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(54) **CONNECTION STRUCTURE FOR MULTI-CORE FIBER AND OPTICAL-FIBER-BUNDLE STRUCTURE, CONNECTION STRUCTURE FOR MULTI-CORE FIBERS, METHOD FOR EXCITING RARE-EARTH-DOPED MULTI-CORE FIBERS, AND MULTI-CORE-OPTICAL-FIBER AMPLIFIER**

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(57) **ABSTRACT**

An optical-fiber-bundle structure is connected to one end of a multi-core fiber. The multi-core fiber has a tapered section formed therein. The outside diameter of the multi-core fiber and the core pitch thereof decrease in the tapered section. It is possible for the multi-core fiber to have an increasing core pitch on the connection-side thereof which connects to the optical-fiber-bundle structure; hence, it is possible to use an easy-to-use large-diameter optical fiber as the optical fiber to be provided in the optical-fiber-bundle structure. When connecting another multi-core fiber to the other end of the multi-core fiber, it is possible to match the outer diameters thereof; hence, when fusion splicing to one another, it is unlikely for a positional shift of the cores to occur.

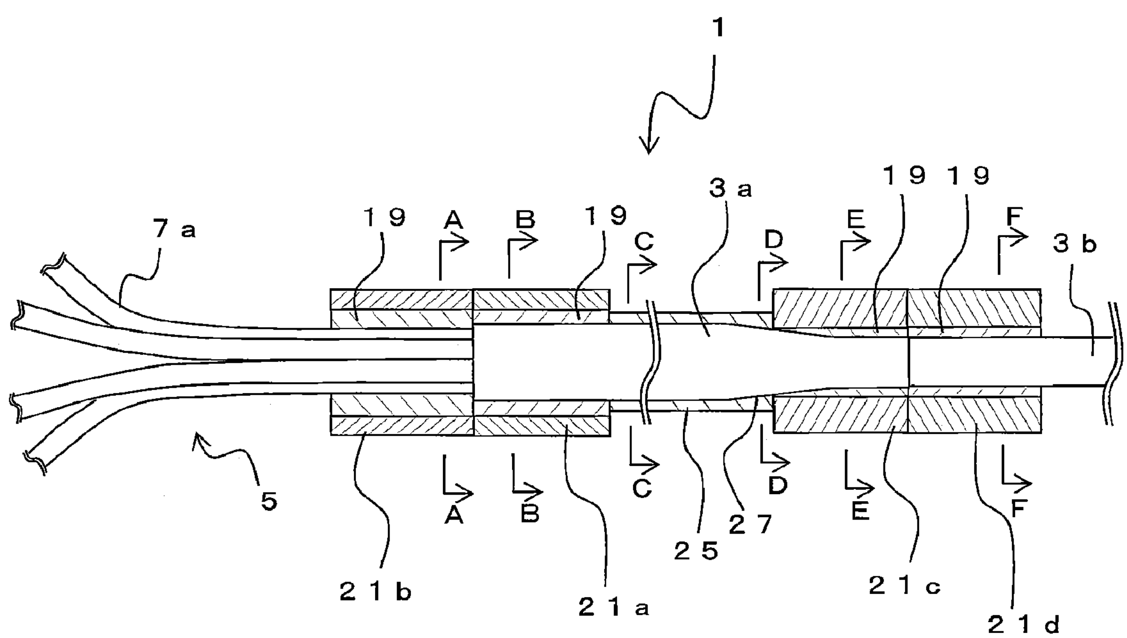


Fig. 1

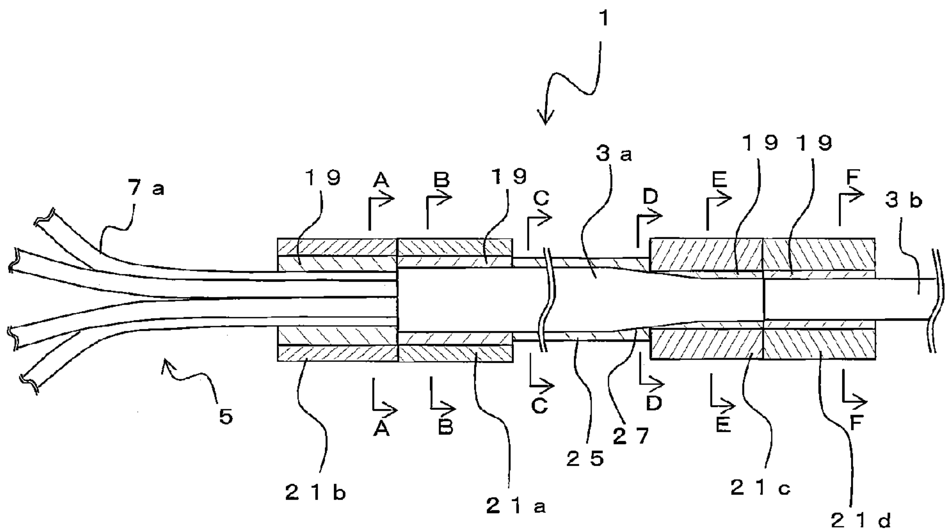
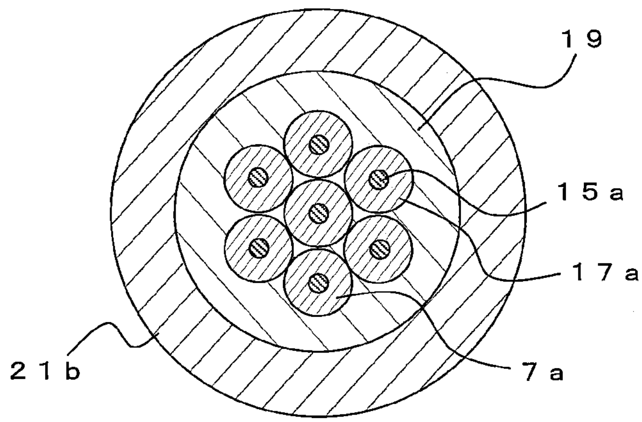


Fig. 2(a)



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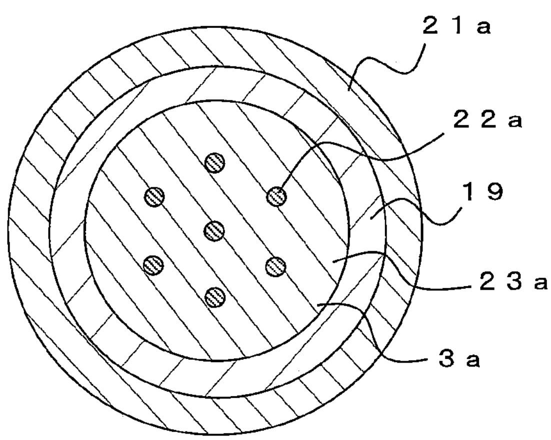

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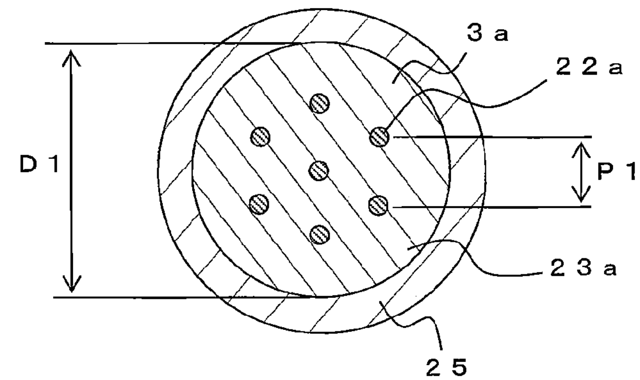

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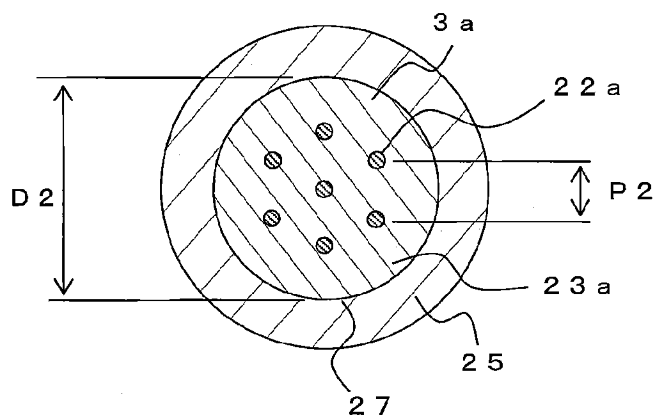

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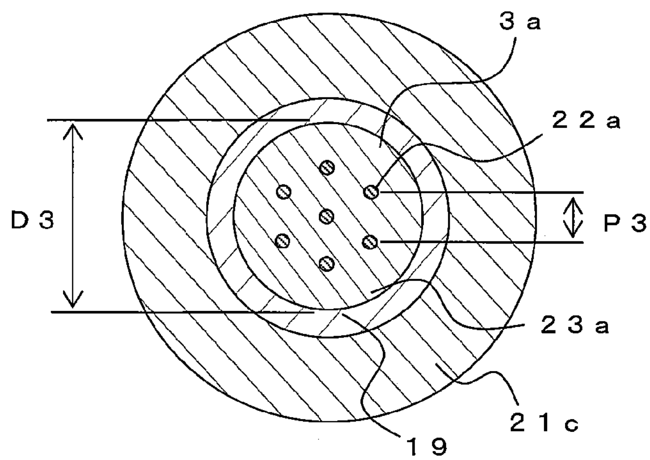

