plurality of cores. The plurality of cores includes a first core having an elliptical shape in a cross section orthogonal to the fiber axis and one or more second cores different from the first core. The non-circularity of the elliptical shape is 0.1% or more. In the cross section orthogonal to the fiber axis, an angle formed by a straight line connecting a center of gravity of the first core and a center of gravity of a core group including one or more second cores and a straight line along a major axis of the elliptical shape is 30 degrees or less. Polarization mode dispersion is 0.2 ps/rtkm or less.

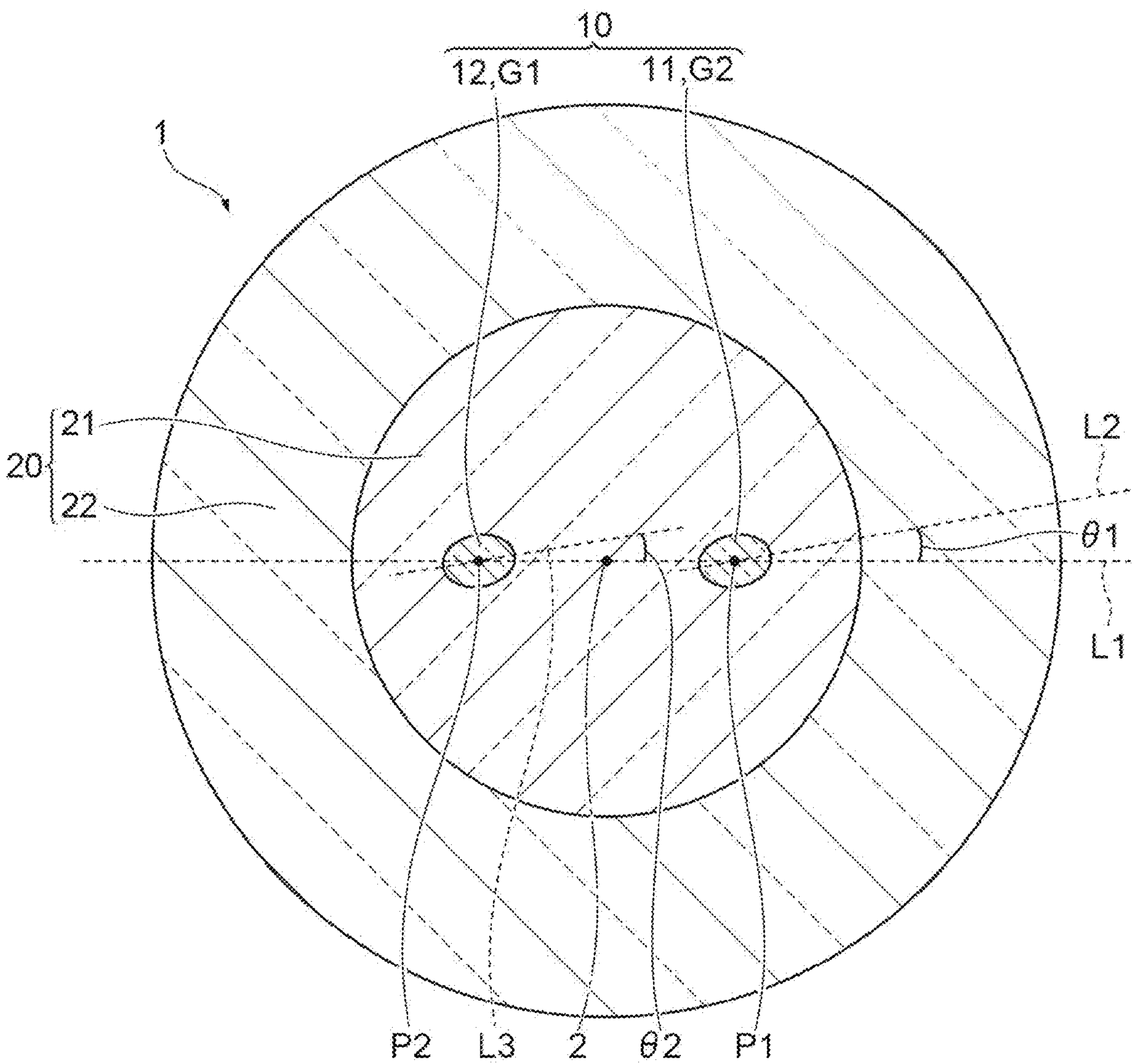
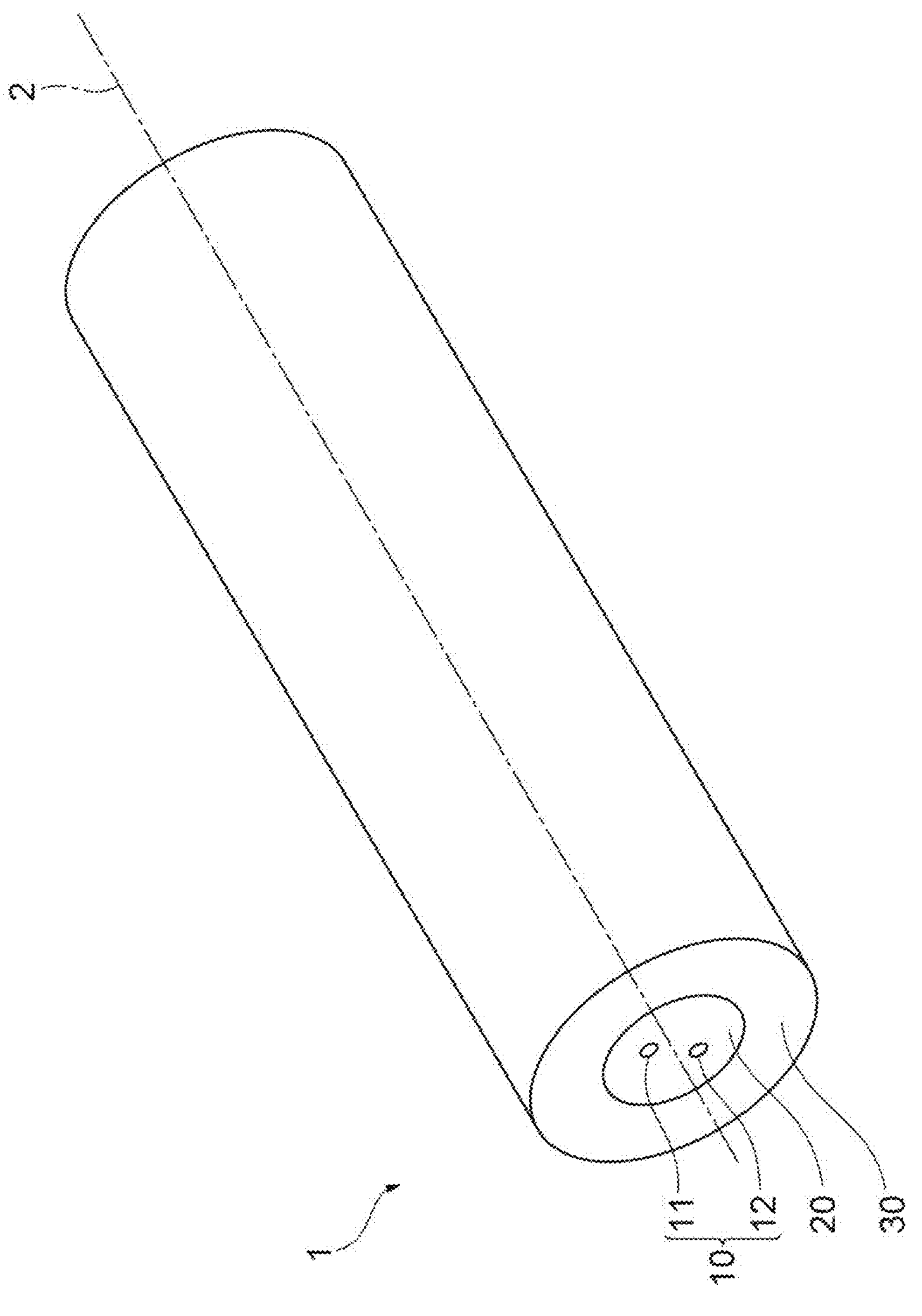


Fig.1



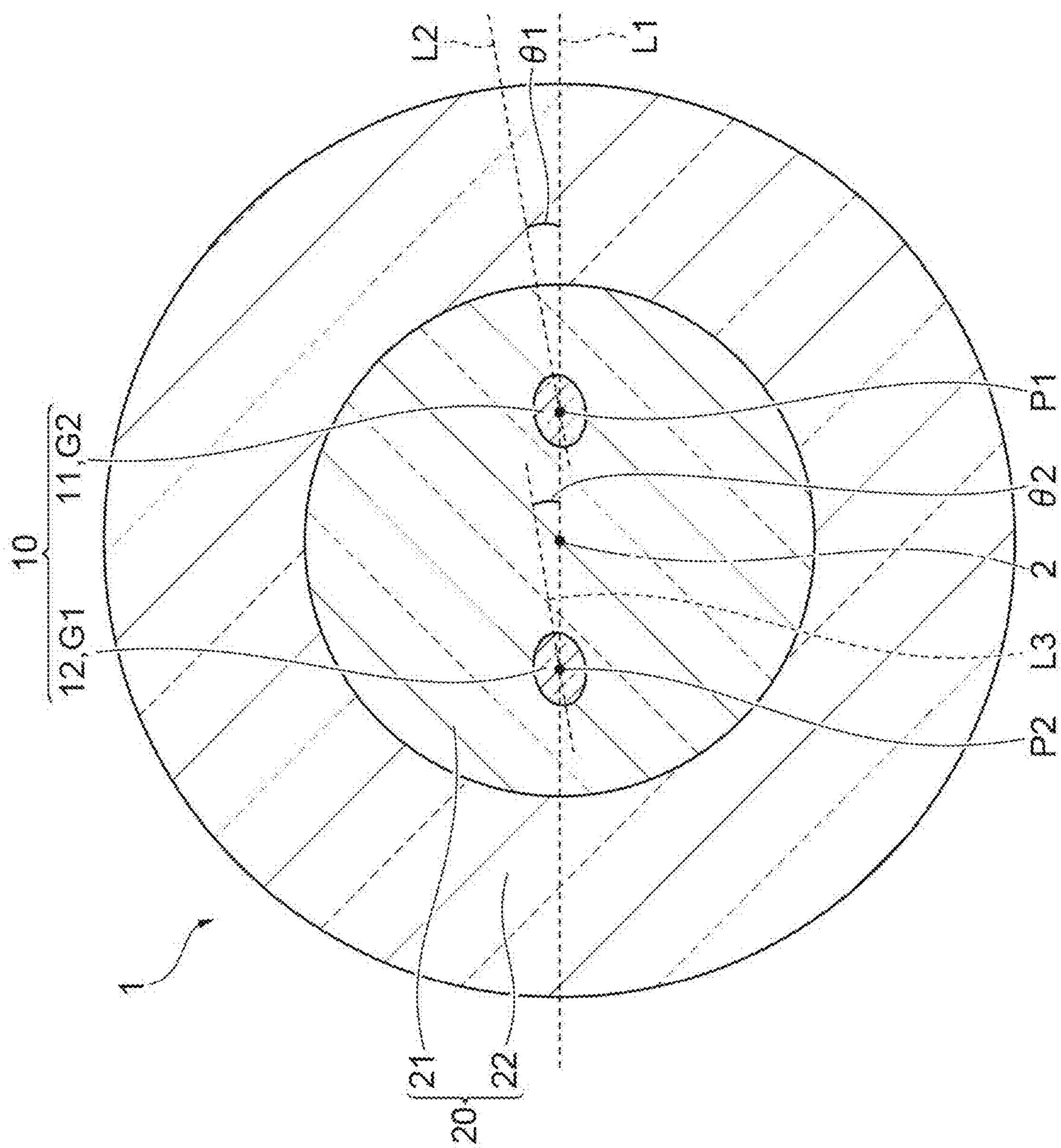
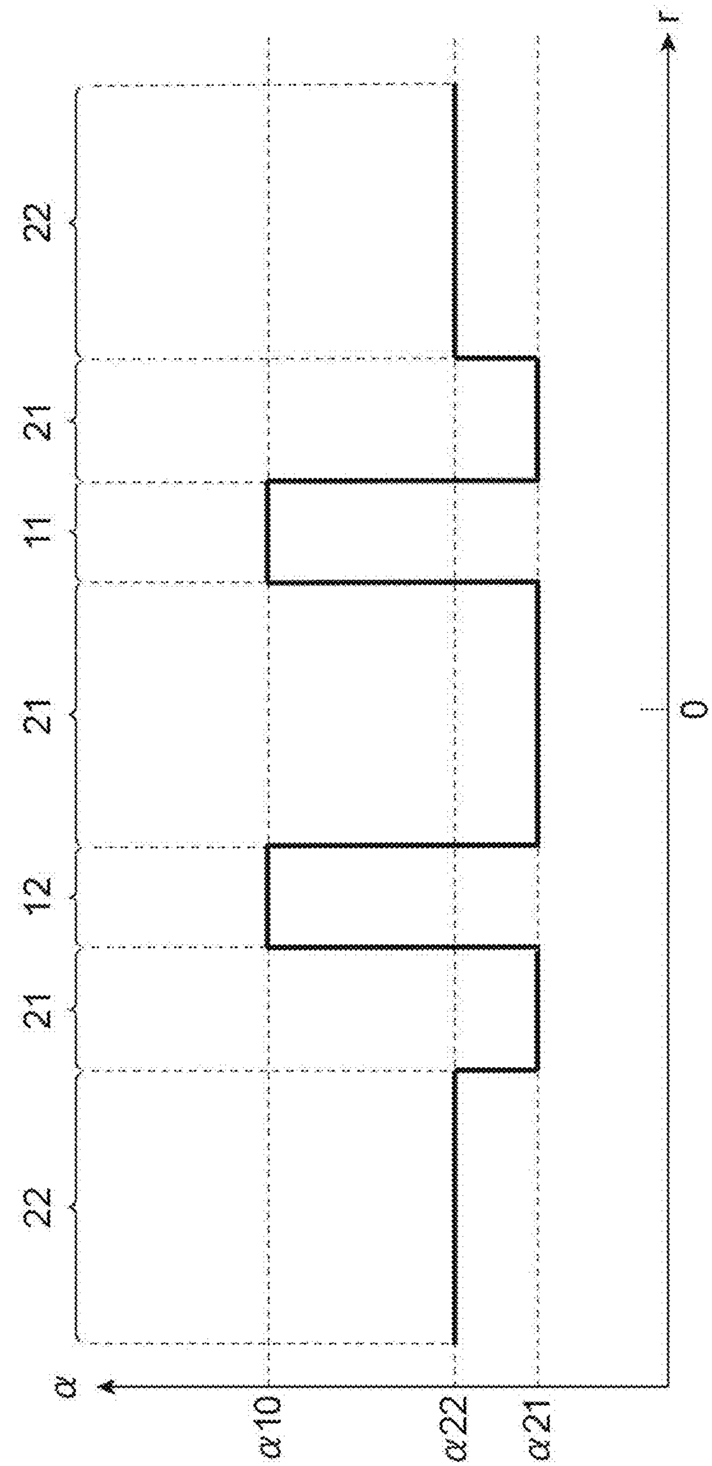