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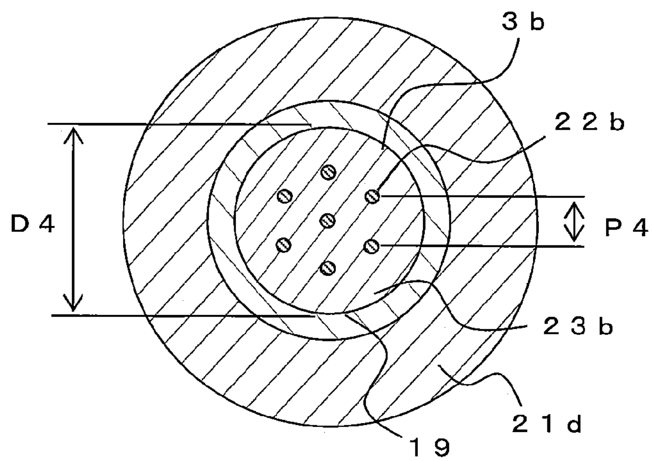

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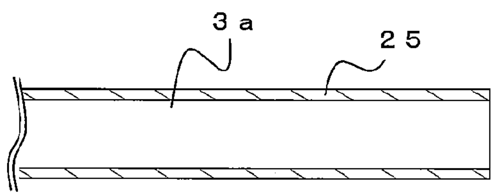

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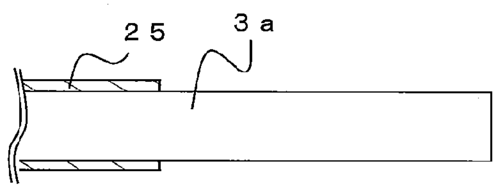

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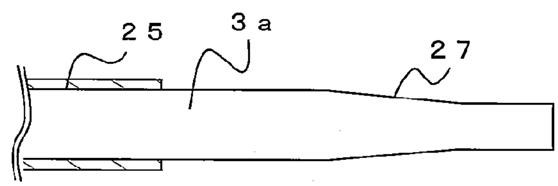

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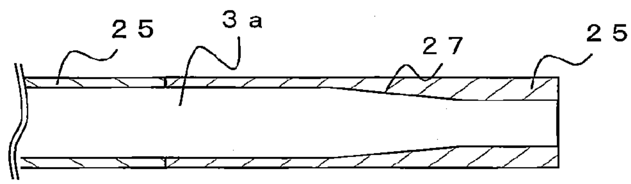

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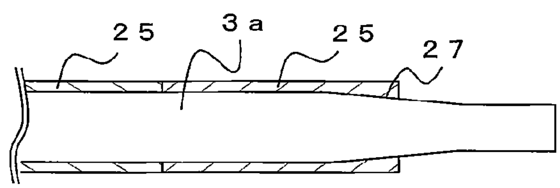


Fig. 6(c)

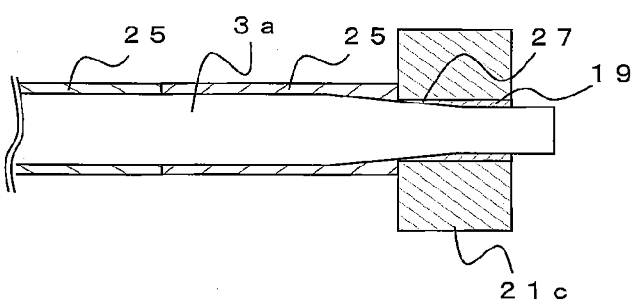
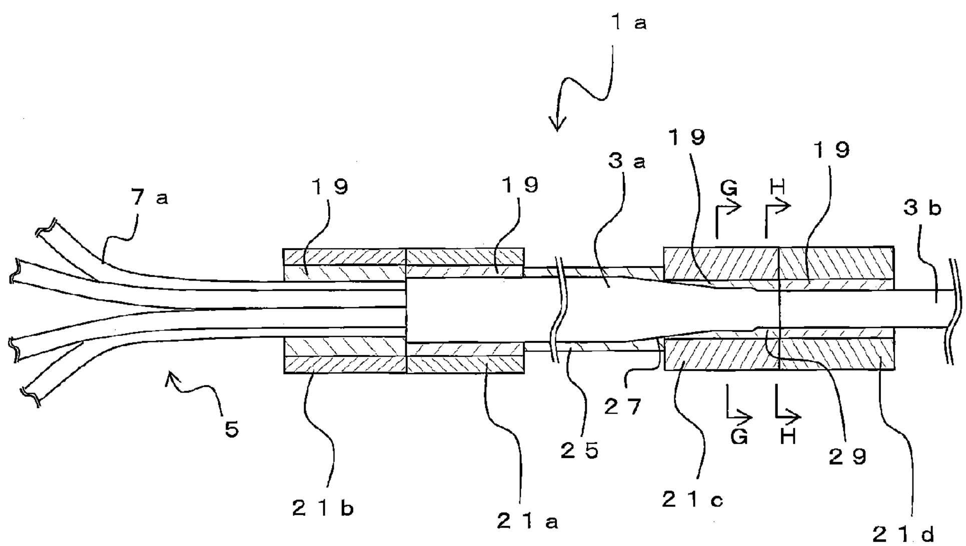


Fig. 7



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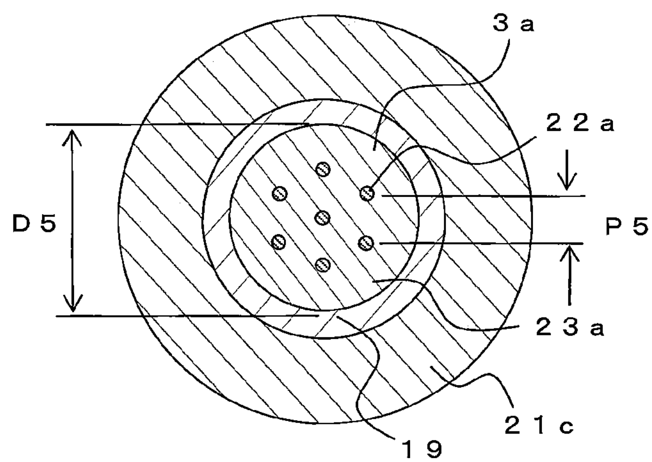

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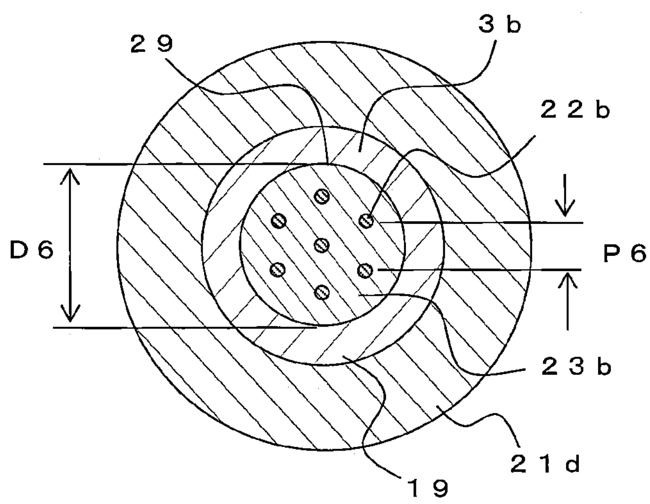