Fig.2

Fig.3



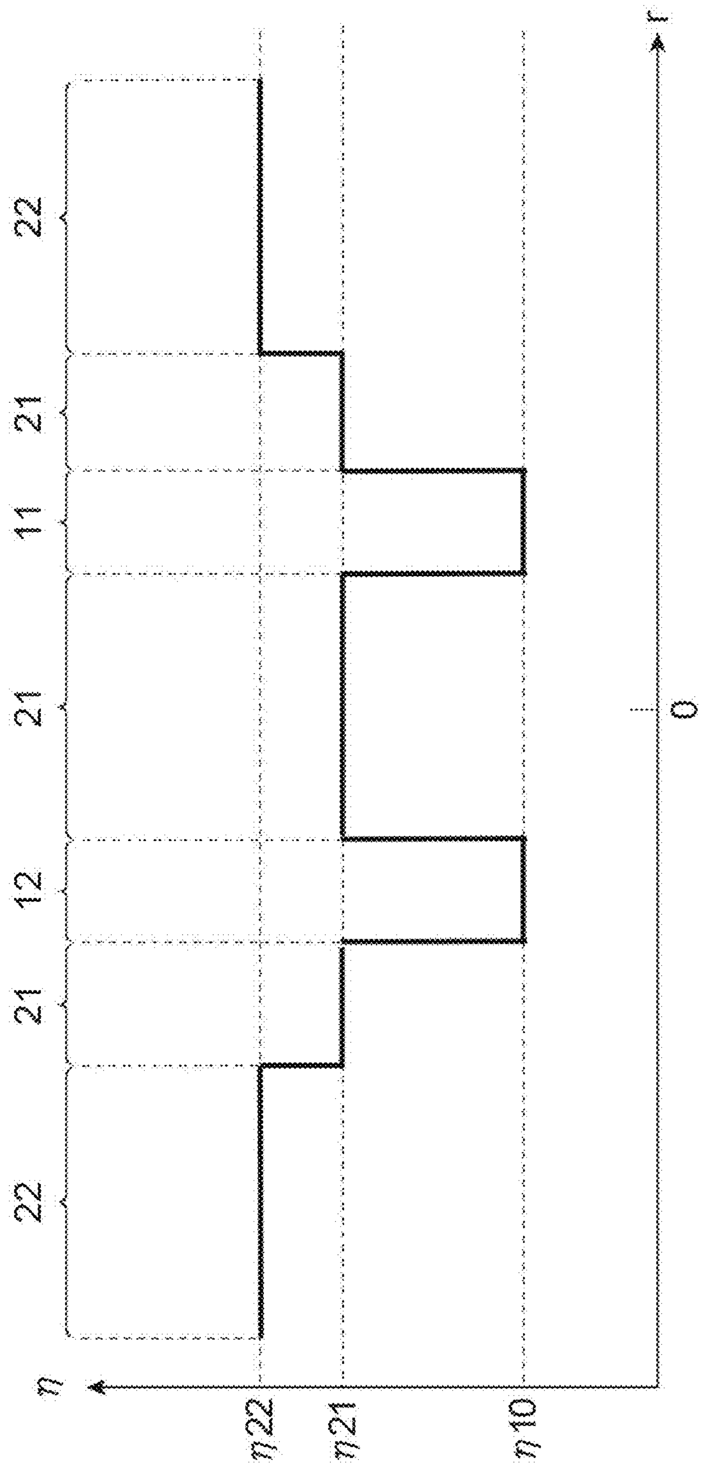
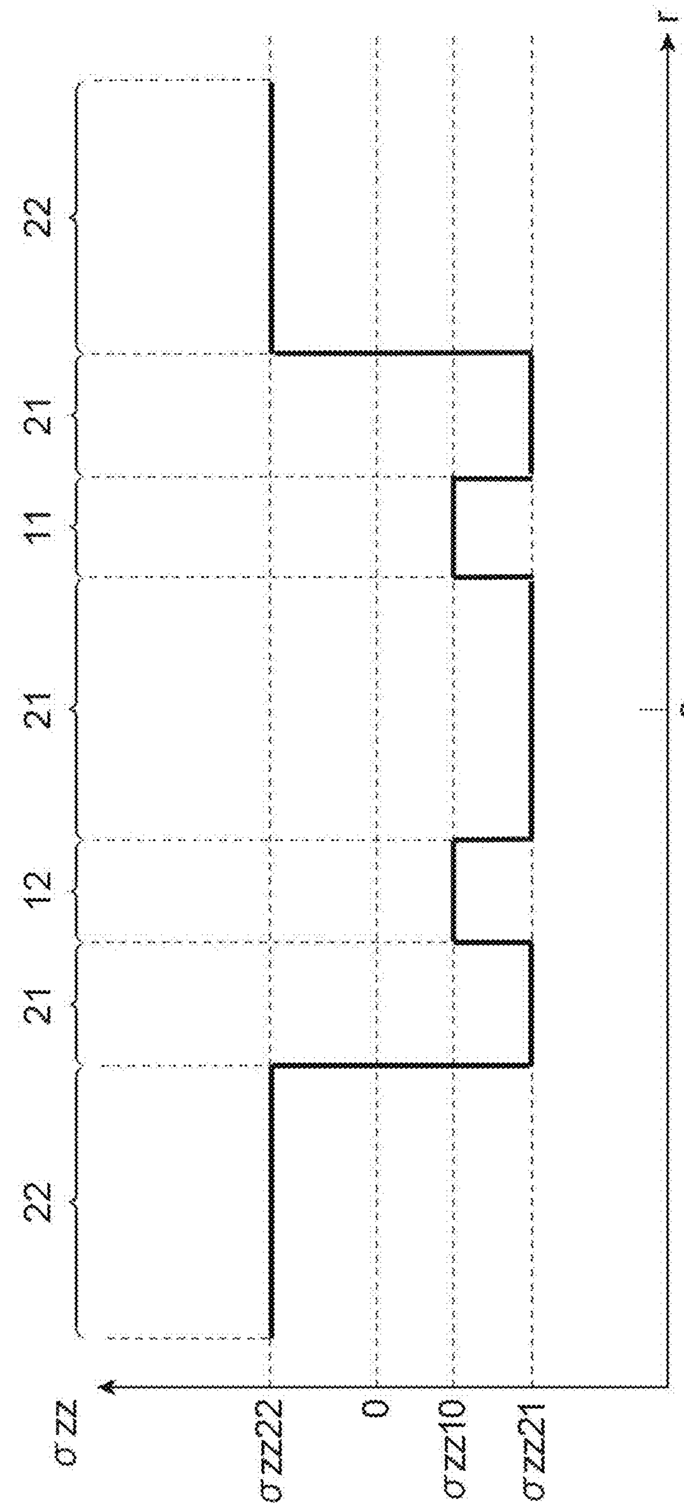


Fig.4

Fig.5



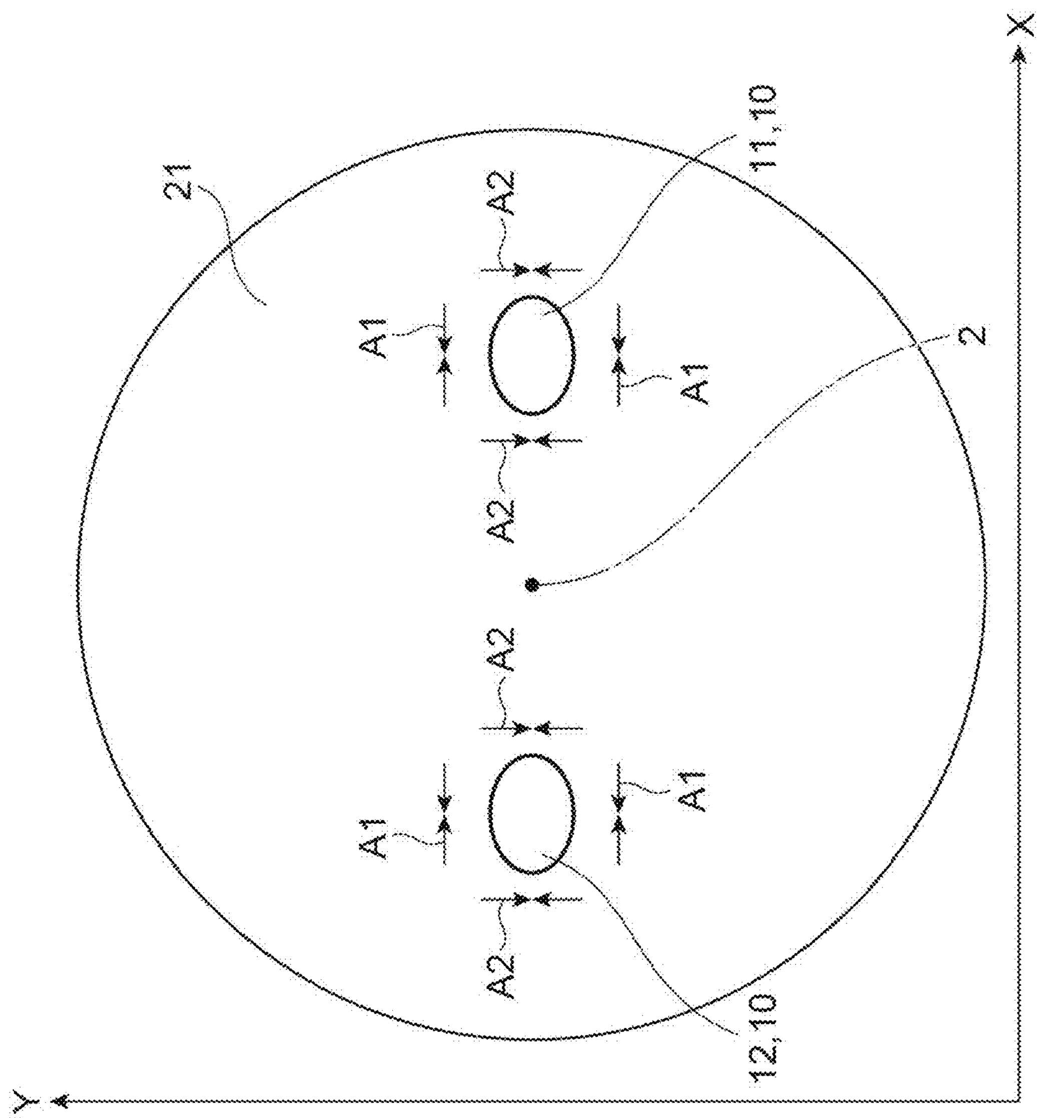


Fig.6

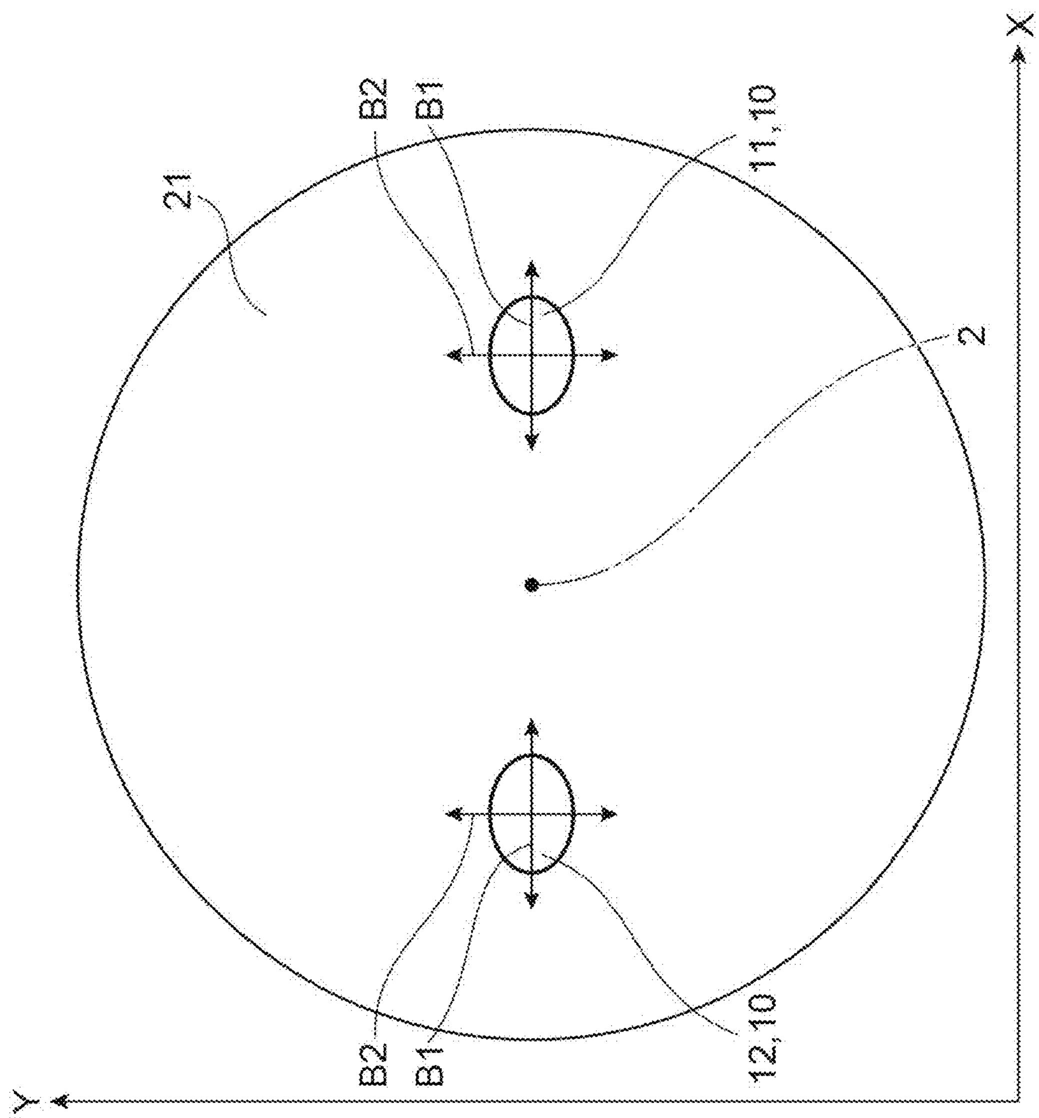


Fig.7

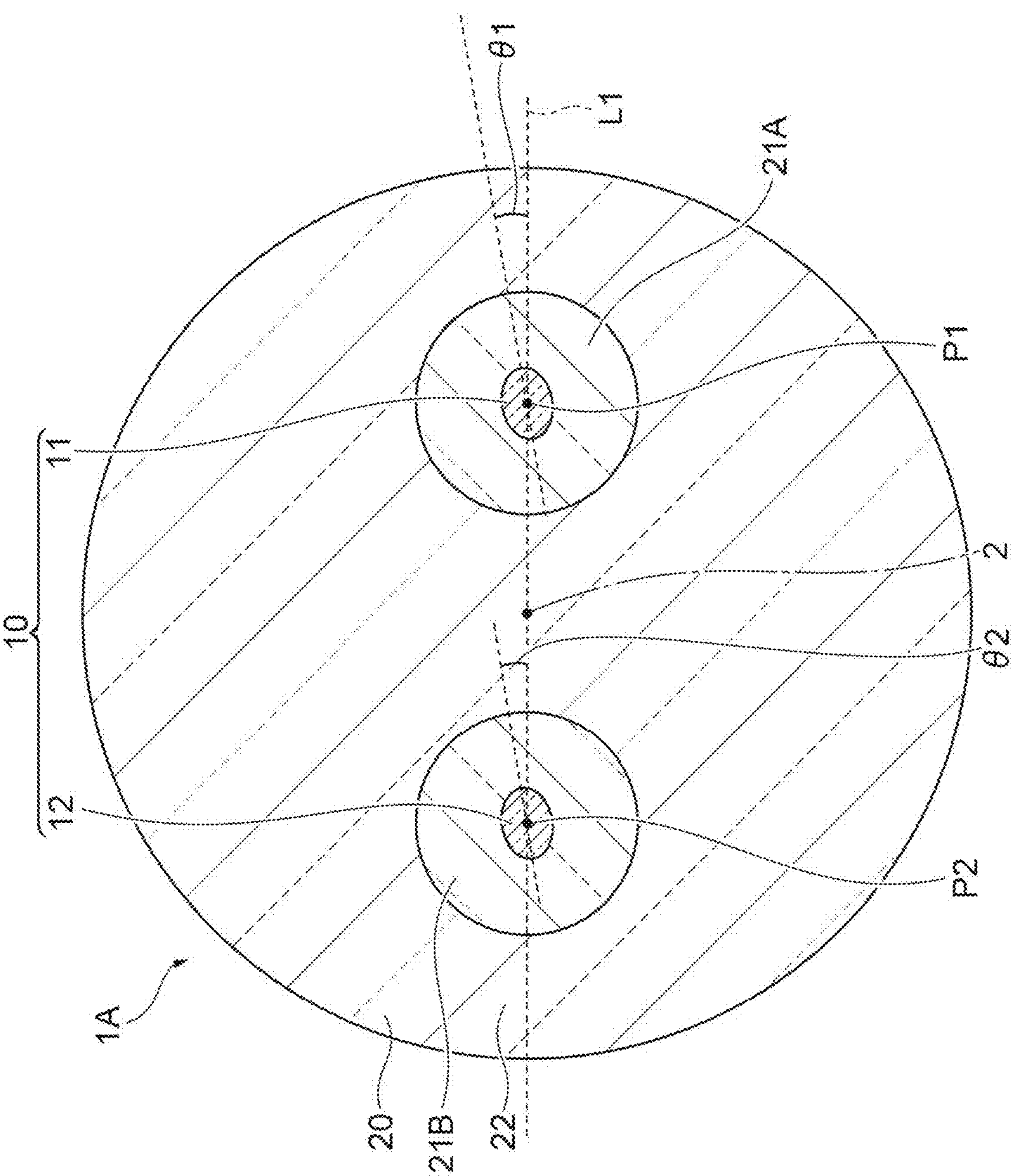