Fig. 9

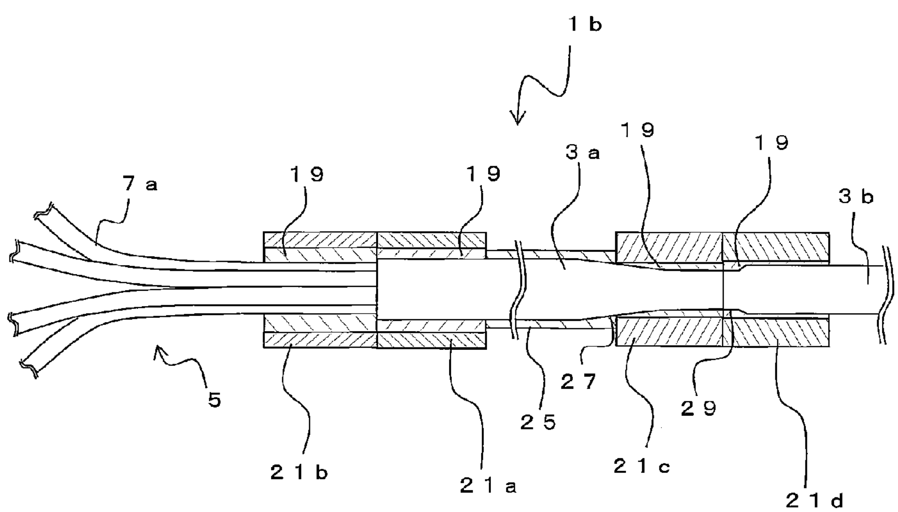


Fig. 10

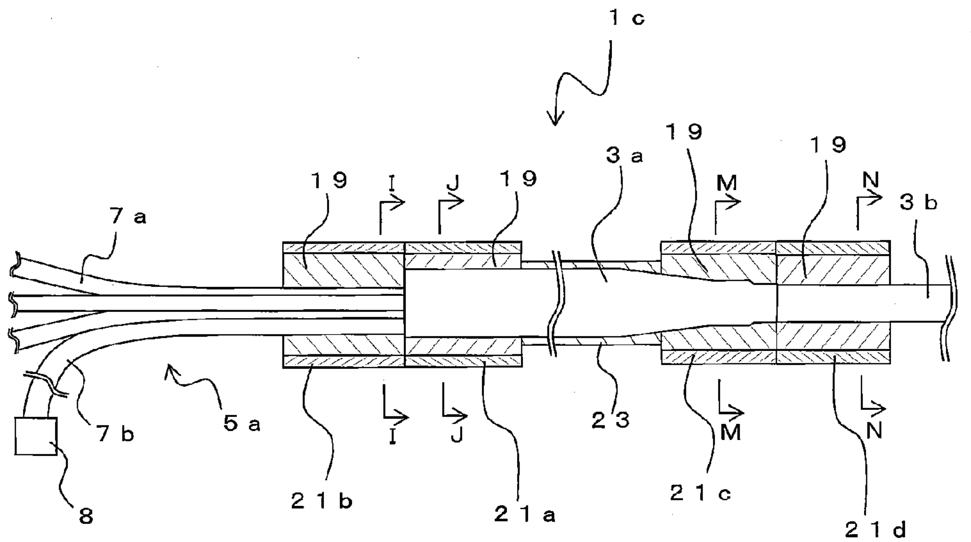
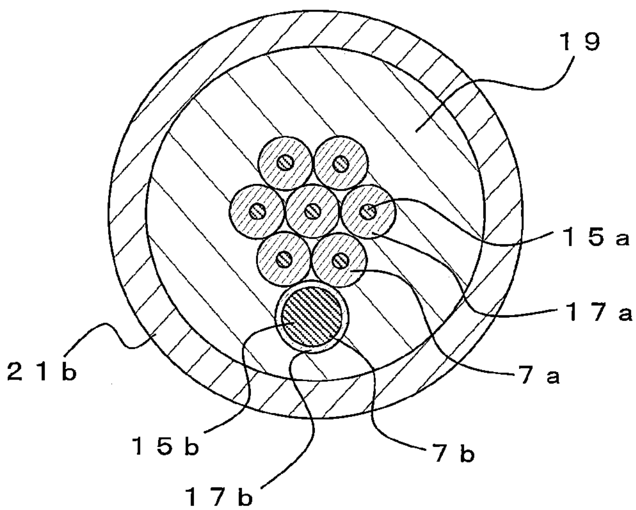


Fig. 11(a)



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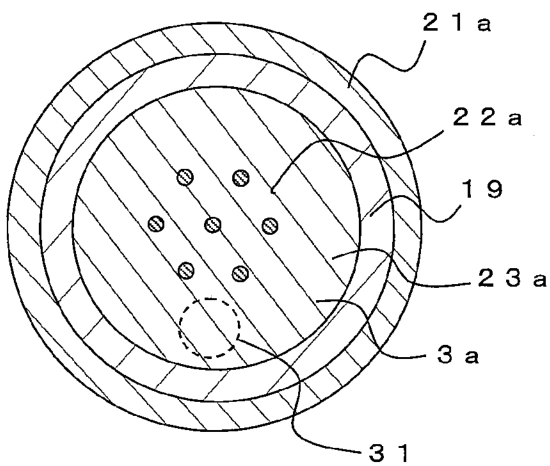

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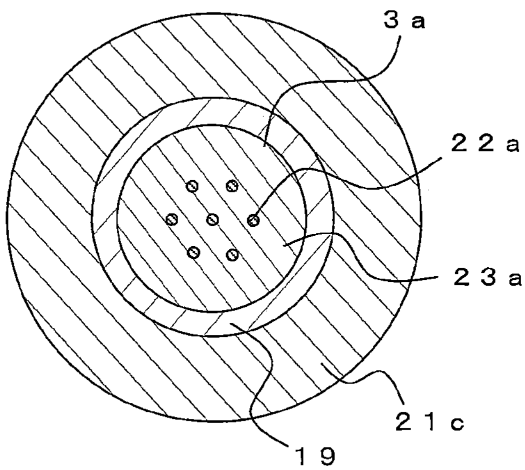

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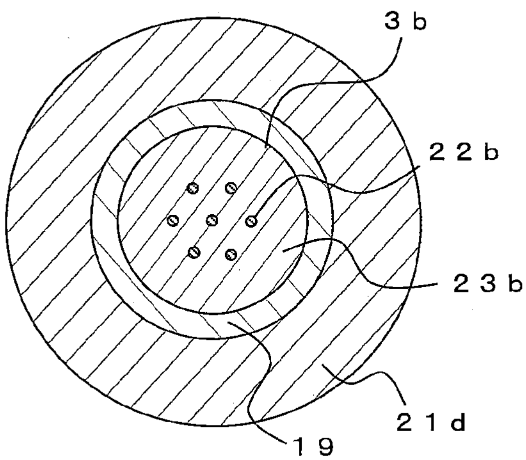


Fig. 13

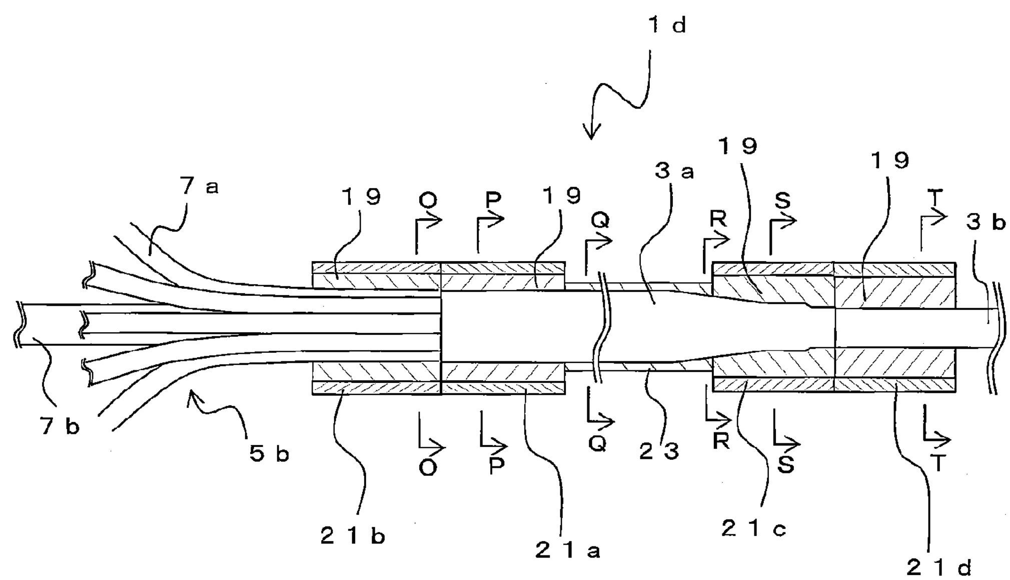
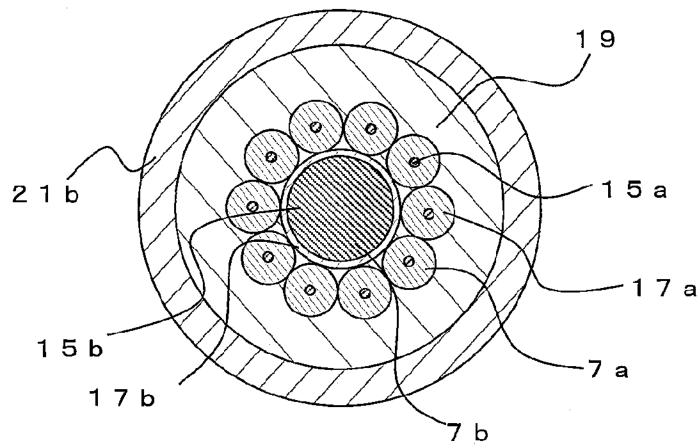


Fig. 14(a)



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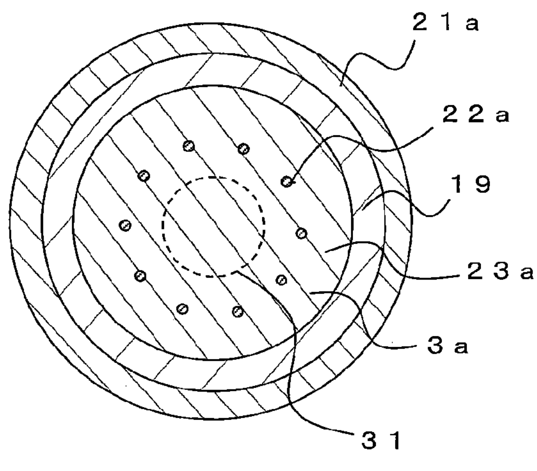
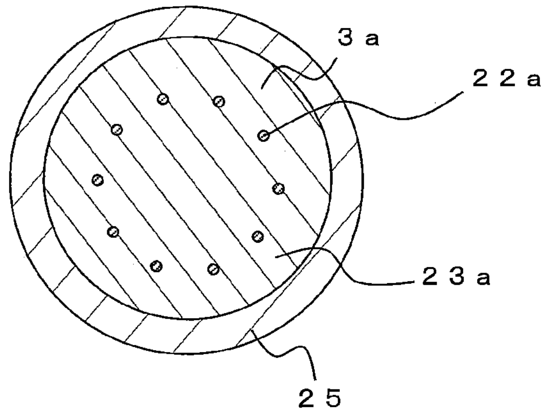


Fig. 15(a)



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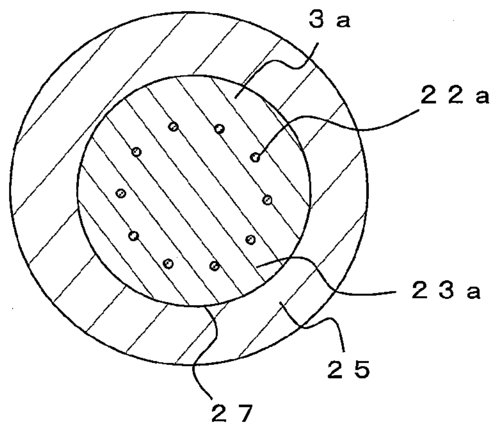