Fig.8

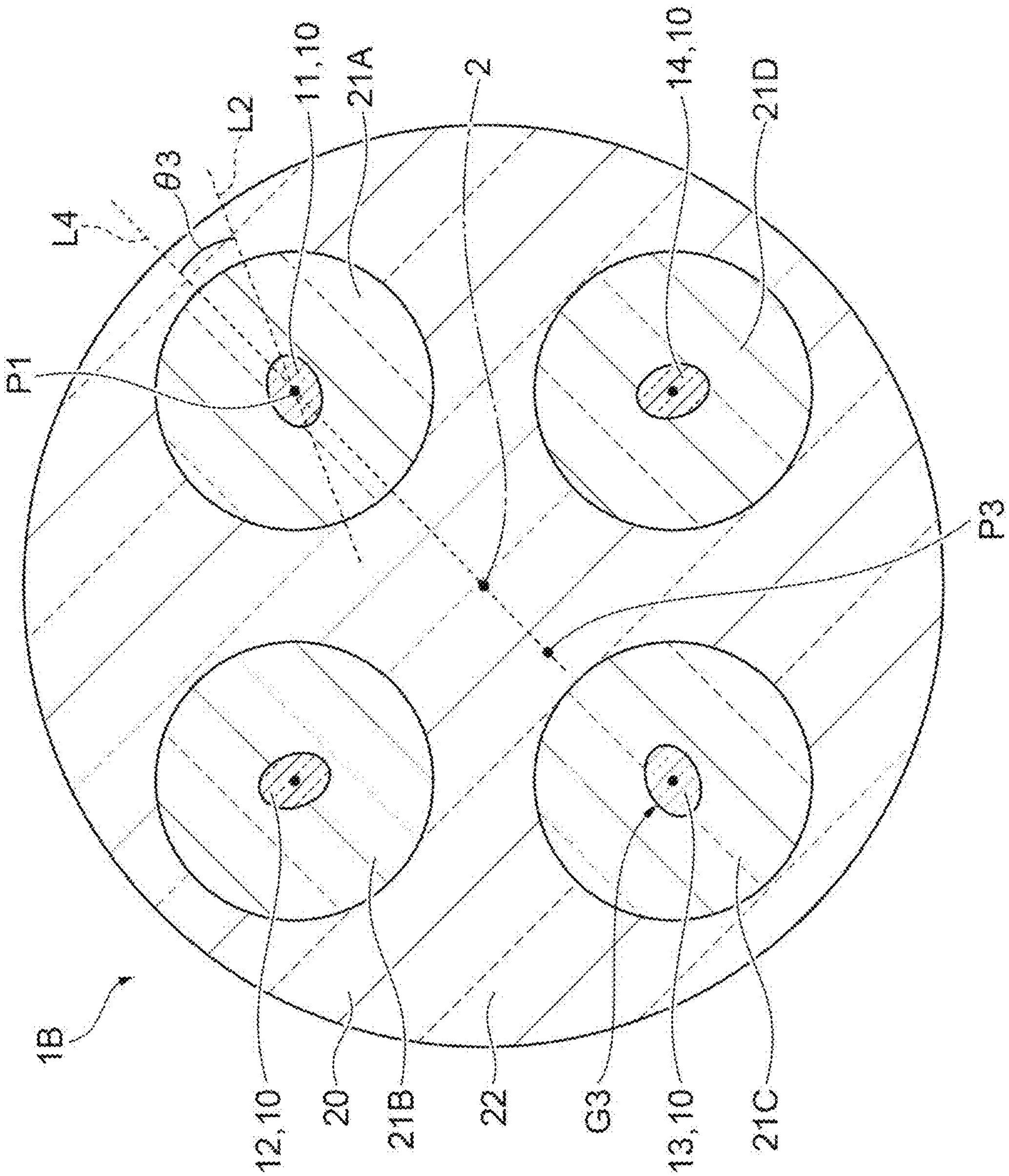


Fig.9

Fig.10

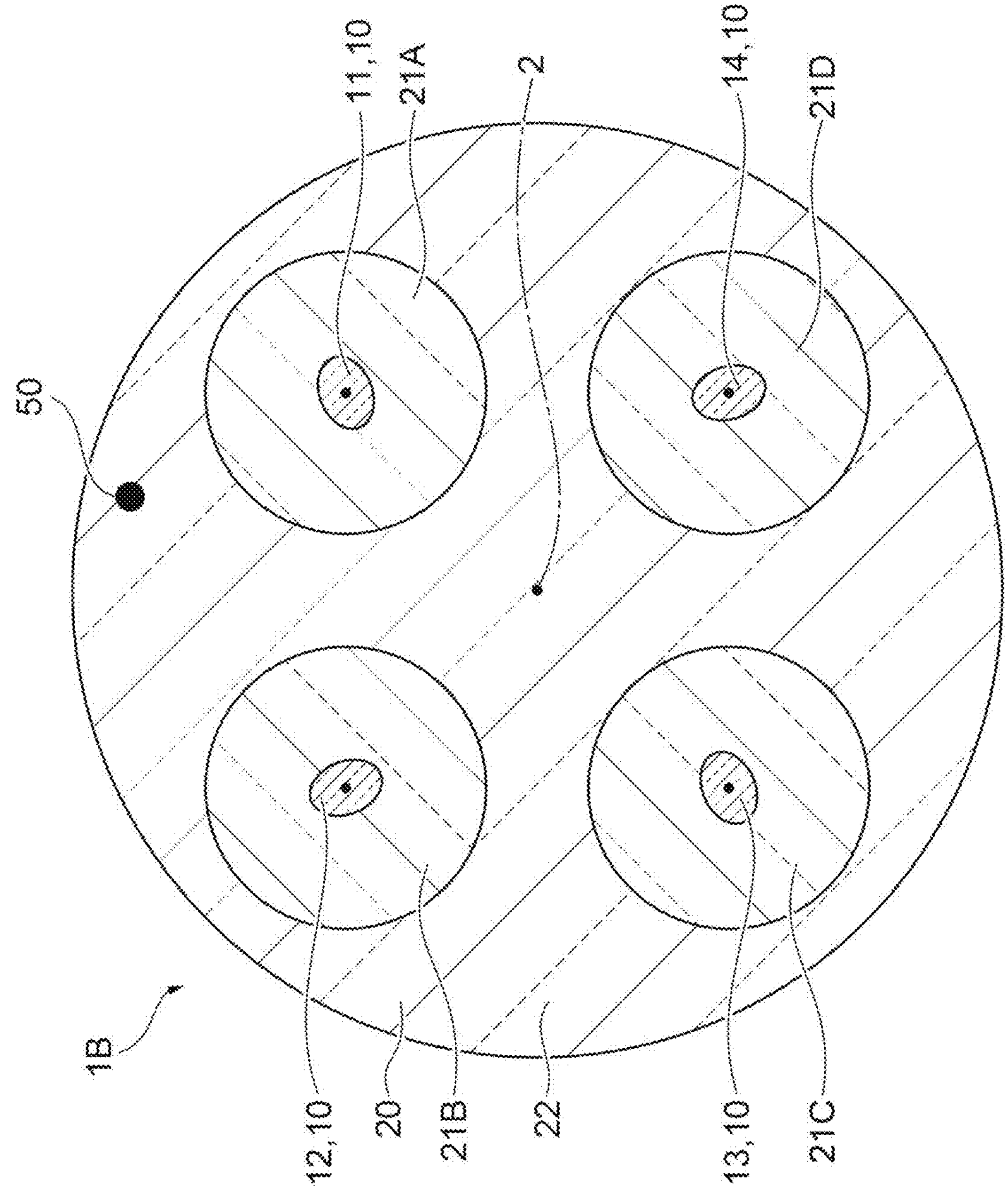
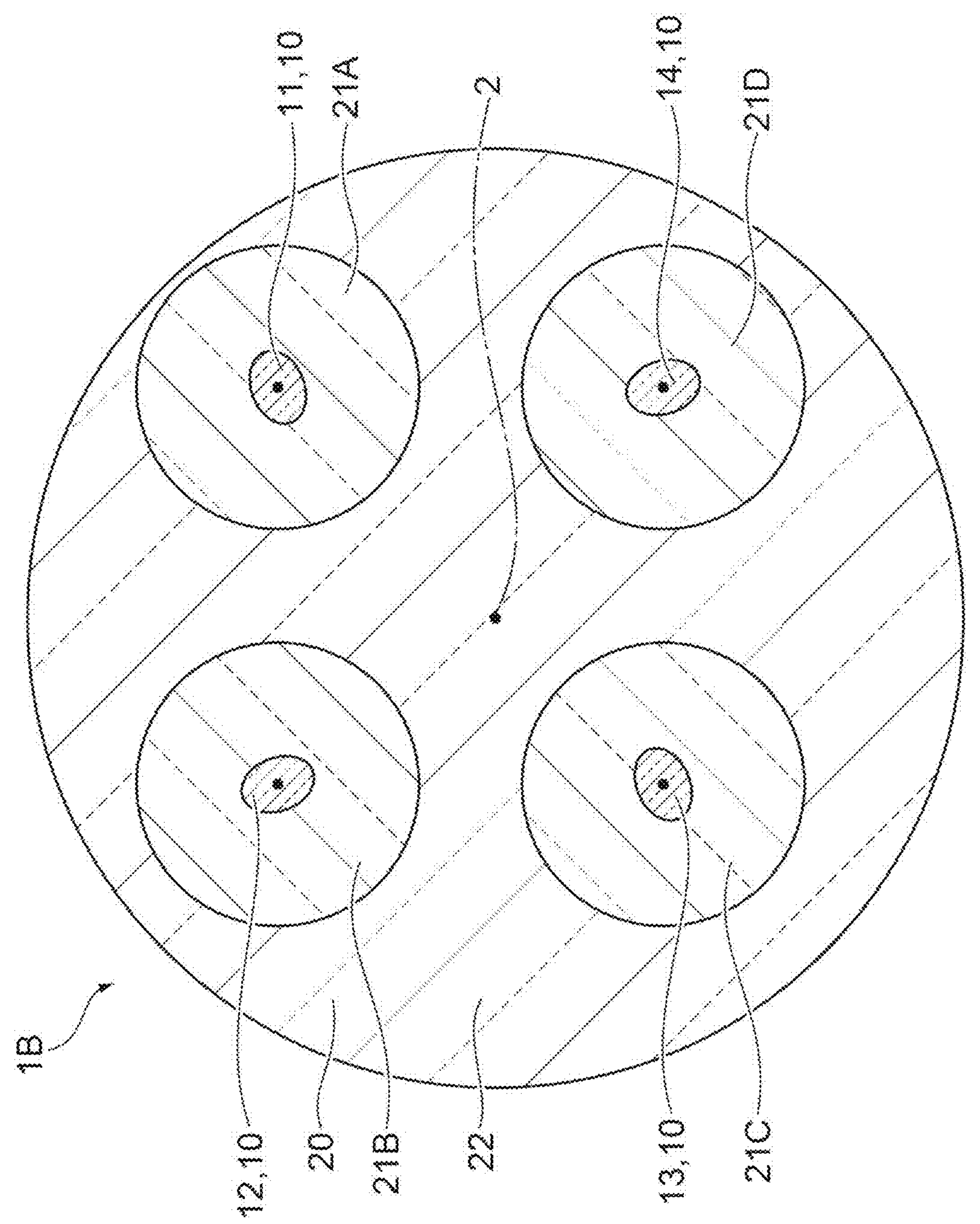


Fig.11



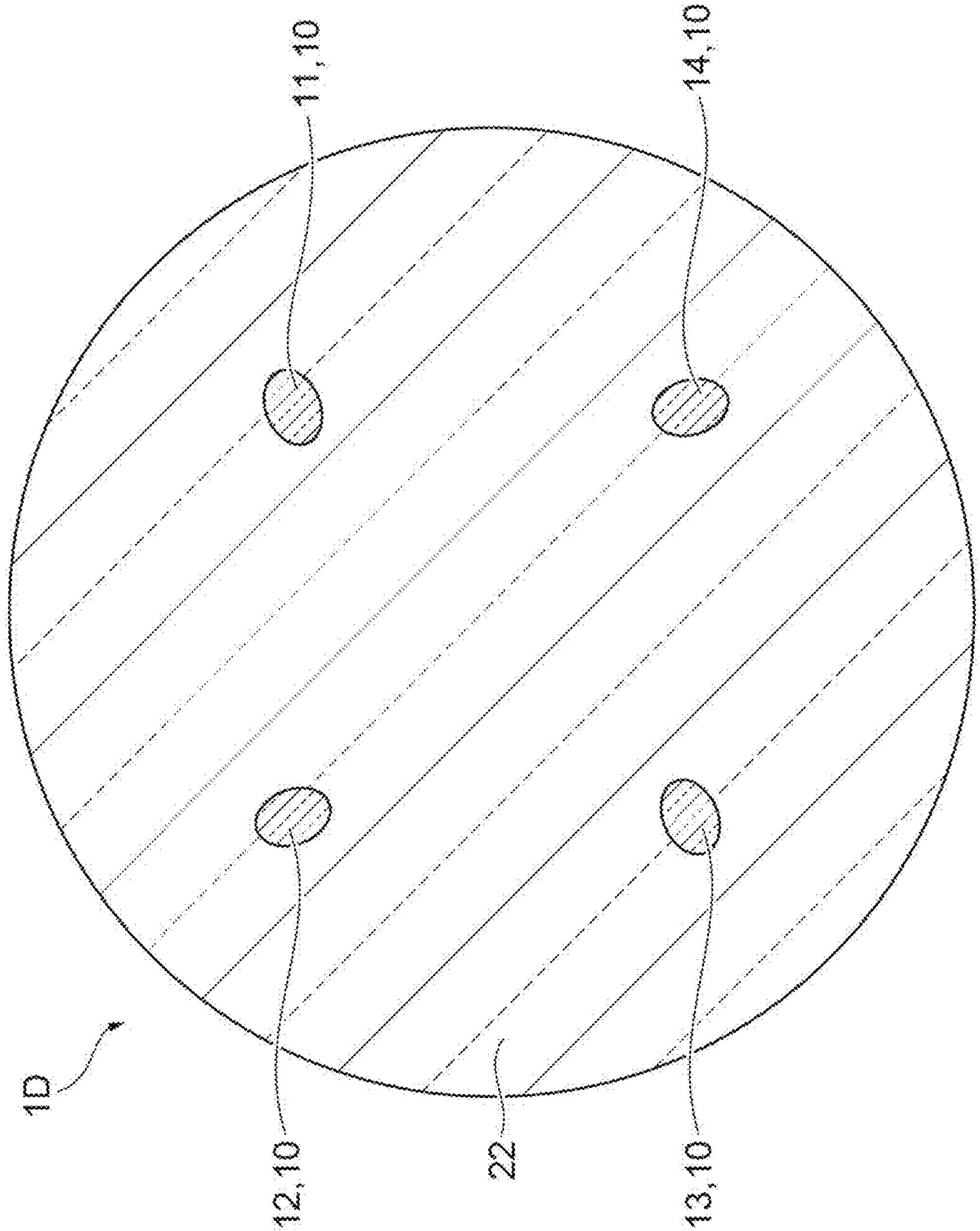


Fig.12

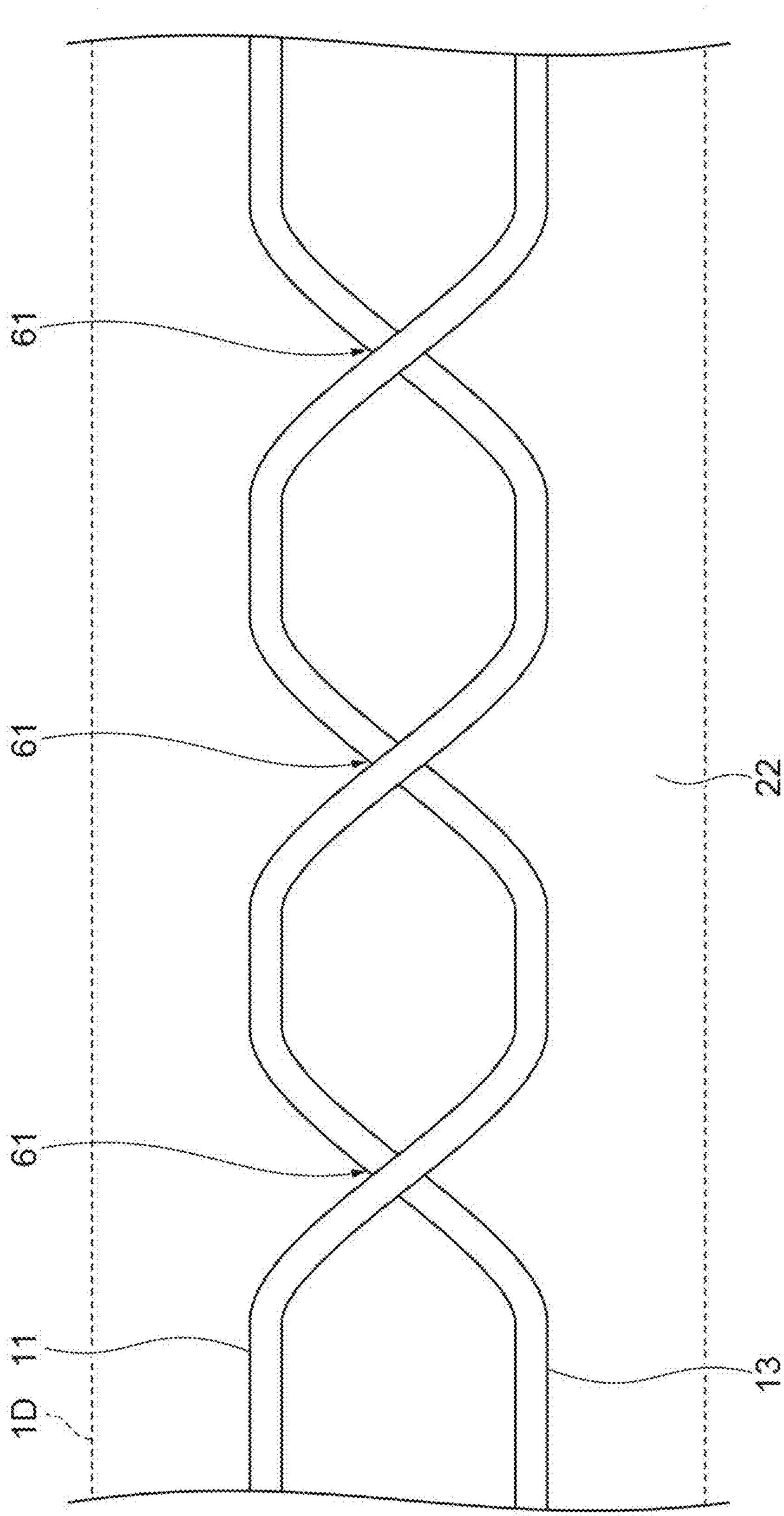


Fig.13

MULTICORE OPTICAL FIBER

TECHNICAL FIELD

[0001] The present disclosure relates to a multicore optical fiber. The present application claims priority based on Japanese Patent Application No. 2024 020217 filed on Feb. 14, 2024 and priority based on Japanese Patent Application No. 2024-178618 filed on Oct. 11, 2024, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0002] There is known a technique for reducing polarization mode dispersion (PMD) in a multicore optical fiber including a plurality of cores and cladding surrounding the plurality of cores. For example, in a method for manufacturing a multicore optical fiber disclosed in US 2015/0307387 A1, a plurality of core canes having no hole in the center is inserted into holes of a soot blank to be cladding, and the core canes and the soot blank are sintered. As a result, low non-axial symmetry is achieved near the center of the core cane, and lower polarization mode dispersion is achieved. US 2011/0206330 A1 discloses that a plurality of multicore units included in a multicore optical fiber has threefold or more rotational symmetry, so that structural asymmetry is reduced and an increase in polarization mode dispersion is prevented.

SUMMARY

[0003] A multicore optical fiber according to an embodiment of the present disclosure includes a plurality of cores along a fiber axis and cladding surrounding the plurality of cores, in which the plurality of cores and the cladding contain silica glass as a main component, a refractive index of each of the plurality of cores is higher than a refractive index of the cladding, a coefficient of thermal expansion of each of the plurality of cores is higher than a coefficient of thermal expansion of the cladding, the plurality of cores includes a first core having an elliptical shape in a cross section orthogonal to the fiber axis and one or more second cores different from the first core, non-circularity of the elliptical shape is 0.1% or more, an angle formed by a straight line connecting a center of gravity of the first core and a center of gravity of a core group including the one or more second cores and a major axis of the elliptical shape in the cross section orthogonal to the fiber axis is 30 degrees or less, and polarization mode dispersion is 0.2 ps/rtkm or less.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1** is a perspective view of an optical fiber according to a first embodiment;

[0005] FIG. **2** is a cross-sectional view of the optical fiber orthogonal to a fiber axis;

[0006] FIG. **3** is a graph schematically illustrating a distribution of a coefficient of thermal expansion in the optical fiber;

[0007] FIG. **4** is a graph schematically illustrating a distribution of viscosity in the optical fiber;

[0008] FIG. **5** is a graph schematically illustrating a distribution of stress in the optical fiber;

[0009] FIG. **6** is a view schematically illustrating in-plane stress in a cross section orthogonal to the fiber axis;

[0010] FIG. **7** is a view schematically illustrating a slow axis direction of birefringence of a fundamental mode in a core;

[0011] FIG. **8** is a cross-sectional view of an optical fiber according to a second embodiment;

[0012] FIG. **9** is a cross-sectional view of an optical fiber according to a third embodiment;

[0013] FIG. **10** is a cross-sectional view of an optical fiber according to a modification;

[0014] FIG. **11** is a cross-sectional view of an optical fiber according to a modification;

[0015] FIG. **12** is a cross-sectional view of an optical fiber according to a modification; and

[0016] FIG. **13** is a view schematically illustrating an internal structure of the optical fiber according to the modification.

DETAILED DESCRIPTION

Problem to be Solved by Present Disclosure

[0017] Even in a multicore optical fiber in which low non-axial symmetry is achieved near the center of a core as disclosed in US 2015/0307387 A1, polarization mode dispersion may be high in a case where the arrangement of the cores does not have threefold or more rotational symmetry. Therefore, there is a demand for a multicore optical fiber capable of reducing polarization mode dispersion even in a case where the arrangement of the cores does not have threefold or more rotational symmetry.

[0018] An object of the present disclosure is to provide a multicore optical fiber capable of reducing polarization mode dispersion.

Effects of Present Disclosure

[0019] The present disclosure provides a multicore optical fiber capable of reducing polarization mode dispersion.

Description of Embodiments of Present Disclosure

[0020] First, contents of embodiments of the present disclosure will be listed and described.

[0021] (1) A multicore optical fiber according to an aspect of the present disclosure includes a plurality of cores along a fiber axis and cladding surrounding the plurality of cores, in which the plurality of cores and the cladding contain silica glass as a main component, a refractive index of each of the plurality of cores is higher than a refractive index of the cladding, a coefficient of thermal expansion of each of the plurality of cores is higher than a coefficient of thermal expansion of the cladding, the plurality of cores includes a first core having an elliptical shape in a cross section orthogonal to the fiber axis and one or more second cores different from the first core, non-circularity of the elliptical shape is 0.1% or more, an angle formed by a straight line connecting a center of gravity of the first core and a center of gravity of a core group including the one or more second cores and a straight line along a major axis of the elliptical shape is 30 degrees or less in the cross section orthogonal to the fiber axis, and polarization mode dispersion is 0.2 ps/rtkm or less.

[0022] In this multicore optical fiber, the plurality of cores includes the first core having the elliptical shape in the cross section orthogonal to the fiber axis and the one or more second cores different from the first core. In addition, the angle formed by the straight line connecting the center of gravity of the first core and the center of gravity of the core group including the one or more second cores and the straight line along the major axis of the elliptical shape of the first core is 30 degrees or less. In this case, birefringence caused by stress caused by the arrangement of the cores and birefringence caused by a shape of the core are canceled out, and birefringence of a waveguide mode propagating through the first core is reduced. As a result, the polarization mode dispersion can be reduced.

[0023] (2) In the above (1), non-circularity of the elliptical shape may be 10% or less. In this case, it is possible to reduce connection loss when the multicore optical fiber is connected to a normal optical fiber having small non-circularity.

[0024] (3) In the above (1) or (2), the plurality of cores and the cladding may contain fluorine, and the concentration of fluorine in the cladding may be higher than the concentration of fluorine in each of the plurality of cores. In this case, the core has a coefficient of thermal expansion larger than a coefficient of thermal expansion of the cladding, and the core contracts more strongly than the cladding due to cooling when the multicore optical fiber is drawn, so that compressive stress remains in the cladding close to the core in a circumferential direction of the core. As a result, although birefringence is caused by stress caused by the arrangement of the cores, the birefringence is canceled out by birefringence caused by the shape of the core, so that polarization mode dispersion can be reduced.

[0025] (4) In any one of the above (1) to (3), the cladding may include first cladding surrounding the plurality of cores and second cladding surrounding the first cladding, the first cladding and the second cladding may contain fluorine, the concentration of fluorine in the first cladding may be higher than the concentration of fluorine in the second cladding, and the plurality of cores may contain at least one kind of alkali element of an alkali element group including an alkali metal element and an alkaline earth metal element. In this case, for example, tensile tension caused by the drawing can be localized in the second cladding, a glass defect caused by the tensile tension can be prevented from occurring in the core and the first cladding, and loss of the multicore optical fiber can be reduced.

[0026] (5) In any one of the above (1) to (4), the plurality of cores may contain at least one kind of element of an alkali element group including an alkali metal element and an alkaline earth metal element, and the concentration of an alkali element in the plurality of cores may be 1 wtppm or more and 3000 wtppm or less. In this case, the viscosity of the core is sufficiently reduced, and excessive loss caused by the high concentration of the alkali element can be reduced. Therefore, the polarization mode dispersion and loss in the multicore optical fiber can be reduced.

[0027] (6) In any one of the above (1) to (5), the angle formed by the straight line connecting the center of gravity of the first core and the center of gravity of the core group including the one or more second cores and the straight line along the major axis of the elliptical shape may be 10 degrees or less. In this case, the polarization mode dispersion can be further reduced.