Fig. 16(a)

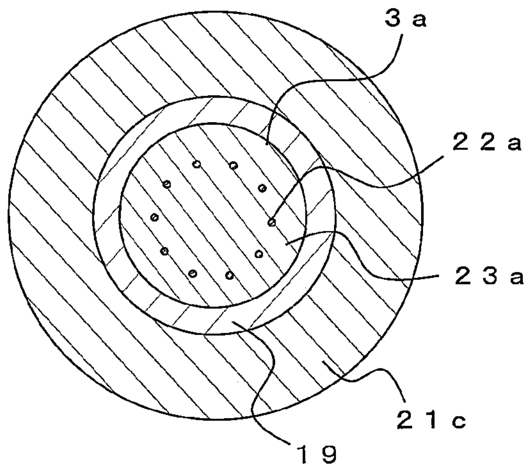


Fig. 16(b)

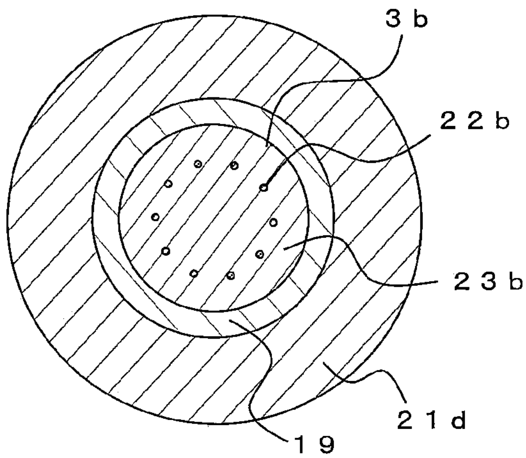


Fig. 17(a)

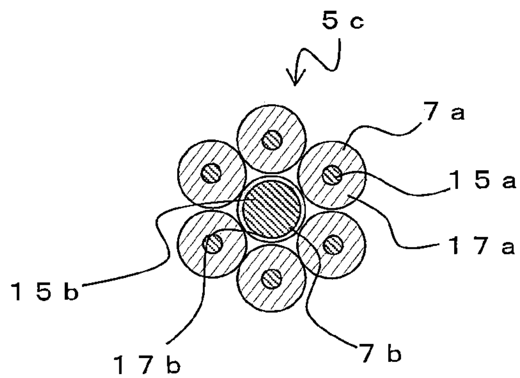
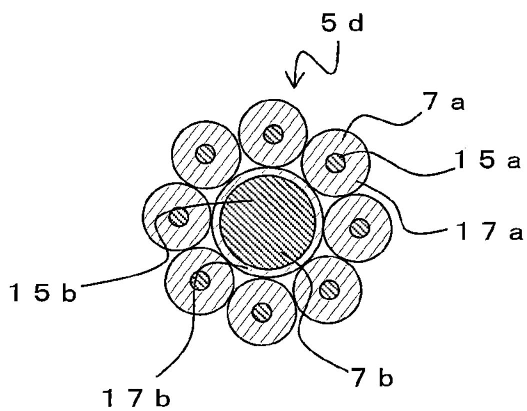


Fig. 17(b)



CONNECTION STRUCTURE FOR MULTI-CORE FIBER AND OPTICAL-FIBER-BUNDLE STRUCTURE, CONNECTION STRUCTURE FOR MULTI-CORE FIBERS, METHOD FOR EXCITING RARE-EARTH-DOPED MULTI-CORE FIBERS, AND MULTI-CORE-OPTICAL-FIBER AMPLIFIER

TECHNICAL FIELD OF THE INVENTION

[0001] This invention relates to a connection structure for a multi-core fiber having a plurality of cores and an optical-fiber-bundle structure, and a connection structure for multi-core fibers.

BACKGROUND OF THE INVENTION

[0002] The transmission capacity of single-core optical fibers used in the present situations is approaching its limit due to the recent rapid traffic increase in optical communications. As a means for further expanding the communication capability, a multi-core fiber, which is a fiber having a plurality of cores formed therein, has been proposed. Using a multi-core fiber reduces the cost for laying optical fibers and allows the communication capability to expand.

[0003] When a multi-core fiber is used as a transmission line, fan-out, which separates each core of the multi-core fiber into single-core fibers, is required. To connect such a multi-core fiber and single-core fibers, there is a method in which optical fibers are in a close-packed arrangement, forming a bundle structure that is to be connected with the multi-core fiber (Patent Document 1).

[0004] Also, there is another method in which a plurality of single-core fibers is bundled to be drawn, integrated, and then connected to a multi-core fiber (Patent Document 2).

[0005] Also, there is another method in which the diameter of one end of a multi-core fiber is enlarged and the light is introduced into the core of the multi-core fiber (Patent Document 3).

RELATED ART

Patent Documents

[0006] [Patent Document 1] WO2012121320A1

[0007] [Patent Document 2] Japanese Patent No. 3415449

[0008] [Patent Document 3] Japanese Unexamined Patent Application Publication No. 2001-145562

SUMMARY OF THE INVENTION

Problems to be Solved by the Invention

[0009] Since manufacturing of an optical-fiber-bundle structure is easy, such a method proposed in Patent Document 1, in which single-core fibers having a cladding diameter equivalent to a core pitch of a multi-core fiber are bundled, has high practicability. Particularly, a multi-core fiber used for long distance transmission requires a large core pitch to prevent deterioration by crosstalk. In this case, it is possible to use single-core fibers having diameters that correspond to the core pitch of the multi-core fiber.

[0010] On the other hand, for short-distance transmission such as in office, it is possible to decrease the core pitch of a multi-core fiber. Therefore, in view of capacity and handling properties (allowable bending radius), it is preferable to reduce the diameter as much as possible. Also, a rare-earth doped multi-core fiber used as an optical amplifier (erbium doped multi-core fiber for example) is used in short distances. Particularly, it is preferable for a cladding-pumped rare-earth-doped multi-core fiber to reduce the cladding diameter and the core pitch in view of pump efficiency. This is because, if the cladding diameter of a rare-earth-doped multi-core fiber is large, the optical density decreases to the pump light of the cladding region so to lower the pump efficiency.

[0011] Thus, if the core pitch of a multi-core fiber is decreased (50 μm or less for example), it is necessary to reduce the diameters of the corresponding single-core fibers. However, such small-diameter optical fibers have low rigidity and poor handling properties. Also, since the cladding thickness is thin, sealing of light into the core becomes leaky and the transmission loss is large. Furthermore, the thin cladding thickness is likely to cause micro-bend loss against external force to occur. Therefore, there is a limit in reducing the diameter of single-core fibers that form an optical-fiber-bundle structure.

[0012] However, as in Patent Document 2, with a method in which a plurality of optical fibers is bundled and then heated and melted to reduce the diameters, the external form of the bundle structure is deformed so that deformation of the cores or un-uniformity of core positions may occur. Therefore, connection loss with a multi-core fiber may become large.

[0013] In the method described in Patent Document 3, sections in which the core pitch is wide are made by changing drawing conditions and the like. However, this method has a problem that it is not possible to cut and connect at any desired places after drawing.

[0014] The present invention was achieved in view of such problems. Its object is to provide a connection method for a multi-core fiber and an optical-fiber-bundle structure with less transmission loss and the like.

Means for Solving Problems

[0015] To achieve the above object, a first invention is a connection structure for a multi-core fiber and an optical-fiber-bundle structure wherein the optical-fiber-bundle structure comprises a plurality of signal light optical fibers that transmit signal lights that are arranged at predetermined intervals, the multi-core fiber comprises cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end on the connection side that is connected to the optical-fiber-bundle structure, and a cladding covering the cores and having a refractive index lower than that of the cores. The multi-core fiber is a tapered fiber having a tapered section in which an outer diameter thereof varies. The outer diameter and the core pitch of the multi-core fiber at the first end are wider than the outer diameter and the core pitch of the multi-core fiber at a second end, which is on the opposite side of the connection part of the optical-fiber-bundle structure.

[0016] The multi-core fiber may be further connected to a second multi-core fiber and the core of the second multi-core fiber may be optically connected with the core of the multi-core fiber.

[0017] The second end of the multi-core fiber approximately matches with the outer diameter of an opposing end of the second multi-core fiber and the outer diameter of at least one of the second end of the multi-core fiber and the opposing end of the second multi-core fiber may be reduced by etching without any changes in the core pitch

[0018] The optical-fiber-bundle structure may further comprise a pump light optical fiber that transmits pump light, and the second multi-core fiber may be a rare-earth-doped multi-core fiber. In this case, the pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light may be connected to the cladding of the first end of the multi-core fiber.

[0019] The pump light optical fiber that transmits pump light may be arranged at the center of the optical-fiber-bundle structure and the signal light optical fibers that transmit signal lights may be arranged on the outer circumference of the pump light optical fiber that transmits pump light.

[0020] The diameter of the pump light optical fiber that transmits pump light may be larger than the diameter of the signal light optical fiber that transmits signal light.

[0021] According to the first invention, since the multi-core fiber is a tapered fiber in which the outer diameter and the core pitch vary, the core pitch on the side of connection part that is connected with the optical-fiber-bundle structure can be increased. Therefore, it is possible to increase the outer diameter of the signal light optical fiber that transmits signal light which is connected with the multi-core fiber. Therefore, the handling properties of the signal light optical fibers that transmit signal lights are excellent and the optical transmission loss can be suppressed.