[0028] (7) In any one of the above (1) to (5), the angle formed by the straight line connecting the center of gravity of the first core and the center of gravity of the core group including the one or more second cores and the straight line along the major axis of the elliptical shape may be 5 degrees or less. In this case, the polarization mode dispersion can be further reduced.

Details of Embodiments of Present Disclosure

[0029] Specific examples of multicore optical fibers according to embodiments of the present disclosure will be described below with reference to the drawings. In the following description, the same reference signs will be used for the same elements or elements having the same functions, and the description will not be repeated to avoid redundancy. Note that the present disclosure is not limited to these examples, indicated by the claims, and intended to include all modifications within the meaning and scope equivalent to the claims.

[0030] With reference to FIGS. **1** and **2**, a configuration of an optical fiber **1** according to a first embodiment will be described. FIG. **1** is a perspective view of the optical fiber **1** according to the first embodiment. FIG. **2** is a cross-sectional view of the optical fiber **1** orthogonal to a fiber axis **2**. In FIG. **2**, illustration of a coating layer **30** is omitted. The optical fiber **1** includes a plurality of cores **10**, cladding **20**, and the coating layer **30**. The optical fiber **1** may be, for example, an optical fiber used for long-distance large-capacity transmission. The optical fiber **1** is a multicore optical fiber (MCF) including the plurality of cores **10** and includes two cores **10** in the present embodiment. Hereinafter, each of the two cores **10** may be described while being distinguished as a core **11** or a core **12**.

[0031] The core **10** is along the fiber axis **2** that is the central axis of the optical fiber **1**. The core **10** contains silica glass as a main component. More specifically, each of the core **11** and the core **12** contains silica glass as a main component. In the present specification, that a certain member contains silica glass as a main component means that 95 mass % or more of the member is formed of silica glass. In other words, 95 mass % or more of the core **10** is formed of silica glass.

[0032] The core **10** (core **11** and core **12**) contains at least one kind of alkali element of an alkali element group including an alkali metal element and an alkaline earth metal element. The alkali element is a term for an alkali metal element and an alkaline earth metal element in general. The alkali metal element is lithium (Li), sodium (Na), potassium (K), rubidium (Rb), or the like. The alkaline earth metal element is magnesium (Mg), calcium (Ca), strontium (Sr), barium (Ba), or the like. The concentration of the alkali element in the core **10** is 1 wtppm or more and 3000 wtppm or less. The concentration of the alkali element in the core **10** may be 10 wtppm or more and 300 wtppm or less.

[0033] The core **10** contains fluorine (F). The concentration of fluorine in the core **10** may be 1000 wtppm or more and 5000 wtppm or less. The composition of the core **10** and the cladding **20** can be calculated from known weight per atom by measuring a ratio of the number of atoms using a known method such as an electron probe micro analyzer (EPMA).

[0034] A refractive index of the core **10** is higher than a refractive index of the cladding **20**. As a result, light input to the optical fiber **1** is guided by the core **10**. A relative refractive index difference of the core **10** with respect to the cladding **20** is, for example, 0.3% or more and 0.6% or less. The refractive indexes of the core **10** and the cladding **20** can be measured by a known method such as a refracted near field (RNF) method. In the optical fiber **1**, a refractive index of a certain region (portion) is defined as an average value of refractive indexes in the region. A diameter (core diameter) of the core **10** is, for example, 7 μm or more and 14 μm or less. A single LP mode including two polarization modes is guided to the core **10**.

[0035] The cladding **20** surrounds the core **10**. As illustrated in FIG. **2**, the cladding **20** has first cladding **21** surrounding the core **10** and second cladding **22** surrounding the first cladding **21**. The cladding **20** contains silica glass as a main component. More specifically, each of the first cladding **21** and the second cladding **22** contains silica glass as a main component. In addition, the cladding **20** contains fluorine. The concentration of fluorine in the cladding **20** is higher than the concentrations of fluorine in the core **11** and the core **12**. More specifically, each of the first cladding **21** and the second cladding **22** contains fluorine. The concentration of fluorine in the first cladding **21** and the second cladding **22** is higher than the concentration of fluorine in the core **11** and the core **12**. The concentration of fluorine in the first cladding **21** is higher than the concentration of fluorine in the second cladding **22**. The concentration of fluorine in the first cladding **21** may be 8000 wtppm or more and 16000 wtppm or less. The concentration of fluorine in the second cladding **22** may be 0.5 times or higher and 0.9 times or less the concentration of fluorine in the first cladding **21**.

[0036] An outer diameter (diameter) of the second cladding **22** may be, for example, 124 μm or more and 126 μm or less. In a case where the diameter of the second cladding **22** is 124 μm or more and 126 μm or less, a standard fusion splicer or a connection means such as a connector can be used when the optical fiber **1** that is a first optical fiber is connected to a second optical fiber. A ratio of an outer diameter (diameter) of the first cladding **21** to an outer diameter of the second cladding **22** may be 0.4 or more and 0.7 or less.

[0037] The coating layer **30** surrounds the cladding **20** and is in close contact with an outer peripheral surface of the cladding **20**. The coating layer **30** is formed of, for example, a resin such as acrylate.

[0038] As illustrated in FIG. **2**, the core **10** has an elliptical shape in a cross section orthogonal to the fiber axis **2**. That the core **10** has an elliptical shape means that the non-circularity of an ellipse when a boundary line between the core **10** and the cladding **20** is fitted to the ellipse is non-zero. In a case where a long diameter of the ellipse is Rmax and a short diameter is Rmin, the non-circularity is $100\times2\times(\mathrm{Rmax}-\mathrm{Rmin})/(\mathrm{Rmax}+\mathrm{Rmin})$ %.

[0039] In the cross section of the optical fiber **1**, a boundary line between regions having different refractive indexes, such as the core **10** and the cladding **20**, is defined as a curve including a point where a gradient of the refractive index is the steepest (in a case where there is a plurality of the points, a center of gravity of the points). For example, the boundary line between the core **10** and the cladding **20** is defined as a closed curve in which a gradient of the refractive index averaged along the closed curve is maximized when the closed curve is set between the core **10** and the cladding **20**. In the present embodiment, the non-circularity of the elliptical shape of the core **10** is 0.1% or more and 10% or less. The non-circularity of the elliptical shape may be 0.3% or more or may be 1% or more. The non-circularity of the elliptical shape of the core **10** is defined as a non-circularity of an ellipse when the boundary line between the core **10** and the cladding **20** is fitted to the ellipse.

[0040] The core **10** has a center of gravity in the cross section orthogonal to the fiber axis **2**. The center of gravity of the core **10** is a center of gravity of a cross-sectional shape of the core **10** (a figure surrounded by the boundary line between the core **10** and the cladding **20**). As illustrated in FIG. **2**, the core **11** has a center of gravity P**1**, and the core **12** has a center of gravity P**2**. FIG. **2** illustrates a straight line L**1** and a straight line L**2**. The straight line L**1** is a straight line connecting the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12**. The straight line L**2** is a straight line along a major axis of an elliptical shape of the core **11**. A straight line L**3** is a straight line along a major axis of an elliptical shape of the core **12**. The major axis of the elliptical shape of the core **10** is defined as, for example, the major axis of an ellipse when the boundary line between the core **10** and the cladding **20** is fitted to the ellipse.

[0041] The arrangement of the cores **10** in the optical fiber **1** will be described. The plurality of cores **10** includes at least one first core and one or more second cores different from the first core. In the optical fiber **1**, in the cross section orthogonal to the fiber axis **2**, the first core is disposed so that an angle formed by a straight line connecting a center of gravity of the first core and a center of gravity of a core group including one or more second cores and a straight line along a major axis of an elliptical shape of the first core is 30 degrees or less. Here, the "core group including one or more second cores" is all the cores **10** excluding the first core among the plurality of cores **10**, and in a case where the number of cores **10** included in the optical fiber **1** is two as in the present embodiment, the core group includes only one core **10**, and in a case where the number of cores **10** is three or more, the core group includes two or more cores **10**.

[0042] In the optical fiber **1**, each of the core **11** and the core **12** is the first core. In other words, in a case where the core **11** is the first core, the core **12** is the second core, and in a case where the core **12** is the first core, the core **11** is the second core. Therefore, in the cross section orthogonal to the fiber axis **2**, the core **11** is disposed so that an angle θ**1** formed by the straight line L**1** connecting the center of gravity P**1** of the core **11** (first core) and the center of gravity P**2** of a core group G**1** of the second core (only core **12** in this example) and the straight line L**2** along the major axis of the elliptical shape of the core **11** is 30 degrees or less. In addition, the core **12** is disposed so that an angle θ**2** formed by the straight line L**1** connecting the center of gravity P**2** of the core **11** (first core) and the center of gravity P**1** of a core group G**2** of the second core (only core **11** in this example) and the straight line L**3** along the major axis of the elliptical shape of the core **12** is 30 degrees or less. The angle formed by the straight line connecting the center of gravity of the first core and the center of gravity of the core group including one or more second cores and the straight line along the major axis of the elliptical shape of the first core may be 10 degrees or less or may be 5 degrees or less.

[0043] In the optical fiber **1**, an interval between the core **11** and the core **12** may be, for example, 15 μm or more and 60 μm or less or may be 25 μm or more and 50 μm or less. The interval between the core **11** and the core **12** is defined as a distance between the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12**. From the viewpoint of reducing crosstalk, the interval between the core **11** and the core **12** may be increased, and from the viewpoint of facilitating the connection of the optical fiber **1**, the interval may be decreased. In a case where the interval between the core **11** and the core **12** is 15 μm or more and 60 μm or less, or 25 μm or more and 50 μm or less, it is possible to facilitate the connection of the optical fiber **1** while reducing the crosstalk.

[0044] FIG. **3** is a graph schematically illustrating a distribution of a coefficient of thermal expansion in the optical fiber **1**. FIG. **3** illustrates a coefficient of thermal expansion α of a portion located on the straight line L**1** in the optical fiber **1** of FIG. **2**. A horizontal axis in FIG. **3** illustrates a position r on the straight line L**1**. A center position r of a line segment connecting the center of gravity P**1** and the center of gravity P**2** is set to 0. A vertical axis in FIG. **3** illustrates the coefficient of thermal expansion α. Specifically, a coefficient of thermal expansion α**10** of the core **11** and the core **12**, a coefficient of thermal expansion α**21** of the first cladding **21**, and a coefficient of thermal expansion α**22** of the second cladding **22** are illustrated. The coefficient of thermal expansion can be measured as elongation or shrinkage due to a change in temperature. The coefficient of thermal expansion in the present specification is a value at 1000° C., but may be a value at a temperature of 700° C. or less at which measurement is easier.

[0045] As described above, each of the core **11**, the core **12**, the first cladding **21**, and the second cladding **22** contains fluorine. The concentration of fluorine in the second cladding **22** is higher than the concentrations of fluorine in the core **11** and the core **12**. As a result, the second cladding **22** has the coefficient of thermal expansion α**10** smaller than the coefficient of thermal expansion α**22** of the core **11** and the core **12**. In addition, the concentration of fluorine in the first cladding **21** is higher than the concentration of fluorine in the second cladding **22**. As a result, the first cladding **21** has the coefficient of thermal expansion α**21** smaller than the coefficient of thermal expansion α**22** of the second cladding **22**.

[0046] FIG. **4** is a graph schematically illustrating a distribution of viscosity in the optical fiber **1**. FIG. **4** illustrates viscosity n of a portion located on the straight line L**1** in the optical fiber **1** of FIG. **2**. A horizontal axis in FIG. **4** illustrates a position r on the straight line L**1**, and a vertical axis in FIG. **4** illustrates the viscosity n. Specifically, viscosity η**10** of the core **11** and the core **12**, viscosity η**21** of the first cladding **21**, and viscosity η**22** of the second cladding **22** are illustrated.