[0022] Also, by further connecting with a second multi-core fiber, a desired optical connection between a multi-core fiber and an optical-fiber-bundle structure can be established with a multi-core fiber for pitch conversion.

[0023] Also, matching the outer diameters at the connection part between the multi-core fiber for pitch conversion and the second multi-core fiber can suppress position shifting of the cores at the time of fusion splicing. On this occasion, it is possible to match both outer diameters easily by reducing the diameter of at least one end of the multi-core fiber for pitch conversion and the other multi-core fiber by etching.

[0024] Also, if the optical-fiber-bundle structure includes the pump light optical fiber that transmits pump light and the second multi-core fiber is a rare-earth doped multi-core fiber, the optical-fiber-bundle structure and the rare-earth doped multi-core fiber can be connected by the multi-core fiber for pitch conversion. On this occasion, it is not necessary to excessively decrease each fiber-diameter of the optical-fiber-bundle structure, and it is also unnecessary to excessively increase the diameter of the rare-earth doped multi-core fiber.

[0025] Also, arranging the pump light optical fiber that transmits pump light at the center of the optical-fiber-bundle structure makes it possible for the pump light to be introduced into the center of the rare-earth doped multi-core fiber. On this occasion, since it is possible to use a larger pump light optical fiber that transmits pump light by making the outer diameter of the pump light optical fiber that transmits pump light larger than the outer diameter of the signal light optical fiber that transmits signal light, large output of pump light can be introduced into the rare-earth doped multi-core fiber.

[0026] A second invention is a connection structure for multi-core fibers, wherein a first multi-core fiber having a plurality of cores is connected with a second multi-core fiber having an outer diameter that is different from that of the first multi-core fiber and a plurality of cores that are optically connected with the cores of the first multi-core fiber. At least one of the first multi-core fiber and the second multi-core fiber has an outer diameter varying section, and the outer diameters of the end part of the first multi-core fiber on the connection-side and the end part of the second multi-core fiber on the connection part are almost equivalent.

[0027] The outer diameter varying section is formed by drawing a multi-core fiber and may include a section in which the core pitch at the cross-section varies along with the outer diameter.

[0028] The outer diameter varying section is formed by etching a multi-core fiber and may include a section in which the core pitch at the cross-section does not vary and only the outer diameter varies.

[0029] According to the second invention, it is possible to efficiently connect multi-core fibers having different outer diameters.

[0030] On this occasion, forming the outer diameter varying section by drawing at least one of the multi-core fibers can vary the core pitch. Also, if the outer diameter varying section is formed by etching, only the outer diameter can be varied without varying the core pitch.

[0031] A third invention is a method for exciting a multi-core fiber, comprising a step of connecting an optical-fiber-bundle structure, a multi-core fiber, and a rare-earth doped multi-core fiber. The optical-fiber-bundle structure comprises a plurality of signal light optical fibers that transmit signal lights, which are arranged at a predetermined pitch, and a pump light optical fiber that transmits pump light. The multi-core fiber comprises cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end thereof on the connection-side that is connected with the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores. The rare-earth doped multi-core fiber comprises cores, which are optically connected to the cores of the multi-core fiber at a second end that is on the opposite side of the connection part of the multicore fiber and the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores. The multi-core fiber is a tapered fiber having a tapered section in which the outer diameter thereof varies and the outer diameter and the core pitch at the first end of the multi-core fiber are wider than the outer diameter and the core pitch at the second end. The pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light is connected to the cladding of the first end of the multi-core fiber.

[0032] A fourth invention is a multi-core amplifier, comprising an optical-fiber-bundle structure, a multi-core fiber, and a rare-earth doped multi-core fiber. The optical-fiber-bundle structure comprises a plurality of signal light optical fibers that transmit signal lights, which are arranged at a predetermined pitch, and a pump light optical fiber that transmits pump light. The multi-core fiber comprises cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end thereof on the connection-side that is connected with the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores. The rare-earth doped multi-core fiber comprises cores, which are optically connected to the cores of the multi-core fiber at a second end that is on the opposite side of the connection part of the multicore fiber and the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores. The multi-core fiber is a tapered fiber having a tapered section in which the outer diameter thereof varies and the outer diameter and the core pitch at the first end of the multi-core fiber are wider than the outer diameter and the core pitch at the second end. The pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light is connected to the cladding of the first end of the multi-core fiber.

[0033] According to the third and the fourth inventions, it is possible to efficiently amplify signal light in multi-core fibers.

Effects of the Invention

[0034] The present invention can provide a connection method for a multi-core fiber and an optical-fiber-bundle structure with less transmission loss and the like.

BRIEF DESCRIPTION OF DRAWINGS

[0035] FIG. **1** shows a connection structure for an optical fiber **1**.

[0036] FIG. **2**(*a*) shows a cross-sectional view of A-A line of the connection structure for an optical fiber **1** in FIG. **1**.

[0037] FIG. **2**(*b*) shows a cross-sectional view of B-B line of the connection structure for an optical fiber **1** in FIG. **1**.

[0038] FIG. **3**(*a*) shows a cross-sectional view of C-C line of the connection structure for an optical fiber **1** in FIG. **1**.

[0039] FIG. **3**(*b*) shows a cross-sectional view of D-D line of the connection structure for an optical fiber **1** in FIG. **1**.

[0040] FIG. **4**(*a*) shows a cross-sectional view of E-E line of the connection structure for an optical fiber **1** in FIG. **1**.

[0041] FIG. **4**(*b*) shows a cross-sectional view of F-F line of the connection structure for an optical fiber **1** in FIG. **1**.

[0042] FIG. **5**(*a*) to FIG. **5**(*c*) show a forming process of a tapered section.

[0043] FIG. **6**(*a*) to FIG. **6**(*c*) show a connection process of the tapered section and a capillary **21***c*.

[0044] FIG. **7** shows a connection structure for an optical fiber **1***a*.

[0045] FIG. **8**(*a*) shows a cross-sectional view of G-G line of the connection structure for an optical fiber **1***a* in FIG. **7**.

[0046] FIG. **8**(*b*) shows a cross-sectional view of H-H line of the connection structure for an optical fiber **1***a* in FIG. **7**.

[0047] FIG. **9** shows a connection structure for an optical fiber **1***b*.

[0048] FIG. **10** shows a connection structure for an optical fiber **1***c*.

[0049] FIG. **11**(*a*) shows a cross-sectional view of I-I line of the connection structure for an optical fiber **1***c* in FIG. **10**.

[0050] FIG. **11**(*b*) shows a cross-sectional view of J-J line of the connection structure for an optical fiber **1***c* in FIG. **10**.

[0051] FIG. **12**(*a*) shows a cross-sectional view of M-M line of the connection structure for an optical fiber **1***c* in FIG. **10**.

[0052] FIG. **12**(*b*) shows a cross-sectional view of N-N line of the connection structure for an optical fiber **1***c* in FIG. **10**.

[0053] FIG. **13** shows a connection structure for an optical fiber **1***d*.

[0054] FIG. **14**(*a*) shows a cross-sectional view of O-O line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0055] FIG. **14**(*b*) shows a cross-sectional view of P-P line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0056] FIG. **15**(*a*) shows a cross-sectional view of Q-Q line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0057] FIG. **15**(*b*) shows a cross-sectional view of R-R line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0058] FIG. **16**(*a*) shows a cross-sectional view of S-S line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0059] FIG. **16**(*b*) shows a cross-sectional view of T-T line of the connection structure for an optical fiber **1***d* in FIG. **13**.

[0060] FIG. **17**(*a*) shows a cross-sectional view of a bundle structure **5***c*.

[0061] FIG. **17**(*b*) shows a cross-sectional view of a bundle structure **5***d*.

DESCRIPTION OF EMBODIMENTS

First Embodiment

[0062] Hereinafter, a connection structure for an optical fiber **1** will be described with reference to the accompanying drawings. FIG. **1** shows the connection structure for an optical fiber **1**, FIG. **2**(*a*) is a cross-sectional view of A-A line in FIG. **1**, FIG. **2**(*b*) is a cross-sectional view of B-B line in FIG. **1**, FIG. **3**(*a*) is a cross-sectional view of C-C line in FIG. **1**, FIG. **3**(*b*) is a cross-sectional view of D-D line in FIG. **1**, FIG. **4**(*a*) is a cross-sectional view of E-E line in FIG. **1**, and FIG. **4**(*b*) is a cross-sectional view of F-F line in FIG. **1**.

[0063] The connection structure for an optical fiber **1** is a connection structure of a bundle structure **5** and multi-core fibers **3***a*, **3***b*. The multi-core fibers **3***a*, **3***b* and an optical fiber **7***a* are made of, for example, quartz glass.

[0064] The bundle structure **5** comprises optical fibers **7***a* that are bundled. The optical fibers **7***a* are signal light optical fibers that transmit signal lights. The optical fibers **7***a* are preferably single-mode optical fibers that are appropriate for long distance transmission and, in this case, the signal light is, for example, single mode at 1550 nm band.

[0065] As shown in FIG. **2**(*a*), the bundle structure **5** has a plurality of optical fibers **7***a* assembled together in a close-packed arrangement. That is, one optical fiber **7***a* is arranged at the center with six optical fibers **7***a* arranged on the circumference thereof. Therefore, all cores **15***a* of each of the optical fibers **7***a* are arranged at equal intervals. Hereinafter, unless specified, each of the optical fibers **7***a* has a fixed outer diameter from one end of the bundle structure **5** to the outside of the other end of the bundle structure **5**. The outer diameters of optical fibers **7***a* may be bundled after being adjusted by chemical etching using hydrofluoric acid and the like, drawing by heating and melting, or the like.