[0047] As described above, the core **11** and the core **12** contain at least one kind of element of the alkali element group including an alkali metal element and an alkaline earth metal element. As a result, the core **11** and the core **12** have the viscosity η**10** lower than the viscosity η**21** of the first cladding **21** and the viscosity η**22** of the second cladding **22**. In addition, the viscosity η**21** of the first cladding **21** is lower than the viscosity η**22** of the second cladding **22**.

[0048] FIG. **5** is a graph schematically illustrating a distribution of stress in the optical fiber **1**. FIG. **5** illustrates stress σzz caused in a portion located on the straight line L**1** in the optical fiber **1** of FIG. **2**. A horizontal axis in FIG. **5** illustrates a position r on the straight line L**1**, and a vertical axis in FIG. **5** illustrates the stress σzz. Specifically, stress σzz**10** caused in the core **11** and the core **12**, stress σzz**21** caused in the first cladding **21**, and stress σzz**22** caused in the second cladding **22** are illustrated. In a direction along the fiber axis **2**, tension is illustrated as being positive and compression is illustrated as being negative.

[0049] As described above, since the second cladding **22** has the relatively high viscosity η**22**, the second cladding **22** has positive axial stress (stress σzz**22**) due to tension when the optical fiber **1** is drawn. Meanwhile, since the viscosity n **10** of the cores **11** and **12** and the viscosity η**21** of the first cladding **21** are relatively low, the cores **11** and **12** and the first cladding **21** have negative axial stress (stress σzz**10**, and σzz**21**). The coefficient of thermal expansion α**21** of the first cladding **21** is smaller than the coefficient of thermal expansion α**10** of the core **11** and the core **12**. Therefore, the first cladding **21** has negative axial stress (stress σzz**21**) larger than that of the core **11** and the core **12** due to contraction caused by cooling when the optical fiber **1** is drawn.

[0050] With reference to FIGS. **6** and **7**, birefringence caused in the core **10** will be described. Specifically, with reference to FIG. **6**, birefringence caused by the stress caused by the arrangement of the cores **10** will be described, and with reference to FIG. **7**, birefringence caused by a shape of the core **10** will be described. FIG. **6** is a view schematically illustrating in-plane stress in a cross section orthogonal to the fiber axis **2**. FIG. **7** is a view schematically illustrating a slow axis direction of birefringence of the fundamental mode in the core **10**. FIGS. **6** and **7** schematically illustrate cross sections of the core **10** and the first cladding **21**, and hatching is omitted for convenience of description. In FIGS. **6** and **7**, a direction along the straight line L**1** (see FIG. **2**) connecting the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12** is defined as an X direction, and a direction orthogonal to the X direction and a direction along the fiber axis **2** is defined as a Y direction. In an example illustrated in FIGS. **6** and **7**, in the cross section orthogonal to the fiber axis **2**, a cross-sectional shape of the core **10** has an elliptical shape, and the core **10** is disposed so that the major axis of the elliptical shape is along the X direction.

[0051] As described above, the first cladding **21** has the coefficient of thermal expansion α**10** smaller than the coefficient of thermal expansion α**21** of the core **10**. In other words, since the coefficient of thermal expansion α**10** of the core **10** is larger than the coefficient of thermal expansion α**21** of the first cladding **21**, the core **10** contracts more strongly than the first cladding **21** due to cooling when the optical fiber **1** is drawn, and compressive stress remains in a circumferential direction of the core **10** in the first cladding **21** close to the core **10**. FIG. **6** illustrates residual compressive stress A**1** and A**2**. Specifically, among the residual compressive stress, compressive stress along the X direction is illustrated as the compressive stress A**1**, and compressive stress along the Y direction is illustrated as the compressive stress A**2**.

[0052] When the compressive stress remaining in the circumferential direction of the first core (for example, core **11**) included in the plurality of cores **10** is examined, in a direction (X direction) in which the second core (for example, core **12**) different from the first core exists, the compressive stress A**2** along a circumferential direction (Y direction) of the first core is weakened by the influence of contraction of the second core. Therefore, anisotropy occurs in the compressive stress along the circumferential direction of the core, and when the compressive stress is averaged, compressive stress along the X direction (direction in which the cores are arranged) becomes relatively large. As a result, a refractive index with respect to polarization in the X direction becomes lower than a refractive index with respect to polarization in the Y direction, and birefringence is caused. Therefore, in this example, birefringence is caused in the core **10** by stress caused by the arrangement of the cores **10**, and a slow axis of the birefringence (polarization direction in which the refractive index is high) is along the Y direction.

[0053] In a case where the core **10** has an elliptical shape as illustrated in FIG. **7**, birefringence is caused also by the shape of the core **10**. FIG. **7** schematically illustrates a slow axis B**1** and a fast axis B**2** of the birefringence caused by the shape of the core **10**. The slow axis B**1** of the birefringence is along the major axis of the elliptical shape, and the fast axis is along the minor axis. In this example, the major axis of the elliptical shape is along the X direction. Therefore, in this example, the slow axis B**1** of the birefringence caused by the shape of the core **10** is along the X direction.

[0054] As described above, the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** have opposite signs, and the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** are combined, whereby birefringence as a whole is reduced. The birefringence is reduced, whereby polarization mode dispersion is reduced.

[0055] In the examples of FIGS. **6** and **7**, the major axis of the elliptical shape of the core **10** coincides with the X direction (that is, the direction along the straight line L**1** connecting the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12**). However, as in the optical fiber **1** illustrated in FIG. **2**, even if the major axis of the elliptical shape does not completely coincide with the straight line L**1**, if the major axis of the elliptical shape is approximately along the straight line L**1** (for example, when the angle formed by the straight line L**1** and the straight lines L**2** and L**3** along the major axis of the elliptical shape is 30 degrees or less,), the birefringence caused by stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** are canceled out, and the birefringence is reduced as a whole. As a result, the polarization mode dispersion is reduced.

[0056] In the optical fiber **1**, birefringence obtained by combining the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** is 10-6 or less.

[0057] The combined birefringence may be 10-7 or less. Unless stated otherwise, the birefringence refers to a value at a wavelength of 1550 nm of a fundamental mode guided into the core **10** (for example, core **11**). In addition, the polarization mode dispersion is 0.2 ps/rtkm or less. The polarization mode dispersion may be 0.1 ps/rtkm or less. Unless stated otherwise, the polarization mode dispersion refers to a value at a wavelength of 1550 nm of the fundamental mode guided to the core **10** (for example, core **11**). The polarization mode dispersion can be measured using a known method such as a Jones matrix eigenanalysis (JME) method. At the time of measurement, measurement light is input to a core that is an object subject to measurement of the multicore optical fiber to be measured of the multicore optical fiber, and measurement light output from the core is captured and measured. Although a known input/output device such as a fan-out device may be used to selectively input and output the measurement light to and from the core to be measured, it is assumed that the polarization mode dispersion of the input/output device is negligibly small or appropriately corrected from a measurement result.

[0058] As described above, in the optical fiber **1** according to the present embodiment, the plurality of cores **10** includes the core **11** and the core **12** having elliptical shapes in the cross section orthogonal to the fiber axis **2**. The angle θ**1** formed by the straight line L**1** connecting the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12** and the straight line L**2** along the major axis of the elliptical shape of the core **11** is 30 degrees or less. In addition, the angle θ**2** formed by the straight line L**1** and the straight line L**3** along the major axis of the elliptical shape of the core **12** is 30 degrees or less. As a result, the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** are canceled out, and birefringence of a waveguide mode propagating through the core **10** is reduced. As a result, the polarization mode dispersion can be reduced. In addition, the angle θ**1** and the angle θ**2** may be 10 degrees or less or may be 5 degrees or less. In this case, the polarization mode dispersion can be further reduced.

[0059] The non-circularity of the elliptical shape of the core **10** is 10% or less. As a result, it is possible to reduce connection loss when the optical fiber **1** is connected to a normal optical fiber having small non-circularity.

[0060] The core **10** and the cladding **20** contain fluorine, and the concentration of fluorine in the cladding **20** is higher than the concentration of fluorine in each of the plurality of cores **10**. As a result, the core **10** has the coefficient of thermal expansion α**10** larger than the coefficient of thermal expansion α**21** of the first cladding **21**, and the core **10** contracts more strongly than the first cladding **21** due to cooling when the optical fiber **1** is drawn, so that the compressive stress remains in the circumferential direction of the core **10** in the first cladding **21** close to the core **10**. As a result, although birefringence is caused by the stress caused by the arrangement of the cores **10**, the birefringence is canceled out by the birefringence caused by the shape of the core **10**, so that the polarization mode dispersion can be reduced.

[0061] The cladding **20** has the first cladding **21** surrounding the core **10** and the second cladding **22** surrounding the first cladding **21**. The first cladding **21** and the second cladding **22** contain fluorine. The concentration of fluorine in the first cladding **21** is higher than the concentration of fluorine in the second cladding **22**. The core **10** contains at least one kind of alkali element of an alkali element group including an alkali metal element and an alkaline earth metal element. In this case, for example, tensile tension caused by the drawing can be localized in the second cladding **22**, a glass defect caused by the tensile tension can be prevented from occurring in the core **10** and the first cladding **21**, and loss of the optical fiber **1** can be reduced.

[0062] The core **10** contains at least one kind of element of the alkali element group including an alkali metal element and an alkaline earth metal element. The concentration of the alkali element in the core **10** is 1 wtppm or more and 3000 wtppm or less. As a result, the viscosity of the core **10** is sufficiently reduced, and excessive loss caused by the high concentration of the alkali element can be reduced. Therefore, the polarization mode dispersion and the loss in the optical fiber **1** can be reduced.

[0063] With reference to FIG. **8**, an optical fiber **1**A according to a second embodiment will be described. FIG. **8** is a cross-sectional view of the optical fiber **1**A according to the second embodiment. FIG. **8** illustrates a cross section of the optical fiber **1**A orthogonal to a fiber axis **2**, and illustration of a coating layer **30** is omitted. The optical fiber **1**A according to the present embodiment is different from the optical fiber **1** according to the first embodiment in that the optical fiber **1**A according to the present embodiment includes a plurality of (two) pieces of first cladding **21**A and **21**B. Except for points to be described below, a core **10** according to the second embodiment has a configuration similar to that of the core **10** according to the first embodiment, and the first cladding **21**A and **21**B according to the second embodiment have configurations similar to that of the first cladding **21** according to the first embodiment.

[0064] The first cladding **21**A surrounds a core **11**, and the first cladding **21**B surrounds a core **12**. The first cladding **21**A and the first cladding **21**B are separated from each other with second cladding **22** interposed therebetween. The second cladding **22** surrounds the first cladding **21**A and the first cladding **21**B. In other words, the first cladding **21**A and **21**B are surrounded by the common second cladding **22**. A ratio of an outer diameter of each piece of the first cladding **21**A and **21**B to an outer diameter of the core **10** may be 2 or more and 5 or less.

[0065] In the optical fiber **1**A, an interval between the core **11** and the core **12** may be, for example, 25 μm or more and 70 μm or less or may be 35 μm or more and 60 μm or less. From the viewpoint of reducing crosstalk, the interval between the core **11** and the core **12** may be increased, and from the viewpoint of facilitating the connection of the optical fiber **1**A, the interval may be decreased. In a case where the interval between the core **11** and the core **12** is 25 μm or more and 70 μm or less, or 35 μm or more and 60 μm or less, it is possible to facilitate the connection of the optical fiber **1**A while reducing the crosstalk.

[0066] Also in the optical fiber **1**A, similarly to the optical fiber **1**, a plurality of cores **10** includes the core **11** and the core **12** having elliptical shapes in the cross section orthogonal to the fiber axis **2**. The angle θ**1** formed by the straight line L**1** connecting the center of gravity P**1** of the core **11** and the center of gravity P**2** of the core **12** and the straight line L**2** along the major axis of the elliptical shape of the core **11** is 30 degrees or less. In addition, an angle θ**2** formed by the straight line L**1** and the straight line L**3** along a major axis of the elliptical shape of the core **12** is 30 degrees or less. As a result, the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** are canceled out, and birefringence of a waveguide mode propagating through the core **10** is reduced. As a result, also in the optical fiber **1**A, polarization mode dispersion can also be reduced.

[0067] With reference to FIG. **9**, an optical fiber **1**B according to a third embodiment will be described. FIG. **9** is a cross-sectional view of the optical fiber **1**B according to the third embodiment. FIG. **9** illustrates a cross section of the optical fiber **1**B orthogonal to a fiber axis **2**, and illustration of a coating layer **30** is omitted. The optical fiber **1**B according to the present embodiment is different from the optical fiber **1** according to the first embodiment in that the optical fiber **1**B according to the present embodiment includes four cores **10** and four pieces of first cladding **21**A, **21**B, **21**C, and **21**D. Hereinafter, the respective four cores **10** may be described while being distinguished as cores **11**, **12**, **13**, and **14**. In addition, except for points to be described below, the core **10** according to the third embodiment has a configuration similar to that of the core **10** according to the first embodiment, and the first cladding **21**A, **21**B, **21**C, and **21**D according to the third embodiment have configurations similar to that of the first cladding **21** according to the first embodiment.

[0068] The first cladding **21**A surrounds the core **11**. The first cladding **21**B surrounds the core **12**. The first cladding **21**C surrounds the core **13**. The first cladding **21**D surrounds the core **14**. The first cladding **21**A, **21**B, **21**C, and **21**D are separated from each other with second cladding **22** interposed therebetween. The second cladding **22** surrounds the first cladding **21**A, **21**B, **21**C, and **21**D. In other words, the first cladding **21**A, **21**B, **21**C, and **21**D are surrounded by the common second cladding **22**. A ratio of an outer diameter of each piece of the first cladding **21**A, **21**B, **21**C, and **21**D to the outer diameter of the core **10** may be 2 or more and 5 or less.

[0069] In the optical fiber **1**B, an interval between the core **11** and the core **12** may be, for example, 25 μm or more and 70 μm or less or may be 35 μm or more and 60 μm or less. From the viewpoint of reducing crosstalk, the interval between the core **11** and the core **12** may be increased, and from the viewpoint of facilitating the connection of the optical fiber **1**B, the interval may be decreased. In a case where the interval between the core **11** and the core **12** is 25 μm or more and 70 μm or less, or 35 μm or more and 60 μm or less, it is possible to facilitate the connection of the optical fiber **1**B while reducing the crosstalk. For a similar reason, an interval between the core **12** and the core **13**, an interval between the core **13** and the core **14**, and an interval between the core **14** and the core **11** may be, for example, 25 μm or more and 70 μm or less or may be 35 μm or more and 60 μm or less.

[0070] Similarly to the core **10** according to the first embodiment, the core **10** (cores **11**, **12**, **13**, and **14**) according to the third embodiment has an elliptical shape in a cross section orthogonal to the fiber axis **2**. In the present embodiment, the non-circularity of the elliptical shape of the core **10** is 0.1% or more and 10% or less. The non-circularity of the elliptical shape may be 0.3% or more or may be 1% or more. FIG. **9** illustrates a straight line L**2** and a straight line L**4**. The straight line L**2** is a straight line along a major axis of an elliptical shape of the core **11**. The straight line L**4** is a straight line L**4** connecting a center of gravity P**1** of the core **11** and a center of gravity P**3** of a core group G**3** including the core **10** (cores **12**, **13**, and **14**) different from the core **11**. In the optical fiber **1**B, in the cross section orthogonal to the fiber axis **2**, the core **11** is disposed so that an angle θ**3** formed by the straight line L**4** connecting the center of gravity P**1** of the core **11** and the center of gravity P**3** of the core group G**3** including the core **10** different from the core **11** and the straight line L**2** along the major axis of the elliptical shape of the core **11** is 30 degrees or less.

[0071] In the optical fiber **1**B, the cores **12**, **13**, and **14** are disposed according to conditions similar to those of the core **11**. In other words, the core **12** is disposed so that an angle formed by a straight line connecting a center of gravity of the core **12** and the center of gravity of a core group including the core **10** (cores **11**, **13**, and **14**) different from the core **12** and a straight line along a major axis of an elliptical shape of the core **12** is 30 degrees or less. The core **13** is disposed so that an angle formed by a straight line connecting a center of gravity of the core **13** and a center of gravity of a core group including the core **10** (cores **11**, **12**, and **14**) different from the core **13** and a straight line along a major axis of an elliptical shape of the core **13** is 30 degrees or less. The core **14** is disposed so that an angle formed by a straight line connecting a center of gravity of the core **14** and a center of gravity of a core group including the core **10** (core **11**, **12**, and **13**) different from the core **14** and a straight line along a major axis of an elliptical shape of the core **14** is 30 degrees or less.

[0072] Also in the optical fiber **1**B, similarly to the optical fiber **1**, a plurality of cores **10** includes the cores **11**, **12**, **13**, and **14** having elliptical shapes in the cross section orthogonal to the fiber axis **2**. The angle θ**3** formed by the straight line L**4** connecting the center of gravity P**1** of the core **11** and the center of gravity P**3** of the core group G**3** including the core **10** (cores **12**, **13**, and **14**) different from the core **11** and the straight line L**2** along the major axis of the elliptical shape of the core **11** is 30 degrees or less. The cores **12**, **13**, and **14** are disposed according to conditions similar to those of the core **11**. As a result, the birefringence caused by the stress caused by the arrangement of the cores **10** and the birefringence caused by the shape of the core **10** are canceled out, and birefringence of a waveguide mode propagating through the core **10** is reduced. As a result, also in the optical fiber **1**B, polarization mode dispersion can be reduced.

[0073] Although the embodiments have been described above, the present disclosure is not necessarily limited to the embodiments described above, and various modifications are possible without departing from the spirit of the present disclosure. In addition, the above-described embodiments may be appropriately combined.

[0074] As illustrated in FIG. **10**, an optical fiber **1**B may have a marker **50** at a position where the symmetry of the arrangement of cores **10** is broken. As a result, each core **10** can be identified in the optical fiber **1**B. The marker **50** may be formed, for example, in cladding **20** (second cladding **22**). The marker **50** may be formed of a material having a refractive index different from a refractive index of the cladding **20** (second cladding **22**). Also in optical fibers **1** and **1**A, a marker for identifying each core **10** may be formed.

[0075] As illustrated in FIG. **11**, in an optical fiber **1**B, a core **10** may be disposed so as not to have rotational symmetry with respect to a fiber axis **2** (cladding center). In this example, a core **11** is disposed close to the outer edge of the cladding **20**, as compared to cores **12**, **13**, and **14**. As a result, each core **10** can be identified in the optical fiber **1**B. Also in optical fibers **1** and **1**A, a core **10** may be disposed so as not to have rotational symmetry with respect to a fiber axis **2** (cladding center).

[0076] In a cross section orthogonal to the fiber axis **2**, the non-circularity of an elliptical shape of the core **10** may be 10% or more. The concentration of an alkali element in the core **10** may be 1 wtppm or less, or may be 3000 wtppm or more. The core **10** may contain, in addition to the alkali element, at least one of fluorine of 1000 wtppm or more and 5000 wtppm or less and chlorine (C**1**) of 100 wtppm or more and 3000 wtppm or less. In this case, the viscosity of the core **10** is reduced, and loss caused by density fluctuation or the like is reduced. The core **10** does not need to contain fluorine.

[0077] As illustrated in FIGS. **12** and **13**, the optical fiber of the present embodiment described above may have a plurality of twists **61** arranged in a longitudinal direction. FIGS. **12** and **13** illustrate an optical fiber **1**D having twists **61** as a modification of the optical fiber **1**B illustrated in FIG. **9**. FIG. **12** is a view schematically illustrating a cross section orthogonal to a longitudinal direction of the optical fiber **1**D. FIG. **13** is a view schematically illustrating an internal structure of the optical fiber **1**D in a case where the optical fiber **1**D is viewed along a direction orthogonal to the longitudinal direction of the optical fiber **1**D. In FIGS. **12** and **13**, illustration of first cladding **21** and a coating layer **30** is omitted. In addition, in FIG. **13**, illustration of cores **12** and **14** are further omitted, second cladding **22** is illustrated by a broken line, and cores **11** and **13** located inside the second cladding **22** are illustrated by a solid line. The optical fiber **1**D has four cores **10** (cores **11**, **12**, **13**, and **14**). Each core **10** has an elliptical shape in a cross section orthogonal to a fiber axis (longitudinal direction of optical fiber **1**D).

[0078] In the optical fiber **1**D, the positions of a plurality of cores **11**,**12**,**13**, and **14** change so as to rotate as a movement is performed along the longitudinal direction, whereby a plurality of twists **61** is formed so as to be positioned along the longitudinal direction of the optical fiber **1**D. The twist **61** is a position (structure) at which a plurality of cores **10** intersects each other in a case where the optical fiber **1**D is viewed along a direction orthogonal to the fiber axis. Since the optical fiber **1**D has the twists **61**, mode coupling occurs between two polarization modes in each core **10**, and polarization mode dispersion caused by stress and shape anisotropy in a cross section of the optical fiber **1**D is randomized by the mode coupling, and accumulation of the polarization mode dispersion is reduced. From this viewpoint, the number of twists (the number of twists **61**) may be 0.1 rotations/m or more. In addition, the number of twists may be 1 rotation/m or more. Note that the number of twists is a value obtained by averaging an absolute value of a rotation angle per unit length in the longitudinal direction. A direction of the twist **61** can be two left and right directions (two directions along a circumferential direction of the optical fiber **1**D), but twists **61** in two directions in the longitudinal direction may be mixed.

[0079] While the twist **61** has an effect of reducing the polarization mode dispersion, the twist **61** comes with a side effect that the arrangement of the plurality of cores **10** rotates in the longitudinal direction, and therefore, if an end portion of the optical fiber **1**D is cut when light is coupled to an end surface of the optical fiber **1**D, the arrangement of the cores changes, which may cause a problem that it is difficult to couple light. In order to reduce the influence of this problem, the number of twists **61** may be 3 rotations/m or less. In addition, the number of twists **61** may be 0.3 rotations/m or less.

What is claimed is:

1. A multicore optical fiber comprising:

a plurality of cores along a fiber axis; and

cladding surrounding the plurality of cores, wherein

the plurality of cores and the cladding contain silica glass as a main component,

a refractive index of each of the plurality of cores is higher than a refractive index of the cladding, a coefficient of thermal expansion of each of the plurality of cores is larger than a coefficient of thermal expansion of the cladding,

the plurality of cores includes a first core having an elliptical shape in a cross section orthogonal to the fiber axis and one or more second cores different from the first core,

non-circularity of the elliptical shape is 0.1% or more,

an angle formed by a straight line connecting a center of gravity of the first core and a center of gravity of a core group including the one or more second cores and a straight line along a major axis of the elliptical shape is 30 degrees or less in the cross section orthogonal to the fiber axis, and

polarization mode dispersion is 0.2 ps/rtkm or less.

2. The multicore optical fiber according to claim **1**, wherein

the non-circularity of the elliptical shape is 10% or less.

3. The multicore optical fiber according to claim **1**, wherein

the plurality of cores and the cladding contain fluorine, and

a concentration of fluorine in the cladding is higher than a concentration of fluorine in each of the plurality of cores.

4. The multicore optical fiber according to claim **1**, wherein

the cladding includes first cladding surrounding the plurality of cores and second cladding surrounding the first cladding,

the first cladding and the second cladding contain fluorine,

a concentration of fluorine in the first cladding is higher than a concentration of fluorine in the second cladding, and

the plurality of cores contains at least one kind of alkali element of an alkali element group including an alkali metal element and an alkaline earth metal element.

5. The multicore optical fiber according to claim **1**, wherein

the plurality of cores contains at least one kind of alkali element of an alkali element group including an alkali metal element and an alkaline earth metal element, and

a concentration of the alkali element in the plurality of cores is 1 wtppm or more and 3000 wtppm or less.

6. The multicore optical fiber according to claim **1**, wherein

the angle is 10 degrees or less.

7. The multicore optical fiber according to claim **1**, wherein

the angle is 5 degrees or less.

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