[0066] Although the example in the drawing shows an example having the seven optical fibers **7***a*, the present invention is not limited thereto. It is only necessary that the number of optical fibers **7***a* is six or more and the close-packed arrangement is possible. For example, the outer diameter of the optical fiber **7***a* in the center may be larger than the outer diameter of the optical fiber **7***a* on the outer circumference side. In this case, it is necessary that the optical fiber in the center is in contact with all the optical fibers on the outer circumference and the adjacent optical fibers on the outer circumference are arranged to be in contact with each other without any gaps. Using the dense bundle structure as above facilitates the optical connection with a plurality of cores of the multi-core fiber **3***a*.

[0067] The optical fibers **7***a* are arranged inside a capillary **21***b*. The optical fibers **7***a* and the capillary **21***b* are bonded with resin **19**. The capillary **21***b* is made of a material having a refractive index lower than the refractive index of the material forming the resin **19**. The resin **19** is made of a material having a refractive index lower than the refractive index of the material forming a cladding **17***a* of the optical fiber **7***a*.

[0068] The bundle structure **5** is connected to one end of the multi-core fiber **3***a*. The end face of the multi-core fiber **3***a* and the end face of the bundle structure **5** are both grounded and arranged to be facing each other. On this occasion, each of the cores **15***a* and the cores **22***a* face each other at the positions in which each of the cores **15***a* and the cores **22***a* are optically connected. The multi-core fiber **3***a* and the bundle structure **5** are connected by bonding or fusion splicing. Also, the capillary **21***a*, **21***b* are bonded. The multi-core fiber **3***a* is, for example, a single-mode fiber, and has a tapered section **27** which is an outer-diameter varying section formed on a part thereof.

[0069] As shown in FIG. **2**(*b*), the end part of the multi-core fiber **3***a* on the connection-side connected to the bundle structure **5** (the one end) is inserted into the capillary **21***a* and fixed with the resin **19**. The capillary **21***a* is made of a material having a refractive index lower than the refractive index of the material forming the resin **19**. The resin **19** is made of a material having a refractive index lower than the refractive index of the material of a cladding **23***a* of the multi-core fiber **3***a*.

[0070] Also, the outer diameter of the cladding **23***a* is approximately equivalent to or slightly larger than a circle circumscribing the optical fibers **7***a* that configure the bundle structure **5**. The cores **22***a* of the multi-core fiber **3***a* are arranged in the positions and at the pitch that correspond to the cores **15***a* of the bundle structure **5** (the optical fibers **7***a*), and the cores **15***a* and the cores **22***a* are optically connected. That is, the seven cores **22***a* in total are arranged at the center of the multi-core fiber **3***a* and at each vertex of a hexagon surrounding it. In this case, all the distances between the core **22***a* at the center and each of the six surrounding cores **22***a* are the same. Also, for the six cores **22***a*, the distances between each of the adjacent cores **22***a* are the same.

[0071] For example, the core pitch of the cores **22***a* of the multi-core fiber **3***a* is 50 μm, and, in this case, the cladding diameter of the optical fiber **7***a* forming the bundle structure **5** is 50 μm.

[0072] As shown in FIG. **3**(*a*), a resin-coating layer **25** is provided on the outer circumference of the part of the multi-core fiber **3***a* that is exposed outside the capillary **21***a*. The resin forming the resin-coating layer **25** is made of a material having a refractive index lower than the refractive index of the material forming the cladding **23***a* of the multi-core fiber **3***a*.

[0073] In FIG. **3**(*a*), the pitch of the cores **22***a* is P**1** and the outer diameter of the cladding **23***a* is D**1**. P**1** is almost equal to the outer diameter of the optical fiber **7***a*.

[0074] As shown in FIG. **3**(*b*), the outer diameter and the core pitch of the multi-core fiber **3***a* decrease in the tapered section **27**. That is, the multi-core fiber **3***a* is reduced in the diameter at the vicinity of the end which is opposite to the connection-side of the bundle structure **5** of the multi-core fiber **3***a* (the other end). Therefore, in the tapered section, a core pitch P**2** is smaller than P**1**, and a cladding diameter D**2** is smaller than D**1**. Since the thickness of the resin-coating layer **25** increases in the tapered section **27**, the overall outer diameter including the resin-coating layer **25** remains substantially constant.

[0075] As shown in FIG. **4**(*a*), the other end of the multi-core fiber **3***a* is inserted into the capillary **21***c* and fixed with the resin **19**. The capillary **21***c* is made of a material having a refractive index lower than the refractive index of the material forming the resin **19**. The resin **19** is made of a material having a refractive index lower than the refractive index of the material forming a cladding **23***a* of the multi-core fiber **3***a*. A core pitch P**3** at the other end of the multi-core fiber **3***a* is further smaller than P**2**, and an outer diameter D**3** is further smaller than D**2**.

[0076] Although the illustrated example shows the tapered section **27** being inserted into the capillary **21***c* at the middle of the tapered section, the entire tapered section **27** may be inserted into the capillary **21***c*, or only the tip side of the tapered section **27** (reduced diameter side) may be inserted into the capillary **21***c*. Also, although the illustrated example shows that the inner diameter of the capillary **21***c* is set between the maximum outer diameter part (D**1**) and the minimum outer diameter part (D**3**) of the multi-core fiber **3***a* (the outer diameters at the both ends of the tapered section **27** respectively), the inner diameter of the capillary **21***c* may be larger than D**1**.

[0077] The multi-core fiber **3***a* is, for example, fusion spliced with another multi-core fiber **3***a*. The multi-core fiber **3***b* is, for example, a single-mode fiber. As shown in FIG. **4**(*b*), the end part of the multi-core fiber **3***b* on the connection-side with the multi-core fiber **3***a* is inserted into a capillary **21***d* and fixed with the resin **19**. The capillary **21***d* is made of a material having a refractive index lower than the refractive index of the material forming the resin **19**. The resin **19** is made of a material having a refractive index lower than the refractive index of the material forming a cladding **23***b* of the multi-core fiber **3***b*.

[0078] The core pitch P**3** of the other end of the multi-core fiber **3***a* is equivalent to a core pitch P**4** of the multi-core fiber **3***b*. For example, the core pitch P**4** is 50 μm or less. If P**4** is 45 μm, for example, the core pitch at the one end of the multi-core fiber **3***a* is 50 μm and the core pitch at the other end can be 45 μm.

[0079] An outer diameter of the cladding **23***b* (D**4**) is approximately equivalent to the outer diameter of the cladding **23***a* (D**3**) or slightly larger than the outer diameter of the cladding **23***a* (D**3**). That is, D**3**≤D**4**. Also, the cores **22***b* of the multi-core fiber **3***b* are arranged in the positions corresponding to the cores **22***a* of the multi-core fiber **3***a*. Therefore, the cores **22***a* and the cores **22***b* are optically connected.

[0080] Thus, the core pitch can be changed by using the multi-core fiber **3***a*, which is a tapered fiber. That is, the multi-core fiber **3***a* can be used as a pitch-changing multi-core fiber. Therefore, it is possible to make the core pitch and the outer diameter of the bundle structure **5** larger than the core pitch and the outer diameter of the multi-core fiber **3***b*.

[0081] Next, a manufacturing method for a tapered fiber will be described. As shown in FIG. **5**(*a*), the multi-core fiber **3***a* having the resin-coating layer **25** on the outer circumference thereof is used. First, as shown in FIG. **5**(*b*), a predetermined range of the resin-coating layer **25** from the end part of the multi-core fiber **3***a* is peeled off. Next, as shown in FIG. **5**(*c*), the part in which the resin-coating layer **25** is peeled off is heated and melted to be drawn. The tapered section **27** is then formed in this way.

[0082] Next, as shown in FIG. **6**(*a*), the outer circumference of the multi-core fiber **3***a*, including the tapered section **27**, is coated by resin to form the resin-coating layer **25** once again. As above, a tapered fiber is formed. Furthermore, as shown in FIG. **6**(*b*), a part of the resin-coating layer **25** from the end part of the multi-core fiber **3***a* to the middle of the tapered section **27** is peeled off. In this state, as shown in FIG. **6**(*c*), the end part of the multi-core fiber **3***a* in which the resin-coating layer **25** is peeled off is inserted into the capillary **21***c* and fixed with the resin **19**. Furthermore, grinding the end face of the capillary **21***c* allows a connection with the multi-core fiber **3***b*.

[0083] As described above, according to the present embodiment, it is possible to easily connect the bundle structure having a relatively wide core pitch with the multi-core fiber **3***b* having a relatively narrow core pitch.

[0084] The multi-core fiber **3***a* has different mode-field diameters at the one end and the other end. Also, in this case, it is preferable to approximately match the mode-field diameter of the one end of the multi-core fiber **3***a* and the mode-field diameter of the optical fiber **7***a*. Also, it is preferable to approximately match the mode-field diameter of the other end of the multi-core fiber **3***a* and the mode-field diameter of the end part of the multi-core fiber **3***b*. This can solve the increase in the transmission loss caused by the mismatching of mode-field diameters at each connection part.

[0085] Although the multi-core fiber **3***b* and the bundle structure **5** are connected through the medium of multi-core fiber **3***a* in this embodiment, the multi-core fiber **3***a* and the multi-core fiber **3***b* may be integrated. That is, the object of the present invention can be achieved by connecting the bundle structure **5** with a multi-core fiber with varying core pitch.

Second Embodiment

[0086] Next, a second embodiment will be described. FIG. **7** shows a connecting structure for an optical fiber **1***a*, and FIG. **8**(*a*) is a cross-sectional view of G-G line in FIG. **7** and FIG. **8**(*b*) is a cross-sectional view of H-H line in FIG. **7**. For the embodiments below, the same notations will be used for the components performing the same functions as in the connection structure for an optical fiber **1**, and redundant explanations will be omitted.

[0087] The connection structure for an optical fiber **1***a* has a configuration that is almost the same as that of the connection structure for an optical fiber **1** except that a diameter-reduction section **29**, which is an outer diameter varying section, is formed at the tip part of a multi-core fiber **3***a*. The diameter-reduction section **29** can be formed by chemical etching using fluoric acid and the like.

[0088] The core pitch and the cladding diameter of the multi-core fiber **3***a* are changed by the tapered section **27**. As shown in FIG. **8**(*a*), the core pitch is P**5** and the cladding diameter is D**5** after diameter reduction. Also, as shown in FIG. **8**(*b*), the core pitch at the diameter-reduction section **29** is P**6** and the cladding diameter is D**6**. In this case, the core pitch P**5** and P**6** are equivalent, but the cladding diameter D**6** is smaller than the cladding diameter D**5**. That is, only the outer diameter becomes smaller at the diameter-reduction section **29** while the core pitch remains the same.

[0089] Here, it is preferable that the cladding diameter at the end part of the multi-core fiber **3***a* is smaller than the cladding diameter of the multi-core fiber **3***b*. For example, if D**5**>D**6**, only the outer diameter of the end part of the multi-core fiber **3***a* is reduced so that D**5**<D**6**. It is not likely for the position shifting between cores at the time of fusion splicing to occur if the cladding diameter of the end part of the multi-core fiber **3***a* matches the cladding diameter of the multi-core fiber **3***b*. That is, the diameter-reduction section **29** can match the cladding diameter of the end part of the multi-core fiber **3***a* with the cladding diameter of the multi-core fiber **3***b*.

[0090] The diameter-reduction section **29** may be formed at the end part of the multi-core fiber **3***b* as in a connection structure for an optical fiber **1***b* shown in FIG. **9**. Also, although drawing is omitted, the diameter-reduction section **29** may be formed at the both end parts of the multi-core fiber **3***a*, **3***b*. Thus, using the diameter-reduction section **29** allows multi-core fibers with different outer diameters to easily connect with each other. For example, the tapered section **27** is formed by drawing process to match the core pitch, and with the matched core pitch, the diameter-reduction section **29** may be formed by etching at the end part of the multi-core fiber on the side with a larger cladding diameter.

[0091] Thus, according to the second embodiment, it is possible to easily connect multi-core fibers having different outer diameters with each other. On this occasion, by matching the outer diameters, it is unlikely for deformation or misalignment of axis of the cores to occur at the time of fusion splicing. Although the bundle structure **5** is connected with the multi-core fibers **3***a*, **3***b* in the illustrated example, the use of the diameter-reduction section **29** and the tapered section **27** makes it effective for connecting multi-core fibers without the bundle structure **5**.

Third Embodiment

[0092] Next, a third embodiment will be described. FIG. **10** shows a connecting structure for an optical fiber **1***c*, and FIG. **11**(*a*) is a cross-sectional view of I-I line in FIG. **10**, FIG. **11**(*b*) is a cross-sectional view of J-J line in FIG. **10**, FIG. **12**(*a*) is a cross-sectional view of M-M line in FIG. **10**, and FIG. **12**(*b*) is a cross-sectional view of N-N line in FIG. **10**.

[0093] The connection structure for an optical fiber **1***c* has a configuration that is almost the same as that of the connection structure for an optical fiber **1** except that the bundle structure **5***a* is used therein. In addition to the optical fibers **7***a*, the bundle structure **5***a* further includes an optical fiber **7***b* bundled. The optical fiber **7***b* is a pump light optical fiber that transmits pump light introduction. Hereinafter, unless specified, each optical fiber **7***b* has a fixed diameter from an end face of the bundle structure **5** to the outside of the bundle structure **5** on the side of the other end.

[0094] A light source **8** for pump light is connected to the optical fiber **7***b*. The light source **8** is, for example, a multi-mode pump light emitter with a wavelength of 980 nm. Although the optical fiber **7***b* may be a single-mode or multi-mode optical fiber, a multi-mode optical fiber is preferable because the core diameter can be increased for high power. In this case, the pump light is, for example, multi-mode light in the wavelength band of 980 nm.

[0095] In the bundle structure **5***a*, the optical fibers **7***a* are in a close-packed arrangement, and the optical fiber **7***b* is further arranged on the outer circumference thereof. The outer diameter of the optical fiber **7***b* is larger than the outer diameter of the optical fiber **7***a*. The optical fiber **7***b* comprises a core **15***b* and a cladding **17***b*. The diameter of the core **15***b* of the optical fiber **7***b* is larger than the diameter of the core **15***a* of the optical fiber **7***a*. In this way, light with more power can be introduced.

[0096] The bundle structure **5***a* is spliced with one end part of the multi-core fiber **3***a*. The outer diameter of the cladding **23***a* of the multi-core fiber **3***a* is approximately equivalent to or slightly larger than a circle circumscribing the optical fibers **7***a*, **7***b* that configure the bundle structure **5***a*. The core **15***b* of the optical fiber **7***b* corresponds to the position of the cladding **23***a* of the multi-core fiber **3***a*. That is, as shown in FIG. **11**(*b*), a pump light introduction section **31** is positioned in the cladding **23***a*.

[0097] If the core pitch of the multi-core fiber **3***a* is 50 μm and the cladding thickness (the distance from the outermost core to the cladding surface) is 75 μm, the outer diameter of the optical fiber **7***b* can be increased up to 62 μm. Furthermore, if the core **15***b* of the optical fiber **7***b* is made to be included in the cladding **23***a* of the multi-core fiber **3***a*, then the outer diameter of the optical fiber **7***b* can be increased up to 73 μm.

[0098] A tapered fiber may also be used as the optical fiber **7***b*. For example, a step index multi-mode optical fiber with a core diameter of 105 μm and cladding diameter of 125 μm can be used as the optical fiber **7***b* before taper processing and the outer diameter at the connection part with the multi-core fiber **3***a* may be drawn processed by heating and melting or the like to correspond to the multi-core fiber **3***a*.

[0099] The pump light is confined in the cladding **23***a* by the resin **19**. Since the resin-coating layer **25** is provided on the part of the multi-core fiber **3***a* that is exposed out of the capillary **21***a*, the pump light is confined in the cladding **23***a*.

[0100] FIG. **12**(*a*) is an end part of the multi-core fiber **3***a* and FIG. **12**(*b*) is an end part of the multi-core fiber **3***b*. In the present embodiment, the multi-core fiber **3***b* is a rare-earth doped multi-core fiber. The rare-earth doped multi-core fiber is, for example, an erbium-doped multi-core fiber (EDF).

[0101] The claddings **23***a*, **23***b* of the multi-core fibers **3***a*, **3***b* are optically connected. Therefore, the pump light introduced into the cladding **23***a* of the multi-core fiber **3***a* is transmitted through the cladding **23***a* of the multi-core fiber **3***a* and then introduced into the cladding **23***b* of the multi-core fiber **3***b*. Introducing the pump light into the multi-core fiber **3***b* can excite an rare-earth element included in the core **22***b*, which is doped by a rare-earth material such as erbium, of the multi-core fiber **3***b* and amplify the signal light inside the core **22***b*. That is, the pump light can bring the energy level of the erbium ions in the core **22***b* to an excited state. By introducing the signal light into the core **22***b* in this state, stimulated emission of the excited erbium ions occurs and the intensity of the signal light is amplified.

[0102] The diameter-reduction section **29** may also be formed in the present embodiment on an end part of either the multi-core fiber **3***a* or **3***b*.

[0103] As described above, according to the third embodiment, the multi-core fiber **3***b* can perform optical amplification. On this occasion, since it is possible to decrease the cladding diameter of the multi-core fiber **3***b*, pump efficiency is excellent. Thus, an efficient multi-core-optical-fiber amplifier can be formed according to the present embodiment.

[0104] Also, the core pitch of the bundle structure **5***a* that is connected with the multi-core fiber **3***b* can be wider than the core pitch of the multi-core fiber **3***b*. Therefore, the outer diameter of the optical fiber **7***a* can be larger than the core pitch of the multi-core fiber **3***b*. Therefore, a connection structure for an optical fiber that is excellent in handling properties and has small optical transmission loss can be obtained.

Fourth Embodiment

[0105] Next, a fourth embodiment will be described. FIG. **13** shows a connecting structure for an optical fiber **1***d*, and FIG. **14**(*a*) is a cross-sectional view of O-O line in FIG. **13**, FIG. **14**(*b*) is a cross-sectional view of P-P line in FIG. **13**, FIG. **15**(*a*) is a cross-sectional view of Q-Q line in FIG. **13**, FIG. **15**(*b*) is a cross-sectional view of R-R line in FIG. **13**, FIG. **16**(*a*) is a cross-sectional view of S-S line in FIG. **13**, and FIG. **16**(*b*) is a cross-sectional view of T-T line in FIG. **13**.

[0106] The connection structure for an optical fiber **1***d* has a configuration that is almost the same as that of the connection structure for an optical fiber **1***c* except that a bundle structure **5***b* is used therein. As shown in FIG. **14**(*a*), the bundle structure **5***b* has an optical fiber **7***b* arranged at the center. The optical fiber **7***b* is connected with the light source **8**, which is omitted in the drawing. Also, the cladding diameter of the optical fiber **7***b* is larger than the cladding diameter of the optical fiber **7***a*. The optical fibers **7***a* are arranged close-packed on the outer circumference of the optical fiber **7***b*.

[0107] In the example shown in the drawing, ten optical fibers **7***a* are arranged close-packed on the outer circumference of the optical fiber **7***b*. In the present invention, as shown in FIG. **14**(*a*), the close-packed arrangement is an arrangement in which the optical fibers **7***a* are positioned at predetermined intervals so to be in contact with each other.

[0108] The bundle structure **5***b* is fusion spliced with the one end of the multi-core fiber **3***a*. As shown in FIG. **14**(*b*), the outer diameter of the cladding **23***a* of the multi-core fiber **3***a* is approximately equivalent to or slightly larger than the circle circumscribing the optical fibers **7***a* that configure the bundle structure **5***b*. The core **15***b* of the optical fiber **7***b* corresponds to the approximately center position of the cladding **23***a* of the multi-core fiber **3***a*. That is, the pump light introduction section **31** is positioned at the approximately center of the cladding **23***a*. The pump light introduced into the cladding **23***a* is confined inside the cladding **23***a* by the resin **19**.

[0109] As shown in FIG. **15**(*a*) and FIG. **15**(*b*), the resin-coating layer **25** is provided on the outer circumference of the multi-core fiber **3***a* that is exposed out of the capillary **21***a*. Thus, since the part of the multi-core fiber **3***a* that is exposed out of the capillary **21***a* is provided with the resin-coating layer **25** on the outer circumference, the pump light is transmitted being confined in the cladding **23***a*.

[0110] FIG. **16**(*a*) shows an end part of the multi-core fiber **3***a* and FIG. **16**(*b*) shows an end part of the multi-core fiber **3***b*. Also, in the present embodiment, the multi-core fiber **3***b* is a rare-earth doped multi-core fiber.

[0111] The claddings **23***a*, **23***b* of the multi-core fibers **3***a*, **3***b* are optically connected. Therefore, the pump light is introduced into the cladding **23***a* of the multi-core fiber **3***a*. Therefore, by introducing the signal light into the core **22***b*, stimulated emission of the excited erbium ions occurs and the intensity of the signal light is amplified.

[0112] The diameter-reduction section **29** may also be formed in the present embodiment on an end part of either of the multi-core fiber **3***a* and **3***b*.

[0113] According to the fourth embodiment, the same effects as the third embodiment can be obtained. Also, since the pump light is introduced to the approximately center of the cladding **23***a*, it is possible to introduce the pump light almost uniformly to each of the cores **22***b*.

[0114] A bundle structure **5***c* as shown in FIG. **17**(*a*) may also be used as another bundle structure having the optical fiber **7***b* arranged at the center thereof. The bundle structure **5***c* includes the optical fibers **7***a*, **7***b* having approximately the same diameters. Therefore, six signal light introduction fibers are arranged on the outer circumference of the pump light introduction fiber at the center.

[0115] Also, a bundle structure **5***d* as shown in FIG. **17**(*b*) may be used. The bundle structure **5***d* includes eight optical fibers **7***a* arranged close-packed on the outer circumference of the optical fiber **7***b*. Thus, in the present invention, it is required that the outer diameter of the optical fiber **7***b* is equal to or larger than the diameter of the optical fiber **7***a* and the optical fibers **7***a* are arranged close-packed without any gaps.

[0116] Although the embodiments of the present invention have been described referring to the attached drawings, the technical scope of the present invention is not limited to the embodiments described above. It is obvious that persons skilled in the art can think out various examples of changes or modifications within the scope of the technical idea disclosed in the claims, and it will be understood that they naturally belong to the technical scope of the present invention.

DESCRIPTION OF NOTATIONS

[0117] **1**, **1***a*, **1***b*, **1***c*, **1***d* . . . connection structure for optical fiber
[0118] **3***a*, **3***b* . . . multi-core fiber
[0119] **5**, **5***a*, **5***b*, **5***c*, **5***d* . . . optical-fiber-bundle structure
[0120] **7***a*, **7***b* . . . optical fiber
[0121] **8** . . . light source
[0122] **15***a*, **15***b* . . . core
[0123] **17***a*, **17***b* . . . cladding
[0124] **19** . . . resin
[0125] **21***a*, **21***b*, **21***c*, **21***d* . . . capillary
[0126] **22***a*, **22***b* . . . core
[0127] **23***a*, **23***b* . . . cladding
[0128] **25** . . . resin-coating layer
[0129] **27** . . . tapered section
[0130] **29** . . . diameter-reduction section
[0131] **31** . . . pump light introduction section

What is claimed is:

1. A connection structure for a multi-core fiber and an optical-fiber-bundle structure wherein:

the optical-fiber-bundle structure comprises a plurality of signal light optical fibers that transmit signal lights that are arranged at predetermined intervals;

the multi-core fiber comprises cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end thereof on the connection side that is connected with the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores; and

the multi-core fiber is a tapered fiber having a tapered section in which the outer diameter thereof varies, the outer diameter and the core pitch at the first end of the multi-core fiber being wider than the outer diameter and the core pitch at a second end of the multi-core fiber, which is on the opposite side of the connection part that is connected with the optical-fiber-bundle structure.

2. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **1**, wherein:

the multi-core fiber is further connected to a second multi-core fiber; and

the core of the second multi-core fiber is optically connected with the core of the multi-core fiber.

3. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **2**, wherein:

the second end of the multi-core fiber approximately matches with the outer diameter of an opposing end of the second multi-core fiber; and

the outer diameter of at least one of the second end of the multi-core fiber and the opposing end of the second multi-core fiber is reduced by etching without any changes in the core pitch

4. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **2**, wherein:

the optical-fiber-bundle structure further comprises a pump light optical fiber that transmits pump light; and

the second multi-core fiber is a rare-earth-doped multi-core fiber.

5. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **4**, wherein:

the pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light is connected to the cladding of the first end of the multi-core fiber.

6. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **4**, wherein:

the pump light optical fiber that transmits pump light is arranged at the center of the optical-fiber-bundle structure and the signal light optical fibers that transmit signal lights are arranged on the outer circumference of the pump light optical fiber that transmits pump light.

7. The connection structure for a multi-core fiber and an optical-fiber-bundle structure according to claim **6**, wherein:

the diameter of the pump light optical fiber that transmits pump light is larger than the diameter of the signal light optical fiber that transmits signal light that transmit signal light.

8. A connection structure for multi-core fibers, wherein:

a first multi-core fiber having a plurality of cores is connected with a second multi-core fiber having an outer diameter that is different from that of the first multi-core fiber and a plurality of cores that are optically connected with the cores of the first multi-core fiber;

at least one of the first multi-core fiber and the second multi-core fiber has an outer diameter varying section; and

the outer diameters of the end part of the first multi-core fiber on the connection-side and the end part of the second multi-core fiber on the connection part are almost equivalent.

9. The connection structure for multi-core fibers according to claim **8**, wherein:

the outer diameter varying section is formed by drawing a multi-core fiber and includes a section in which the core pitch at the cross-section thereof varies along with the outer diameter.

10. The connection structure for multi-core fibers according to claim **8**, wherein:

the outer diameter varying section is formed by etching a multi-core fiber and includes a section in which the core pitch at the cross-section thereof does not vary and only the outer diameter varies.

11. A method for exciting a rare-earth doped multi-core fiber, comprising a step of:

connecting

an optical-fiber-bundle structure comprising a plurality of signal light optical fibers that transmit signal lights, which are arranged at a predetermined pitch, and a pump light optical fiber that transmits pump light;

a multi-core fiber comprising cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end thereof on the connection-side that is connected with the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores; and an rare-earth doped multi-core fiber comprising cores and claddings that are doped with a rare-earth material, the cores and the claddings being optically connected to the cores and the claddings of the multi-core fiber respectively at a second end that is on the opposite side of the connection part of the multicore fiber and the optical-fiber-bundle structure,

wherein

the multi-core fiber is a tapered fiber having a tapered section in which the outer diameter thereof varies and the outer diameter and the core pitch at the first end of the multi-core fiber are wider than the outer diameter and the core pitch at the second end;

the pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light is connected to the cladding of the first end of the multi-core fiber;

pump light is introduced into the pump light optical fiber that transmits pump light; and

the pump light is transmitted through the cladding of the multi-core fiber, introduced into the cladding of the rare-earth doped multi-core fiber, and excites a rare-earth material included in the cores of the rare-earth doped multi-core fiber.

12. A multi-core-optical-fiber amplifier, comprising:

an optical-fiber-bundle structure comprising a plurality of signal light optical fibers that transmit signal lights, which are arranged at a predetermined pitch, and a pump light optical fiber that transmits pump light;

a multi-core fiber comprising cores, which are optically connected to the signal light optical fibers that transmit signal lights at a first end thereof on the connection-side that is connected with the optical-fiber-bundle structure, and a cladding having a refractive index lower than that of the cores and covering the cores;

an rare-earth doped multi-core fiber comprising cores and claddings that are doped with a rare-earth material, the cores and the claddings being optically connected to the cores and the claddings of the multi-core fiber respectively at a second end that is on the opposite side of the connection part of the multicore fiber and the optical-fiber-bundle structure; and

a light source that introduces pump light into the core of the pump light optical fiber that transmits pump light, wherein

the multi-core fiber is a tapered fiber having a tapered section in which the outer diameter thereof varies and the outer diameter and the core pitch at the first end of the multi-core fiber are wider than the outer diameter and the core pitch at the second end; and

the pump light optical fiber that transmits pump light is a multi-mode fiber and the core of the pump light optical fiber that transmits pump light is connected to the cladding of the first end of the multi-core fiber.

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